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Predictive Modeling of Changes in B35 Biodiesel Fuel Characteristics Treated with Ultrafine Bubbles During Storage

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ABSTRACT - This study investigated predictive modeling of changes in B35 biodiesel fuel characteristics treated with ultrafine bubbles (UFB) during storage. B35 biodiesel, consisting of 35% palm oil biodiesel and 65% diesel fuel, has been widely implemented in Indonesia as part of the national renewable energy program. However, maintaining fuel quality and stability during storage remains a major challenge. In this study, B35 biodiesel samples are treated with oxygen injection using UFB technology at durations of 10, 20, and 30 minutes and stored for seven weeks under controlled conditions. Fuel characteristics, including kinematic viscosity, density, water content, total acid number, and oxidation stability, are evaluated weekly. The results showed that increasing UFB injection duration tended to increase kinematic viscosity, density, and total acid number, while water content and oxidation stability tended to decrease during storage. The developed predictive models generally exhibited polynomial regression patterns. The models demonstrated good predictive performance for density, water content, and oxidation stability, whereas the predictive performance for viscosity was relatively lower. One-way ANOVA showed that UFB injection duration has no significant effect ($P > 0.05$) on viscosity, density, and total acid number, but significantly affected water content and oxidation stability ($P < 0.05$). These findings provide important insights into the storage stability of B35 biodiesel fuel treated with UFB technology.

Keywords : B35 biodiesel, fuel quality, storage, ultrafine bubbles

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INTRODUCTION

In recent years, the demand for environmentally friendly alternative energy sources has increased significantly due to the depletion of fossil fuel reserves and growing global concerns regarding climate change (Borowski 2022; Owusu & Asumadu-Sarkodie 2016). In Indonesia, one of the renewable energy sources that continues to be widely developed is biofuel, particularly biodiesel (Silalahi et al., 2020). Biodiesel is produced through a chemical reaction between alcohol and vegetable oil or animal fat, generating glycerol as a by-product. Compared with conventional fossil fuels, biodiesel is biodegradable, non-toxic, and characterized by lower exhaust emissions, making it a more environmentally sustainable fuel alternative (Balat 2006; Vyas et al., 2010).

To support energy diversification and reduce greenhouse gas emissions, the Indonesian government has implemented biodiesel blending programs such as B20, B30, and B35 (Wirawan et al., 2024). B35 biodiesel consists of a blend of 35% palm oil-based biodiesel and 65% diesel fuel (Mufidah et al., 2024), and its nationwide implementation has been officially adopted across Indonesia (Wirawan et al., 2024). Despite its environmental advantages, maintaining the quality and stability of biodiesel during storage remains a major challenge due to its hygroscopic nature and susceptibility to degradation (Masudi et al., 2022). Prolonged storage can alter several important fuel properties, including density, kinematic viscosity, total acid number, and calorific value, potentially exceeding the recommended fuel quality standards (Jose & Anand 2016; Mufidah et al., 2024). Biodiesel degradation generally occurs more rapidly than in conventional diesel fuel because biodiesel contains a higher proportion of unsaturated methyl esters that are highly susceptible to oxidation reactions (Jose & Anand 2016). Several factors contribute to fuel degradation during storage, including exposure to oxygen, moisture, light, heat, metal contamination, and other radical initiators (Christensen & McCormick 2014; Jain & Sharma 2010).

One emerging approach to improving biodiesel quality and storage stability is the application of ultrafine bubbles (UFB) in the fuel system (Asbanu et al., 2025; Herodian 2025). Ultrafine bubbles are gas bubbles with diameters smaller than 200 nanometers (International Organization for Standardization 2013). These bubbles possess unique physicochemical properties, including high internal pressure, large interfacial surface area, and long-term stability in liquid media (Agarwal et al., 2017; Hata et al., 2019). Previous studies have reported that the application of UFB in biodiesel fuel can enhance combustion efficiency, improve combustion performance (Asbanu et al., 2025), increase diesel engine power, and reduce specific fuel consumption (Herodian 2025).

However, studies investigating the quantitative effects of UFB addition on the changes in biodiesel fuel characteristics during storage, particularly for B35 biodiesel, remain limited. Therefore, a predictive model is needed to accurately describe the changes in the physical and chemical characteristics of B35 biodiesel during storage, both with and without UFB treatment. This study aims to develop a predictive model for changes in the characteristics of B35 biodiesel fuel treated with ultrafine bubbles during storage. The developed model is expected to provide useful insights for evaluating fuel stability and supporting the development of more reliable biodiesel storage and distribution systems for industrial and transportation applications in the future.

METHODOLOGY

This study used B35 biodiesel fuel obtained from a commercial fuel station in Bogor Regency, Indonesia. The experimental data were collected from untreated fuel samples (control) and fuel samples treated with oxygen injection using ultrafine bubble (UFB) technology at three different injection durations, namely 10, 20, and 30 minutes. Each sample was stored in sealed one-liter plastic bottles for seven weeks under controlled storage conditions, and fuel characterization tests were conducted weekly. All experiments were performed using laboratory-based experimental methods.

The evaluated fuel characteristics included kinematic viscosity, density, water content, total acid number, and oxidation stability. Each measurement was repeated three times to improve data reliability and accuracy. All laboratory analyses were conducted at the Oil and Gas Testing Center (LEMIGAS), South Jakarta, Indonesia. The experimental setup used in this study consisted of an oxygen concentrator system, an air hose, a fine bubble diffuser, and a biodiesel treatment container, as illustrated in Figure 1.

