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STABILITY AND PHYSICOCHEMICAL PROPERTIES OF B35 BIODIESEL**

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Effects of Oxygen Ultrafine Bubble Injection on the Storage Stability and Physicochemical Properties of B35 Biodiesel

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Abstrak

The implementation of B35 biodiesel has significantly contributed to renewable energy utilization in the transportation sector. However, the higher fatty acid methyl ester (FAME) content in B35 biodiesel increases its susceptibility to physicochemical degradation during storage, making storage stability a critical concern. Oxygen ultrafine bubble (UFB) technology has recently been reported to improve diesel combustion performance, yet its influence on the storage stability of biodiesel has not been comprehensively investigated. This study evaluated the effects of oxygen UFB injection on the physicochemical properties and storage stability of B35 biodiesel during seven weeks of storage. Normal B35 biodiesel (CN48) and oxygen UFB-treated B35 biodiesel were comparatively evaluated based on kinematic viscosity, density, water content, total acid number, and oxidation stability at weekly intervals. The experimental results demonstrated that oxygen UFB treatment increased viscosity and density while reducing water content and oxidation stability, whereas the total acid number remained relatively unaffected immediately after treatment. During storage, both untreated and UFB-treated fuels exhibited gradual increases in viscosity, density, water content, and acid number, accompanied by a decline in oxidation stability. Nevertheless, all measured parameters remained within the quality limits specified by the Indonesian Directorate General of Oil and Gas Standard No. 170.K/HK.02/DJM/2023 after seven weeks of storage. These findings indicate that although oxygen ultrafine bubble injection modifies several physicochemical characteristics of B35 biodiesel, it does not compromise its storage quality within the investigated storage period. The results provide important insights into the feasibility of applying oxygen ultrafine bubble technology to biodiesel fuels while maintaining compliance with national fuel quality standards.

Keywords: B35 biodiesel; ultrafine bubble; storage stability; physicochemical properties; oxidation stability

Introduction

The increasing demand for renewable and sustainable energy has accelerated the implementation of biodiesel blends in diesel engines worldwide. In Indonesia, the government has progressively increased the mandatory biodiesel blending ratio from B10 in 2014 to B15 in 2015, B20 in 2016, B30 in 2020, and most recently B35 in 2023 as part of its national strategy to strengthen energy security, reduce dependence on imported fossil fuels, and support energy transition policies. The implementation of the B35 program is expected to provide economic benefits through higher domestic biodiesel utilization while simultaneously reducing greenhouse gas emissions from the transportation sector (BPDPKS, 2023; Hardiyanto & Prawoto, 2023).

Compared with conventional petroleum diesel, biodiesel possesses several advantageous characteristics, including lower sulfur content and improved environmental performance. However, the higher proportion of fatty acid methyl esters (FAME) also introduces several

technical challenges associated with long-term fuel quality. Biodiesel contains oxygenated compounds and unsaturated fatty acids that are more susceptible to oxidative degradation than petroleum diesel. During oxidation, these compounds produce hydroperoxides, organic acids, and polymeric products that gradually alter the physicochemical properties of the fuel (Goto et al., 2010). Furthermore, biodiesel exhibits stronger hygroscopic characteristics than conventional diesel, allowing it to absorb moisture more readily during storage, which subsequently promotes microbial growth and accelerates fuel deterioration. Consequently, storage stability has become one of the most critical issues in maintaining biodiesel quality throughout transportation and storage processes.

Fuel degradation during storage may significantly affect several critical quality parameters, including kinematic viscosity, density, water content, total acid number, and oxidation stability. Changes in these properties influence fuel atomization, combustion characteristics, injector performance, corrosion behavior, and overall engine reliability. For this reason, Indonesian fuel specifications establish strict quality requirements for B35 biodiesel, particularly regarding parameters directly related to storage stability (ESDM, 2023).

Recently, ultrafine bubble (UFB) technology has attracted considerable attention in various engineering applications because of its capability to generate micro- and nanoscale gas bubbles with exceptionally high gas dissolution efficiency. In diesel fuel applications, oxygen UFB has been introduced as an approach to increase dissolved oxygen concentration, thereby improving combustion characteristics. Previous studies demonstrated that oxygen UFB treatment enhanced diesel engine performance by increasing engine power while reducing specific fuel consumption (Gultom, 2023). In addition, oxygen UFB has been reported to reduce exhaust emissions, including SO₂, NO, and NO_x, from diesel engines operated with various diesel fuels (Farafisha, 2023). These findings indicate that oxygen UFB technology offers promising potential for improving diesel combustion performance.

Despite these promising findings, previous investigations have primarily focused on engine performance and exhaust emission characteristics immediately after oxygen UFB treatment. The influence of oxygen ultrafine bubbles on the long-term physicochemical stability of biodiesel during storage has received limited attention. Because oxygen simultaneously functions as an oxidizing agent, increasing dissolved oxygen concentration may accelerate oxidation reactions in biodiesel containing unsaturated FAME molecules. Consequently, improvements in combustion performance may be accompanied by undesirable changes in storage stability, particularly in viscosity, density, water content, total acid number, and oxidation stability. To date, comprehensive experimental studies evaluating these storage-related parameters under controlled storage conditions remain scarce. This represents an important knowledge gap before oxygen UFB technology can be considered for practical implementation in commercial biodiesel fuels.

The present study addresses this gap by evaluating the effects of oxygen ultrafine bubble injection on the storage stability of commercial B35 biodiesel (CN48) during seven weeks of storage. The investigation comparatively examines untreated and oxygen UFB-treated fuels through periodic measurements of kinematic viscosity, density, water content, total acid number, and oxidation stability. The measured properties are subsequently evaluated against the Indonesian B35 fuel quality specifications to determine whether oxygen UFB treatment affects compliance with national fuel standards. The findings provide new insights into the feasibility of applying oxygen ultrafine bubble technology to biodiesel fuels while maintaining acceptable physicochemical stability during storage.

Materials and Methods

2.1 Fuel Sample

Commercial B35 biodiesel (CN48), consisting of 65% petroleum diesel and 35% fatty acid methyl ester (FAME), was used as the experimental fuel. The fuel complied with the Indonesian B35 fuel specification established by the Directorate General of Oil and Gas (ESDM, 2023). Untreated B35 biodiesel served as the control sample, whereas three additional fuel samples were prepared by oxygen ultrafine bubble (UFB) injection with bubbling durations of 10, 20, and 30 min, designated as UFB-10, UFB-20, and UFB-30, respectively. The overall experimental design, treatment conditions, storage duration, and monitored physicochemical parameters are summarized in Table 1.

Table 1. Experimental design and analytical parameters used in this study.

Bahan bakar yang digunakan	Perlakuan		Parameter yang diamati
	Lama proses bubbling	Lama penyimpanan	
Biosolar B35	10 menit	Minggu ke-0	Viskositas kinematik, Densitas, Kandungan air Angka asam, Stabilitas oksidasi.
	20 menit	sampai	
	30 menit	minggu ke-7	

2.2 Oxygen Ultrafine Bubble Treatment

Oxygen ultrafine bubbles were generated using an oxygen concentrator connected to an ultrafine bubble generator. The oxygen produced by the concentrator was continuously supplied into the generator, where ultrafine bubbles were formed and dispersed into the biodiesel sample. Three bubbling durations (10, 20, and 30 min) were applied to evaluate the effect of oxygen exposure on fuel properties. The experimental setup of the oxygen concentrator and ultrafine bubble generator used in this study is shown in Fig. 1.



Figure 1. Oxygen concentrator and ultrafine bubble generator used for biodiesel treatment (reproduced from Farafisha, 2023).

Following treatment, each fuel sample was immediately transferred into sealed storage bottles for subsequent physicochemical analyses.

2.3 Storage Conditions

All fuel samples were stored in sealed containers under laboratory conditions for seven weeks. Physicochemical analyses were performed immediately after UFB treatment (week 0) and subsequently at weekly intervals until the seventh week. This storage period was selected to

evaluate the evolution of fuel quality during short-term storage while following the recommended handling practice for biodiesel blends.