The oxygen concentrator supplied oxygen gas from ambient air at a flow rate ranging from 1 to 5 L/min with an oxygen concentration of approximately 68%. The oxygen was delivered through the air hose to the fine bubble diffuser immersed in the biodiesel fuel, generating ultrafine bubbles within the fuel medium. This injection system enabled the uniform dispersion of oxygen bubbles throughout the fuel during treatment. The UFB treatment was applied for 10, 20, and 30 minutes to evaluate its effect on changes in B35 biodiesel fuel characteristics during storage. The overall research procedure, including sample preparation, UFB treatment, storage, fuel characterization testing, predictive model development, and statistical analysis, is summarized in the research flowchart presented in Figure 2.

Research flowchart

The research procedure consisted of several sequential stages, beginning with the preparation of B35 biodiesel fuel samples and laboratory instruments. The fuel samples were then subjected to experimental treatments involving different UFB injection durations (0, 10, 20, and 30 minutes). After treatment, all samples were stored for seven weeks under controlled environmental conditions. Weekly testing was conducted to evaluate changes in fuel characteristics, including viscosity, density, water content, total acid number, and oxidation stability. The collected data were subsequently analyzed using regression-based predictive modeling and Analysis of Variance (ANOVA). Finally, the developed models were evaluated using Root Mean Square Error (RMSE) and coefficient of determination (R^2) to determine the best predictive model for describing changes in B35 biodiesel characteristics during storage.

Test instrument preparation

Prior to the experiments, all laboratory instruments were calibrated and operated in accordance with standard laboratory procedures. Instrument operation and testing procedures were conducted under the supervision of LEMIGAS

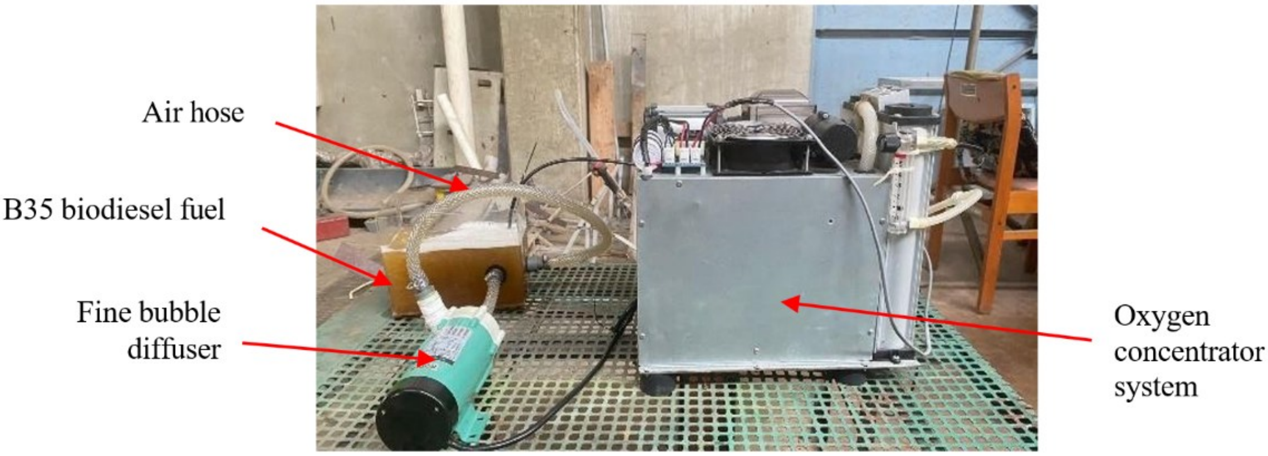

Figure 1. Experimental setup for ultrafine bubble (UFB) injection into B35 biodiesel fuel.