2.4 Physicochemical Characterization

Five physicochemical parameters closely associated with biodiesel storage stability were evaluated throughout the storage period: kinematic viscosity, density, water content, total acid number, and oxidation stability. Kinematic viscosity and density were simultaneously measured using an Anton Paar SVM 3001 Cold Properties analyzer. Water content was determined using Karl Fischer titration (AQUA 40.00 Oil Module), while total acid number was measured using a Metrohm 916 autotitrator. Oxidation stability was evaluated using an Anton Paar RapidOxy 100 oxidation stability tester operating under accelerated oxidation conditions according to the instrument procedure.

2.5 Experimental Procedure

The overall experimental procedure consisted of four sequential stages: (1) preparation of untreated B35 biodiesel samples; (2) oxygen ultrafine bubble injection for 10, 20, and 30 min; (3) storage of untreated and treated biodiesel samples for seven weeks; and (4) weekly determination of kinematic viscosity, density, water content, total acid number, and oxidation stability. The overall experimental workflow is illustrated in Fig. 2.

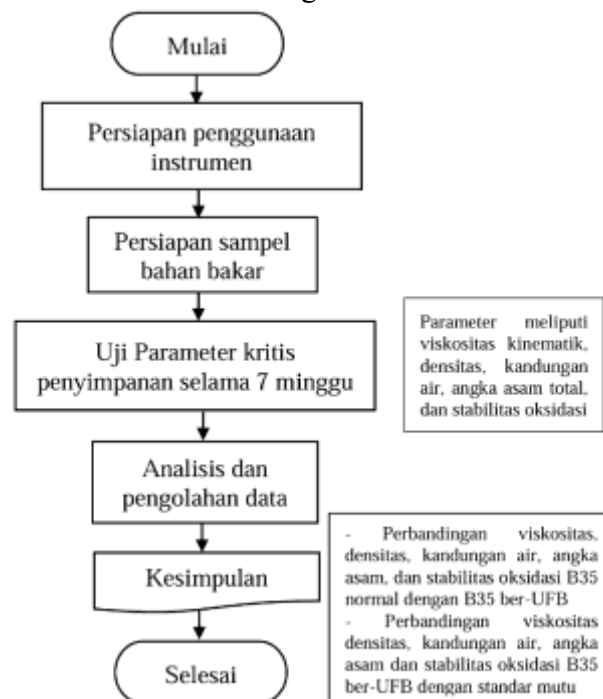


Fig 2. Experimental workflow for oxygen ultrafine bubble treatment and storage stability evaluation of B35 biodiesel.

2.6 Data Analysis

The physicochemical properties obtained from untreated and oxygen UFB-treated biodiesel samples were comparatively analyzed to evaluate the effect of oxygen ultrafine bubble treatment and storage duration. Temporal changes in each parameter were assessed through weekly observations over the seven-week storage period. The measured values were subsequently compared with the quality requirements specified in the Indonesian National Standard for B35

biodiesel (Directorate General of Oil and Gas Decree No. 170.K/HK.02/DJM/2023) to determine whether the treated fuels remained within the acceptable quality limits during storage.

Results and Discussion

3.1 Initial Physicochemical Characteristics of B35 Biodiesel

Prior to oxygen ultrafine bubble (UFB) treatment, the physicochemical properties of the commercial B35 biodiesel were evaluated to verify compliance with the Indonesian fuel quality specification. Five key physicochemical parameters associated with biodiesel storage stability, namely kinematic viscosity, density, water content, total acid number (TAN), and oxidation stability, were selected for subsequent investigation. As summarized in Table 2, the untreated B35 biodiesel satisfied all quality requirements specified by the Directorate General of Oil and Gas (Decree No. 170.K/HK.02/DJM/2023), confirming that the fuel was suitable as the baseline material for evaluating the effects of oxygen UFB treatment during storage.