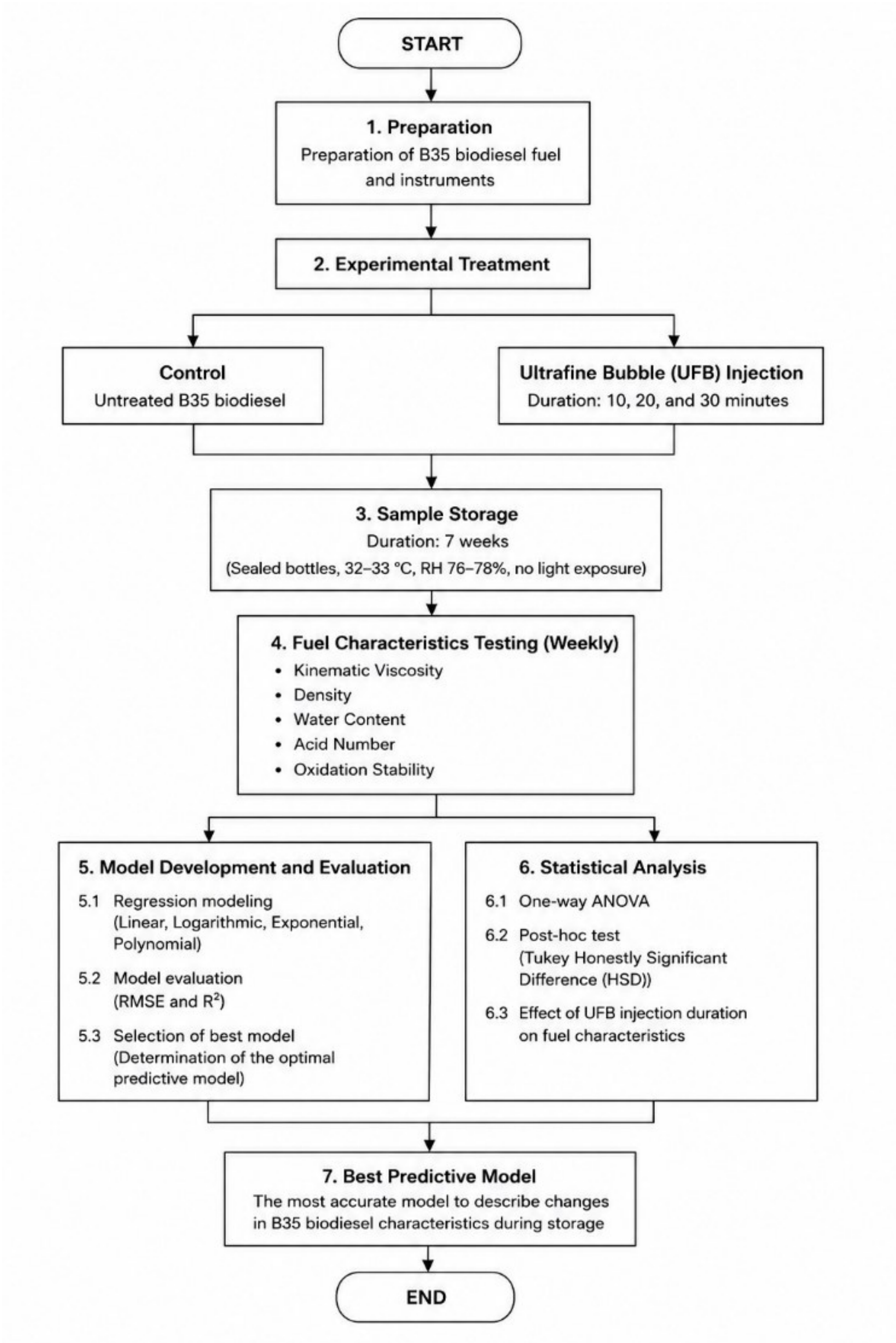

Figure. 2. Research flowchart

laboratory analysts to ensure measurement accuracy, testing consistency, and laboratory safety during the experimental process.

Fuel sample preparation

The fuel samples consisted of untreated B35 CN48 biodiesel fuel and biodiesel samples treated with oxygen injection using UFB technology at bubbling durations of 10, 20, and 30 minutes. During the injection process, the oxygen flow rate was maintained at a constant value of 1 L/min. Oxygen gas generated by the concentrator was delivered through a hose to the UFB nozzle installed in the generator system. Each treatment used 2 liters of biodiesel fuel placed inside the UFB generator tank. After the bubbling process was completed, the treated fuel samples were transferred into tightly sealed plastic bottles and stored in a closed room at a temperature of 32–33° C and relative humidity of 76–78%. Storage in sealed containers without direct light exposure was intended to minimize fuel degradation during the storage period (Mufidah et al., 2024).

Fuel characteristics testing

Fuel characterization tests were conducted weekly for seven consecutive weeks. The initial measurements were performed immediately after the UFB treatment (week 0). Before testing, all fuel samples were homogenized by gently shaking the storage bottles. Kinematic viscosity was measured using a kinematic viscometer based on ASTM D445, while density measurements were conducted using ASTM D4052 at 40°C. Oxidation stability was analyzed using an oxidation stability tester following ASTM D7545 at pressures above 700 kPa. Water content analysis was performed using the Karl Fischer titration method, whereas total acid number was determined using an automatic titration system. For viscosity and density measurements, the samples were initially rinsed using a syringe before being injected into the measurement chamber to minimize contamination. Water content measurements involved gravimetric determination of sample mass before and after injection into the Karl Fischer chamber. For total acid number analysis, approximately 10 ± 0.0090 g of biodiesel sample was mixed with a solvent consisting of 2-propanol, toluene, and distilled water in a ratio of 250:245:5 mL prior to automatic titration until the equivalence point was reached.

Model development

Predictive models were developed to describe the relationship between UFB injection duration as the independent variable and the measured fuel characteristics as dependent variables, including viscosity, density, water content, total acid number, and oxidation stability. Several regression approaches were evaluated, including linear, logarithmic, exponential, and polynomial regression models.

Simple linear regression model

Linear regression was used to determine the best linear relationship between the independent variable and the observed response variables. The linear regression equation can be expressed as:

$$y = ax + b \tag{1}$$

$$a = \frac{\sum_{n-1}^{N} x_n y_n - (\sum_{n-1}^{N} x_n)(\sum_{n-1}^{N} y_n)}{\sum_{n-1}^{N} x_n^2 - (\sum_{n-1}^{N} x_n)^2} \tag{2}$$

$$b = \frac{\sum_{n-1}^{N} y_n}{N} - b\frac{(\sum_{n-1}^{N} x_n)}{N} \tag{3}$$

where N is the number of data points, $x_n = x_1 + x_2 + \cdots x_7$ is the storage time of B35 biodiesel, $y_n = y_1 + y_2 + \cdots y_7$ is the number of dependent variables (viscosity, density, water content, total acid number, and oxidation stability) (James et al., 2023; Ostertagová 2012).