Table 2. Initial physicochemical properties of commercial B35 biodiesel and comparison with the Indonesian fuel quality specification.

Property	Unit	Measured value	Indonesian specification
Density	kg m ⁻³	831.43	815–880
Kinematic viscosity	mm ² s ⁻¹	3.193	2.0–5.0
Water content	mg kg ⁻¹	301.73	≤400
Total acid number	mg KOH g ⁻¹	0.2267	≤0.30
Oxidation stability	min	166.27	≥45

The initial characterization confirmed that the untreated biodiesel possessed excellent storage-related properties before oxygen enrichment. In particular, the oxidation stability reached 166.27 min, which was considerably higher than the minimum requirement of 45 min, indicating a high resistance to oxidative degradation. Likewise, the measured viscosity, density, water content, and total acid number all complied with the Indonesian B35 specification. These results demonstrate that any subsequent physicochemical changes observed during storage originated from oxygen UFB treatment and the natural aging process rather than from inadequate initial fuel quality.

Immediately after oxygen UFB treatment, several physicochemical properties exhibited measurable changes. The most noticeable effects were observed in viscosity, density, water content, and oxidation stability. Increasing the bubbling duration progressively increased viscosity and density, whereas water content decreased as oxygen exposure became longer. Conversely, oxidation stability declined with increasing oxygen injection time, indicating that elevated dissolved oxygen promoted the initial stage of biodiesel oxidation. In contrast, the total acid number remained nearly unchanged immediately after treatment, suggesting that the oxidation reactions initiated during bubbling had not yet progressed sufficiently to generate appreciable amounts of acidic degradation products.

These observations indicate that oxygen ultrafine bubbles primarily altered the physicochemical equilibrium of biodiesel through enhanced oxygen dissolution rather than extensive chemical degradation. Because the bubbling process was relatively short, oxidation was likely limited to the formation of primary oxidation intermediates such as hydroperoxides, while secondary oxidation products, including aldehydes, ketones, organic acids, and polymeric compounds, had not yet accumulated. This interpretation agrees with the well-established

oxidation mechanism of biodiesel reported by Goto et al. (2010) and Knothe (2006), in which hydroperoxide formation precedes the generation of acidic and polymeric degradation products during prolonged storage.

Overall, the initial characterization demonstrates that oxygen UFB treatment slightly modified several physicochemical properties without immediately compromising compliance with the Indonesian fuel quality specification. Therefore, the untreated B35 biodiesel provided a reliable reference condition, while the oxygen-enriched samples established the initial state for evaluating storage-induced physicochemical changes during the subsequent seven-week storage period..

3.2 Effect of Oxygen Ultrafine Bubble Treatment on Kinematic Viscosity During Storage

Kinematic viscosity is one of the most important fuel properties because it directly influences fuel injection, atomization quality, spray formation, and combustion efficiency in diesel engines. Throughout the seven-week storage period, all fuel samples exhibited a gradual increase in viscosity regardless of treatment. However, oxygen UFB-treated biodiesel consistently showed higher viscosity than untreated fuel, with the greatest increase observed in the sample subjected to the longest bubbling duration (30 min). Although viscosity increased throughout storage, all values remained well below the maximum limit of $5.0 \text{ mm}^2 \text{ s}^{-1}$ specified for Indonesian B35 biodiesel. The temporal variation in kinematic viscosity for all experimental groups is presented in Fig. 3.

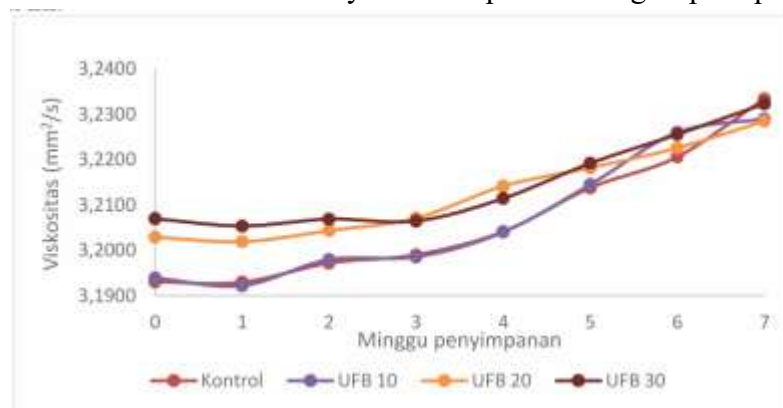


Figure 3. Changes in kinematic viscosity of untreated and oxygen UFB-treated B35 biodiesel during seven weeks of storage.