Logarithmic regression model

The logarithmic regression model describes a response pattern that changes rapidly at the beginning and gradually stabilizes over time. The model can be expressed as:

$$Y_i = \alpha + \beta\, lox\, X_i + \epsilon_i \tag{4}$$

where Y is the quantitative response, X is the predictor, α, β are the regression coefficients, and ϵ_i is the additive error for the i-th observation. In a linear logarithmic model, the literal interpretation of the estimated coefficient β is that a one-unit increase in $logX$ will result in an expected increase in Y of β units (Benoit 2011).

Exponential regression model

Exponential regression was applied to determine exponential relationships between storage duration and fuel characteristic changes. The mathematical formulation of the exponential model is presented in Equations (5)–(7) in the Appendix. This model represents an extension of linear regression using logarithmic transformation techniques (Tanaka et al., 1995).

Polynomial regression model

Polynomial regression was used to describe nonlinear relationships between storage duration and fuel characteristic changes. The general polynomial equation used in this study is presented in Equation (8) in the Appendix, where (k) represents the polynomial order (Ostertagová 2012).

Model evaluation and statistical analysis

Model performance was evaluated using Root Mean Square Error (RMSE) and coefficient of determination (R^2). RMSE was used to evaluate prediction error, while R^2 was used to determine the goodness-of-fit between predicted and observed data. Higher R^2 values indicate better predictive performance of the developed model. To evaluate the effect of UFB injection duration on fuel characteristics, one-way Analysis of Variance (ANOVA) was performed at a 95% confidence level ($P < 0.05$). When significant differences were observed, further analysis was conducted using the Tukey Honestly Significant Difference (HSD) post-hoc test.

RESULT AND DISCUSSION

Characteristics of B35 Biodiesel fuel

The Decree of the Director General of Oil and Gas Number 146.K/10/DJM/2020 concerning the Standards and Quality (Specifications) of Diesel Fuel Marketed Domestically is used as a reference in determining the minimum and maximum limits for each characteristic of 35% biodiesel blended biodiesel fuel (B35). More detailed test results for

Table 1. Characteristics of B35 Biodiesel Fuel

Number	Characteristics	Test Results[1)]	Standard[2)]	Test Method (ASTM)
1	Cetane Number	57.20	Min. 51	D613
2	Specific Gravity (15°C) (Kg/m³)	831.43	815 – 860	D4052
3	Viscosity (40°C) (mm²/s)	3.19	2.0 – 4.5	D445
4	Sulfur Content (% m/m)	0.01	Maks. 0.05	D2522
5	90% Distillation Evaporation Volume (°C)	341.10	Maks. 370	D86
6	Flash Point (°C)	65.00	Min. 55	D93
7	Cloud Point (°C)	8.00	Maks. 18	D5773
8	Pour Point (°C)	-	Maks. 18	D97
9	Water Content (ppm)	301.73	Maks. 425	D6304
10	FAME Content (% v/v)	36.00	35.00	D7371
11	Total Acid Number (mgKOH/g)	0.23	Maks. 0.6	D664
12	Visual Appearance	Clear and bright	Clear and bright	-
13	Lubricity (HFRR wear scar dia @60°C) (micron)	261.20	Maks. 460	D6079
14	Oxidation Stability (minutes)	166.27	Min. 45	D7545

the characteristics of B35 biodiesel fuel can be seen in Table 1. Table 1 shows that the B35 biodiesel fuel test results meet the quality standards set by the government. Some parameters even have values significantly higher than the minimum standards. According to Hoang (2021), a mixture of biodiesel and diesel fuel can produce good atomization, rapid evaporation, and the formation of a homogeneous mixture, which helps diesel engines achieve optimal combustion, aiming for maximum power and minimal pollution emissions.

Several important parameters that affect engine efficiency include calorific value, density, viscosity, cetane number, flash point, pour point, iodine value, and copper content (Palani et al., 2022). Parameters that affect fuel stability during storage include acid value, iodine value, peroxide value, and viscosity (Bouaid et al., 2007; Jain & Sharma 2010). Storage stability refers to the ability of a liquid fuel to maintain its physical and chemical properties without changing due to interaction with the environment (Bouaid et al., 2007). In this study, B35 biodiesel fuel was injected with UFB injection at varying injection times and then stored for seven weeks. Parameters measured during storage included kinematic viscosity, density, water content, total acid number, and oxidation stability.

Changes in characteristics of biodiesel B35 during storage

The characteristics of B35 biodiesel fuel changed during storage and were influenced by UFB injection duration. In general, viscosity, density, and total acid number tended to increase with storage time, whereas oxidation stability gradually decreased. Water content showed fluctuations during storage but generally remained lower in samples treated with longer UFB injection durations. Figure 3 presents the overall trends in the physical and chemical characteristics of B35 biodiesel fuel during seven weeks of storage under different UFB injection durations. The figure indicates that storage duration had a greater influence on fuel characteristics than UFB treatment duration; however, differences among UFB treatments were observed, particularly in water content, total acid number, and oxidation stability.

As shown in Figure 3, storage duration generally exerted a greater influence on fuel characteristics than UFB injection duration. Viscosity, density, and total acid number tended to increase throughout the storage period, whereas oxidation stability gradually decreased. Differences among UFB treatments were most apparent for water content and oxidation stability, indicating that UFB injection may influence the storage behavior of B35 biodiesel fuel.