The immediate increase in viscosity following oxygen UFB treatment indicates that dissolved oxygen promoted the initial oxidation of unsaturated FAME molecules. Oxygen molecules dispersed as ultrafine bubbles possess a substantially larger interfacial area than conventional gas bubbles, enhancing oxygen dissolution within the fuel. This condition facilitates the initiation of free-radical oxidation reactions that gradually modify the molecular structure of biodiesel. As oxidation progresses, peroxide compounds and higher molecular-weight oxidation products are generated, increasing intermolecular interactions and consequently raising fuel viscosity. Similar behaviour has been reported for biodiesel exposed to oxidative environments during storage (Knothe, 2006; Kaseem et al., 2018).

Storage duration further amplified the viscosity increase for all treatments. This behaviour is characteristic of biodiesel degradation because prolonged exposure to dissolved oxygen promotes continuous oxidation of FAME molecules. Besides oxidative reactions, gradual moisture absorption and possible microbial contamination may also contribute to viscosity increases by producing insoluble degradation products within the fuel. Nevertheless, the viscosity increment

observed in this study remained relatively small, indicating that oxidation during seven weeks of storage had not reached an advanced stage capable of severely degrading fuel quality.

An interesting observation is that the difference between UFB-treated samples and the control became less pronounced as storage progressed. Initially, oxygen injection produced measurable viscosity differences among treatments; however, all samples gradually converged toward similar values after several weeks of storage. This behaviour suggests that natural oxidation occurring during storage eventually became the dominant mechanism governing viscosity evolution, thereby reducing the relative influence of the initial oxygen enrichment. Consequently, oxygen UFB primarily accelerated the early stage of oxidation rather than fundamentally altering the long-term degradation pathway of B35 biodiesel.

From an engineering perspective, the observed viscosity increase is unlikely to adversely affect diesel engine operation because all measured values remained comfortably within the national specification. Therefore, oxygen UFB treatment can be considered compatible with short-term storage from the standpoint of fuel viscosity.

3.3 Effect of Oxygen Ultrafine Bubble Treatment on Fuel Density During Storage

Fuel density determines the mass of fuel delivered during each injection event and therefore influences combustion efficiency, engine power output, and fuel consumption. Similar to viscosity, fuel density exhibited a gradual increase throughout the storage period for both untreated and oxygen UFB-treated biodiesel. The highest density was consistently observed in the UFB-30 sample, while untreated biodiesel showed the lowest values. Nevertheless, all measured densities remained well within the acceptable range of 815–880 kg m⁻³ specified for commercial B35 biodiesel. The changes in fuel density during the seven-week storage period are presented in Fig. 4.

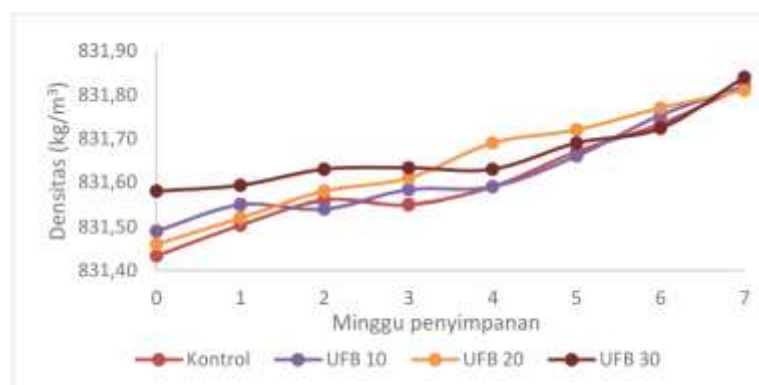


Figure 4. Changes in density of untreated and oxygen UFB-treated B35 biodiesel during seven weeks of storage.