Figure 3a and 3b show that viscosity and density values increased with storage time under all treatment conditions. Similar trends were observed regardless of UFB injection duration, indicating that storage time played a dominant role in influencing these fuel properties. These findings are consistent with those reported by Fathurrahman et al. (2024), who observed changes in fuel viscosity and density during storage. The primary cause of the increase in viscosity and density is associated with changes in fuel composition and the presence of water in the fuel during storage (Hoang & Pham 2019). Increased viscosity and density may reduce engine performance by affecting fuel atomization, evaporation, and combustion efficiency. In addition, these changes can lead to higher fuel consumption and increased emissions of CO and CO_2, although NOx emissions may decrease (Elsanusi et al., 2017; Khanjani & Sobati 2021; Koc & Abdullah 2013).

Nevertheless, the kinematic viscosity, density, and water content of B35 biodiesel fuel measured under different UFB injection durations and stored for seven weeks remained within the limits specified by relevant fuel quality standards. The measured viscosity values were well below the maximum threshold of 11.5 mm^2/s at 100°C specified in EN ISO 3104 (Cengiz et al., 2022) and remained within the viscosity range required by the Directorate General of Oil and Gas, Ministry of Energy and Mineral Resources of the Republic of Indonesia. High viscosity and density indicate reduced fuel quality and may cause operational problems such as poor atomization, incomplete combustion, sediment formation, and reduced evaporation rates (Hoang & Pham 2019). These parameters are important indicators of fuel quality because they directly influence fuel injection characteristics, spray momentum, and air–fuel

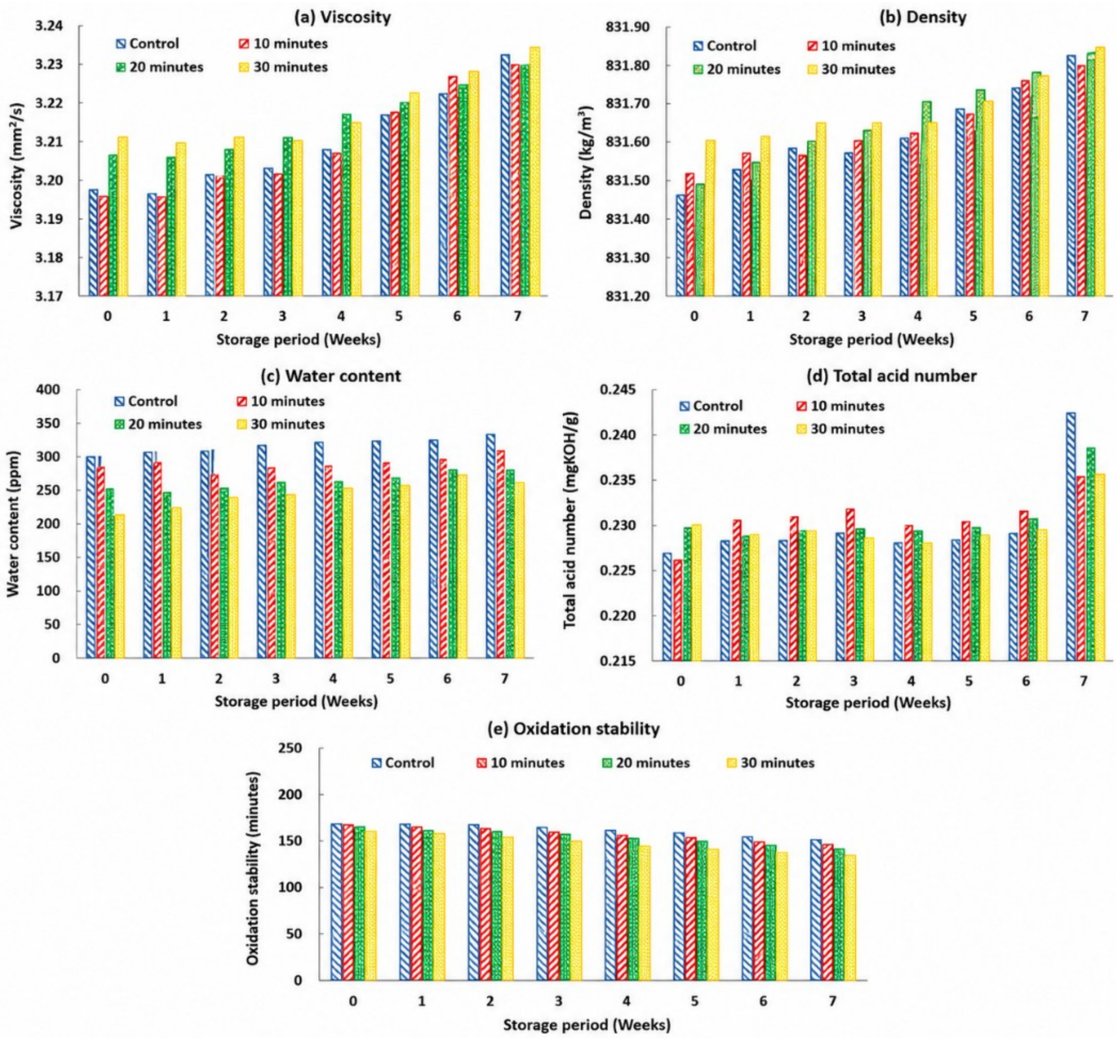

Figure 3. Changes in the physical and chemical characteristics of B35 biodiesel fuel during seven weeks of storage under different UFB injection durations. The results show increasing trends in viscosity, density, and total acid number, whereas oxidation stability decreases with storage time. (a) Viscosity, (b) Density, (c) Water Content, (d) Total Acid Number, and (e) Oxidation Stability (Wimarnaya & Herodian 2024)

mixing during combustion (Cengiz et al., 2022; Corach et al., 2021; Ramírez Verduzco 2013; Pratas et al., 2011).