The increase in density immediately after oxygen UFB treatment is closely associated with enhanced oxygen dissolution within the fuel. Although the absolute increase was relatively small, the additional dissolved oxygen slightly altered the overall mass-to-volume ratio of the biodiesel. Moreover, early-stage oxidation reactions generated oxygen-containing intermediate compounds that contributed to a marginal increase in fuel density. These observations closely parallel the behaviour observed for viscosity, indicating that both parameters are governed by similar physicochemical processes during oxygen enrichment.

Storage time further increased density across all treatments. As shown in Fig. 4, all samples exhibited a gradual upward trend throughout the storage period, with the UFB-treated biodiesel

generally maintaining slightly higher density values than the untreated control. This behaviour is commonly associated with the gradual formation of oxidation products, moisture accumulation, and possible microbial activity occurring during biodiesel storage. Water possesses a higher density than diesel fuel; therefore, gradual moisture absorption resulting from the hygroscopic nature of biodiesel contributes to the observed increase in density. In addition, oxidative degradation changes the molecular composition of the fuel by producing heavier oxygenated compounds, further increasing fuel density. Similar storage-induced density increases have previously been reported for biodiesel blends stored under constant environmental conditions (Kaseem et al., 2018).

Although oxygen UFB accelerated the initial increase in density, the differences among treatments became progressively smaller with increasing storage time. This observation again suggests that the natural aging process of biodiesel eventually dominates fuel degradation regardless of the initial oxygen concentration introduced by ultrafine bubbles. Therefore, while oxygen UFB modifies the initial physicochemical characteristics of B35 biodiesel, its long-term influence on density remains limited during the seven-week storage period investigated. From a practical perspective, the relatively stable density values indicate that oxygen UFB treatment does not significantly alter fuel metering characteristics or compromise compliance with Indonesian fuel quality standards. Consequently, the application of oxygen ultrafine bubble technology appears compatible with short-term biodiesel storage from the standpoint of fuel density.

3.4 Effect of Oxygen Ultrafine Bubble Treatment on Water Content During Storage

Water content is one of the most critical indicators of biodiesel storage quality because excessive moisture accelerates hydrolysis, promotes microbial contamination, and facilitates oxidative degradation during storage. Throughout the seven-week storage period, all B35 biodiesel samples exhibited an increasing trend in water content, regardless of oxygen UFB treatment. However, oxygen ultrafine bubble treatment initially reduced the water content of biodiesel, and the reduction became more pronounced with increasing bubbling duration. The lowest initial water content was observed in the UFB-30 sample, whereas the untreated biodiesel exhibited the highest moisture level. Despite the gradual increase during storage, all samples remained below the maximum allowable limit of 400 ppm specified by the Indonesian fuel quality standard for B35 biodiesel. The variation in water content throughout the storage period is presented in Fig. 5.

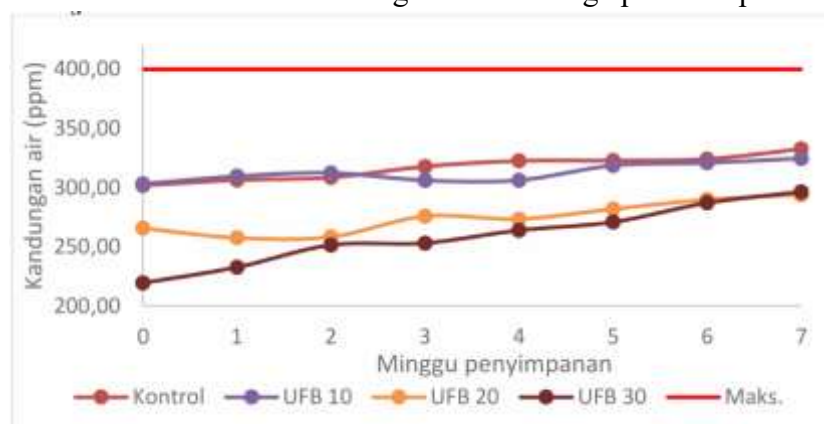


Figure 5. Changes in water content of untreated and oxygen UFB-treated B35 biodiesel during seven weeks of storage. The red horizontal line indicates the maximum allowable water content (400 ppm) specified by the Indonesian B35 fuel standard.