The results also showed that increasing UFB injection duration tended to increase kinematic viscosity and density (Figures 3a and 3b), while reducing water content (Figure 3c) in B35 biodiesel fuel. However, viscosity, density, and water content generally increased with storage time. This phenomenon may be associated with the behavior of ultrafine bubbles in liquid media. UFBs injected under pressure can enhance gas solubility and influence the interaction between dissolved gases and water molecules within the fuel. As pressure decreases, gas release and bubble stabilization processes occur, affecting mass transfer and diffusion mechanisms within the biodiesel fuel (Sharif et al., 2019; Smirnov & Berry 2015). Furthermore, liquid viscosity and density influence bubble formation, stability, and diffusion characteristics, thereby affecting fuel properties during storage (Martín et al., 2007).

Water present in biodiesel fuel may also contribute to an increase in total acid number through the formation of carbonic acid (H_2CO_3) from dissolved CO_2. Carbonic acid can dissociate into bicarbonate (HCO_3^-) and hydrogen ions (H^+), thereby increasing fuel acidity. The presence of UFBs may enhance CO_2 dissolution and contribute to changes in the total acid number (Pal et al., 2025). This trend can be observed in Figure 3d, where the total acid number of untreated biodiesel (control) increased steadily and showed a marked increase during the seventh week of storage. In

Table 2. Analysis of variance (ANOVA) for the regression model equation and coefficient of change in the characteristics of B35 biodiesel fuel during storage.

	Sum of Squares	Degrees of Freedom (DF)	Mean Square	F-Value	Prob > F
Model: Viscosity					
- Regression	0.000	3	0.000	1.337	0.286
- Residual	0.002	24	0.001		
- Total	0.003	27			
Model: Density					
- Regression	0.016	3	0.005	0.672	0.577
- Residual	0.195	24	0.008		
- Total	0.212	27			
Model: Water content					
- Regression	18660.976	3	6220.325	31.27	<0.001
- Residual	4774.224	24	198.926		
- Total	23435.200	27			
Model: Total acid number					
- Regression	0.000	3	0.000	1.654	0.203
- Residual	0.000	24	0.000		
- Total	0.000	27			
Model: Oxidation stability					
- Regression	181.930	3	60.643	7.394	0.001
- Residual	196.853	24	8.202		
- Total	378.783	27			

contrast, the UFB-treated samples exhibited fluctuations but generally followed an increasing polynomial trend. Despite this increase, the highest total acid number observed after seven weeks of storage (0.243 mgKOH/g) remained well below the maximum limit of 0.6 mgKOH/g specified by the Directorate General of Oil and Gas, Ministry of Energy and Mineral Resources of the Republic of Indonesia. The total acid number in B35 fuel is the free fatty acid resid ue from crude oil or fat used as a raw material for biodiesel production. High total acid number in fuel can cause corrosion and other problems in engines and fuel systems (Mufidah et al., 2024).

The increase in total acid number during storage is a result of increased peroxides and hydrolysis of fatty acid methyl esters into acids (Bouaid et al., 2007; Jose & Anand 2016). UFB injection into B35 biodiesel fuel is the addition of oxygen produced from an oxygen concentrator, which is then passed through a fine bubble diffuser. The results showed that oxidation stability decreased with the length of UFB injection time and the length of storage time (Figure 3e). The availability of oxygen in B35 biodiesel fuel stimulates oxidation reactions and accelerates the fuel degradation process during storage. Fatty acid chain oxidation is a complex process that occurs through various mechanisms. Biodiesel oxidation is caused by the unsaturation of the fatty acid chain and the presence of double bonds in the molecule, which provides a high level of reactivity with O_2, especially when in contact with air or water (Jain & Sharma 2010).

The results of the Analysis of Variance (ANOVA) with a 5% confidence level showed that the UFB injection time did not significantly affect viscosity, density, and total acid number. However, it significantly affected water content and oxidation stability (Table 2). Table 2 shows that the longer the UFB injection time in B35 fuel, the lower the water content and oxidation stability. While the reduced water content in B35 fuel is generally considered beneficial, the water content increases during storage. This increase in water content during storage causes an increase in

Table 3. Polynomial model of changes in the characteristics of B35 biodiesel fuel during storage with UFB injection time treatment.

Parameter	Polynomial Equation	R²	RMSE
Viscosity	$y = (-0.000001k^2 - 0.00004k + 0.001)x^2 + (-0.000009k^2 + 0.0003k - 0.0008)x + (0.00001k^2 + 0.00008k + 3.1926)$	0.5427	0.022
Density	$y = (0.00001k^2 - 0.0003k + 0.0047)x^2 + (-0.0001k^2 + 0.0028k + 0.0155)x + (0.0002k^2 - 0.0016k + 831.46)$	0.9276	0.036
Water Content	$y = (-0.0032k^2 + 0.0979k - 0.1724)x^2 + (0.0395k^2 - 0.9875k + 5.3528)x + (-0.1094k^2 + 0.4397k + 304.18)$	0.9378	7.221
Total Acid Number	$y = (0.000001k^2 - 0.00003k + 0.0004)x^2 + (-0.000007k^2 + 0.0002k - 0.0017)x + (0.000004k^2 - 0.00003k + 0.2285)$	0.7739	0.002
Oxidation Stability	$y = (-0.0004k^2 + 0.0153k - 0.1114)x^2 + (0.004k^2 - 0.1451k - 0.4719)x + (-0.0054k^2 - 0.0436k + 166.03)$	0.9711	0.812

Description: k = bubbling time (minutes), x = week.

kinematic viscosity, density, and total acid number, and reduces oxidation stability.

Model development and validation

A model for changes in the characteristics of B35 biodiesel fuel was developed based on the relationship between UFB injection time (the independent variable) and the dependent variables (kinematic viscosity, density, water content, and oxidation stability). The models evaluated included linear, exponential, logarithmic, and polynomial regression. Model error was determined based on the Mean Squared Error (RMSE) and the coefficient of determination (R^2). The analysis results show that changes in the characteristics of B35 biodiesel fuel form a polynomial model, as presented in Table 3. The developed models were subsequently validated by comparing the predicted values with the experimental observations using the coefficient of determination (R^2) and root mean square error (RMSE). Figure 4 presents the relationship between the predicted and actual values for viscosity, density, water content, total acid number, and oxidation stability of B35 biodiesel fuel during storage.

As shown in Figure 4, the predictive models generally exhibited good agreement between the predicted and actual values, indicating their capability to describe changes in biodiesel fuel characteristics during storage. The density, water content, and oxidation stability models demonstrated strong predictive performance, as evidenced by the close distribution of data points around the fitted regression curves and their high coefficients of determination (R^2 = 0.9276). In contrast, the viscosity and total acid number models showed greater data dispersion, suggesting that these parameters were more difficult to predict accurately due to their more complex variation patterns during storage.

The validation results indicate that the density, water content, and oxidation stability models can predict changes in fuel characteristics with high accuracy. The oxidation stability model exhibited the best predictive performance, with an R^2 value of 0.9711 and an RMSE value of 0.812, followed

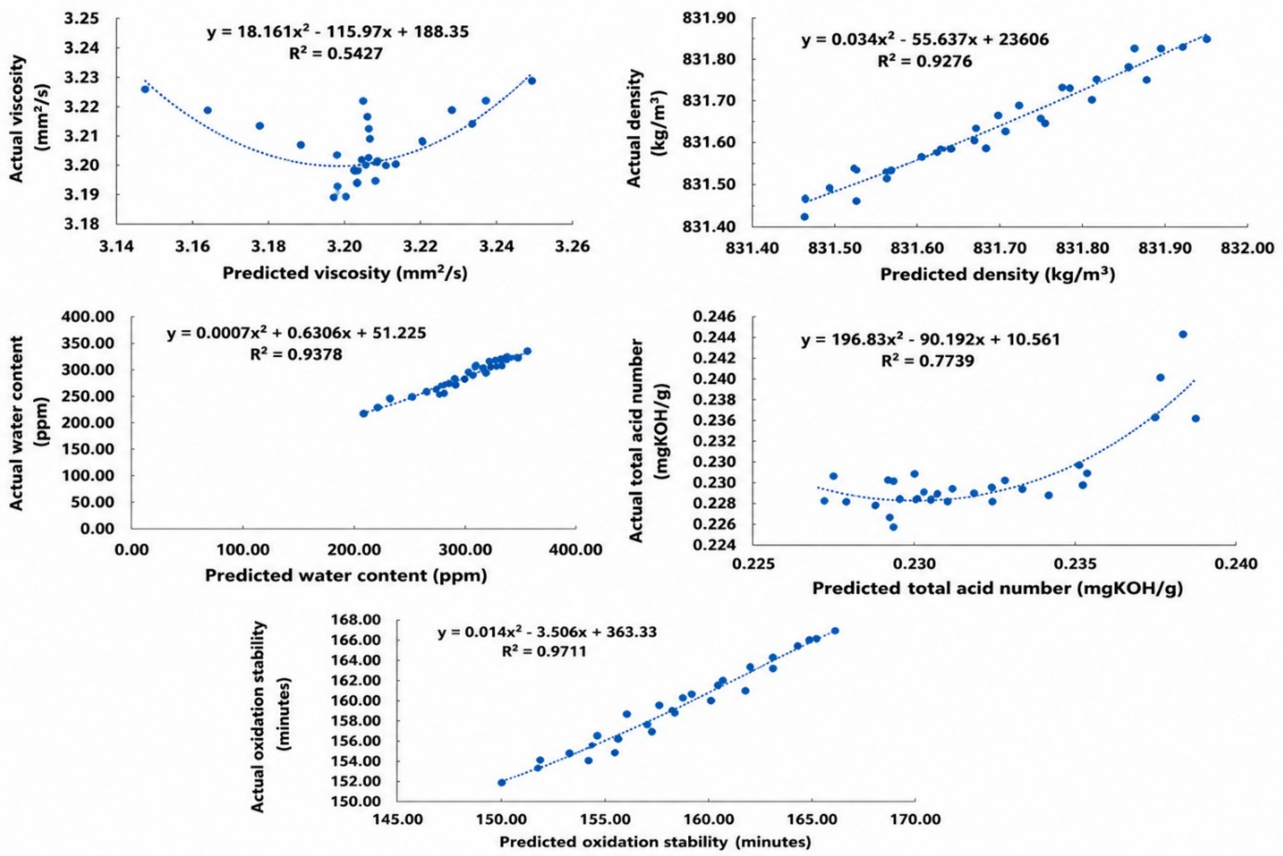

Figure 4. Validation of the predictive models for changes in B35 biodiesel fuel characteristics during storage: (a) viscosity, (b) density, (c) water content, (d) total acid number, and (e) oxidation stability.

by the water content model (R^2 = 0.9378; RMSE = 7.221) and the density model (R^2 = 0.9276; RMSE = 0.036). These results indicate that the developed polynomial models are capable of describing the effects of storage duration and UFB treatment on these fuel properties. The total acid number model showed moderate predictive capability, with an R^2 value of 0.7739 and an RMSE value of 0.002. Although the model was able to capture the general trend of increasing acidity during storage, fluctuations in the measured values reduced the overall prediction accuracy.