The reduction in water content immediately after oxygen UFB treatment suggests that the bubbling process facilitated the removal or displacement of dissolved moisture within the biodiesel. During ultrafine bubble injection, continuous gas dispersion promotes mixing and increases gas-liquid interfacial interactions, which may enhance the release of dissolved water molecules from the fuel matrix. This phenomenon became more evident as bubbling duration increased from 10 to 30 min, indicating that longer oxygen exposure improved the effectiveness of moisture reduction.

As illustrated in Fig. 5, all fuel samples experienced a gradual increase in water content during storage despite their different initial moisture levels. Nevertheless, oxygen UFB-treated biodiesel consistently exhibited lower water content than the untreated control throughout most of the storage period, particularly for the UFB-20 and UFB-30 treatments. Furthermore, all measured values remained well below the specification limit of 400 ppm, indicating that moisture accumulation during storage was insufficient to compromise fuel quality.

Although UFB treatment reduced the initial water content, prolonged storage resulted in a gradual increase in moisture for all treatments. Biodiesel is inherently hygroscopic because fatty acid methyl ester (FAME) molecules readily absorb water vapor from the surrounding environment. Even under sealed storage conditions, periodic opening of sample containers during weekly analyses allows humid air to enter the storage bottles, resulting in gradual moisture accumulation through condensation. Similar behaviour has been reported for biodiesel during storage, where atmospheric moisture progressively increases the water content of fuel blends (Khalid et al., 2003; Fregolente et al., 2012).

Increasing water content has important implications for biodiesel stability. Water serves as a favorable medium for microbial growth, and microbial metabolism may subsequently accelerate the formation of organic acids and other degradation products that influence viscosity, density, and oxidation stability. Consequently, water accumulation is often regarded as one of the earliest indicators of biodiesel deterioration during storage. The relatively modest increase observed throughout the present study indicates that moisture absorption remained limited during the seven-week storage period and did not yet reach levels capable of substantially degrading fuel quality.

Interestingly, although oxygen UFB treatment introduced additional oxygen into the biodiesel, the treated samples consistently maintained lower water content than the untreated control throughout most of the storage period. This finding suggests that oxygen ultrafine bubble treatment does not promote moisture accumulation and may even provide a short-term drying effect immediately after treatment. Nevertheless, because all samples showed increasing water content over time, appropriate storage practices remain essential to preserve biodiesel quality during prolonged storage. From an operational perspective, the final water content of all treatments remained well below the Indonesian specification of 400 ppm, indicating that oxygen UFB-treated B35 biodiesel retained acceptable storage quality with respect to moisture during the investigated storage period.

3.5 Effect of Oxygen Ultrafine Bubble Treatment on Total Acid Number During Storage

The total acid number (TAN) is widely used to evaluate the extent of biodiesel degradation because it reflects the accumulation of acidic oxidation products generated during storage. High acidity may accelerate corrosion of storage tanks, fuel distribution systems, and engine components, making TAN one of the essential quality parameters for commercial biodiesel. Unlike viscosity, density, and water content, oxygen ultrafine bubble treatment produced no measurable

immediate effect on the total acid number of B35 biodiesel. All fuel samples exhibited nearly identical TAN values immediately after oxygen injection regardless of bubbling duration, indicating that oxygen dissolution alone was insufficient to generate detectable quantities of acidic degradation products. This observation suggests that although oxidation reactions may have been initiated during UFB treatment, they had not progressed to the secondary oxidation stage responsible for producing organic acids. The variation in total acid number during the seven-week storage period is presented in Fig. 6.