The viscosity model exhibited the lowest predictive performance, with an R^2 value of 0.5427 and an RMSE value of 0.022. This finding suggests that viscosity changes during storage are influenced by more complex mechanisms that may not be fully represented by the polynomial model developed in this study. According to Zheng et al. (2020), the viscosity of diesel–biodiesel blends tends to fluctuate and gradually increase during storage due to oxidation reactions, moisture interactions, and changes in fuel composition. Such dynamic behavior makes viscosity more difficult to predict using conventional regression models. Therefore, advanced approaches, such as artificial intelligence or machine learning-based models, may provide improved predictive accuracy for viscosity estimation in future studies.

CONCLUSION

Based on the experimental results, increasing the duration of ultrafine bubble (UFB) injection tended to increase the kinematic viscosity, density, and total acid number of B35 biodiesel fuel during storage, while water content and oxidation stability decreased with longer UFB injection duration. The changes in fuel characteristics observed throughout the seven-week storage period indicate that UFB treatment influences both the physical and chemical stability of biodiesel fuel. The predictive models developed in this study generally exhibited polynomial regression patterns in describing changes in B35 biodiesel characteristics during storage.

The developed models demonstrated good predictive performance for density, water content, and oxidation stability, while the predictive performance for viscosity was relatively lower compared with the other parameters. Statistical analysis using one-way ANOVA showed that UFB injection duration had no significant effect ($P > 0.05$) on viscosity, density, and total acid number, but significantly affected water content and oxidation stability ($P < 0.05$). Overall, the findings of this study provide important insights into the storage stability of B35 biodiesel fuel treated with UFB technology and may contribute to the development of more reliable biodiesel storage and distribution strategies for future industrial and transportation applications.

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DECLARATIONS

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

Author Contribution

Sam Herodian: Writing – original draft, Data curation, Conceptualization. Emi Yuliarita: Methodology & Data curation. Ahmad Thoriq: Writing – review & editing, Supervision, Methodology. Erniati: Writing – review & editing, Supervision, Methodology. Anto Tri Sugiarto: Resources, methodology, writing – review & editing.

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None

Competing interest

None

The use of AI or AI-assisted technologies

None

GLOSSARY OF TERMS AND SYMBOLS

Terms & Symbols	Definition	Unit
ASTM	American Society for Testing and Materials	International standards organization
ANOVA	Analysis of Variance	Statistical analysis method
B20	Blend of 20% biodiesel and 80% diesel fuel	Fuel blend composition
B30	Blend of 30% biodiesel and 70% diesel fuel	Fuel blend composition
B35	Blend of 35% biodiesel and 65% diesel fuel	Fuel blend composition
CN48	Cetane Number 48	Fuel ignition quality index
CO	Carbon Monoxide	Combustion gas
CO_2	Carbon Dioxide	Greenhouse gas
DF	Degrees of Freedom	Statistical parameter
EN ISO 3104	European Standard for Petroleum Product Viscosity Testing	Testing standard
H_2CO_3	Carbonic Acid	Weak acid formed from dissolved CO_2
HCO_3^-	Bicarbonate Ion	Carbonic acid dissociation product

HSD	Honestly Significant Difference	Tukey post-hoc statistical test
k	Bubbling or UFB injection time	minute
kPa	Kilopascal	Pressure unit
LEMIGAS	Oil and Gas Testing Center, Indonesia	Research and testing institution
NOx	Nitrogen Oxides	Pollutant gases formed during combustion
O_2	Oxygen Gas	Oxidizing gas
P	Probability value (P-value)	Statistical significance indicator
R^2	Coefficient of Determination	Regression goodness-of-fit indicator
RMSE	Root Mean Square Error	Prediction error indicator
SSE	Sum of Squared Errors	Regression error parameter
SST	Total Sum of Squares	Total data variation
UFB	Ultrafine Bubbles	Bubble diameter < 200 nm
x	Storage duration	week
y	Response or dependent variable	Predicted/measured parameter
$\hat{y}$	Predicted value of response variable	Regression prediction
yi	Observed value of response variable	Experimental observation
β	Regression coefficient	Regression parameter
β_0	Intercept coefficient	Regression constant
β_1, β_2, β_3	Polynomial regression coefficients	Regression parameters
εi	Random error term	Statistical residual
µm	Micrometer	Length unit
mm^2/s	Square millimeter per second	Kinematic viscosity unit
mgKOH/g	Milligram potassium hydroxide per gram	Total acid number unit
ppm	Parts per million	Concentration unit
°C	Degree Celsius	Temperature unit

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APPENDIX

$$\ln y = ax + b \tag{7}$$

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 x^2 + \beta_3 x^3 + \cdots + \beta_k x^k, e_i, \quad \text{for } i = 1,2, \ldots.. n \tag{8}$$

$$\text{RMSE} = \frac{\text{SSE}}{\text{df}_E} = \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n-(k+1)} \tag{9}$$

$$R^2 = 1 - \frac{\text{SSE}}{\text{SST}} = \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y}_i)^2} \tag{10}$$