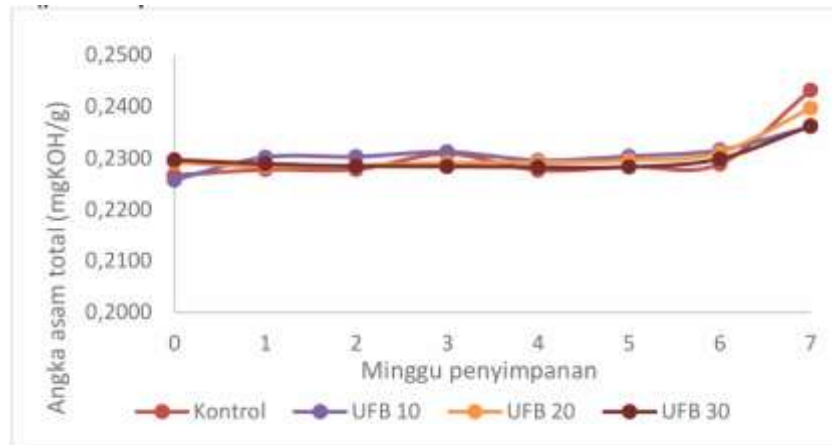


Figure 6. Changes in total acid number (TAN) of untreated and oxygen UFB-treated B35 biodiesel during seven weeks of storage.

During storage, the total acid number remained relatively stable throughout the first six weeks for both untreated and UFB-treated biodiesel. As shown in Fig. 6, only minor fluctuations were observed during the early storage period, while a noticeable increase became evident in the seventh week for all treatments. The untreated biodiesel (Control) exhibited the highest TAN at the end of storage, whereas the UFB-treated samples followed a similar increasing trend but remained at comparable levels. This delayed response indicates that acid formation occurred gradually and was primarily associated with long-term oxidative degradation rather than with the oxygen injection process itself. Biodiesel oxidation generally proceeds through several sequential stages, beginning with free-radical initiation, followed by hydroperoxide formation, and finally decomposition into aldehydes, ketones, low-molecular-weight organic acids, and polymeric compounds. Consequently, measurable increases in TAN typically appear only after oxidation has progressed sufficiently (Goto et al., 2010; Wibowo et al., 2016).

The relatively small increase in TAN throughout the storage period also corresponds well with the observed changes in water content. Although moisture gradually increased during storage, the overall water concentration remained below the critical level that would strongly promote microbial proliferation. Since microbial activity is closely associated with organic acid production, limited microbial growth likely contributed to the slow increase in TAN observed in the present study. This relationship further supports the importance of controlling moisture during biodiesel storage to minimize both microbial contamination and acid formation.

Another noteworthy observation is that oxygen UFB treatment did not substantially accelerate acid formation despite increasing dissolved oxygen within the fuel. The close similarity among the four curves in Fig. 6 indicates that the oxidation promoted by ultrafine bubbles remained at an early stage during the investigated storage period and did not significantly increase the concentration of acidic oxidation products. This observation is consistent with the results presented in the previous sections, where viscosity and density exhibited only moderate increases

while oxidation stability showed a more pronounced decline. Collectively, these findings suggest that oxygen UFB treatment primarily promoted the initiation stage of oxidation without substantially accelerating the formation of secondary acidic degradation products within seven weeks of storage.

From a practical standpoint, the highest TAN measured at the end of the storage period remained considerably lower than the Indonesian maximum specification of $0.60 \text{ mg KOH g}^{-1}$, demonstrating that all fuel samples maintained acceptable chemical stability throughout the investigation. Nevertheless, because TAN showed a tendency to increase during the final stage of storage, longer-term investigations extending beyond seven weeks are recommended to determine whether prolonged storage eventually leads to accelerated acid formation in oxygen UFB-treated biodiesel.

3.6 Effect of Oxygen Ultrafine Bubble Treatment on Oxidation Stability During Storage

Oxidation stability is one of the most critical quality indicators for biodiesel because it determines the fuel's resistance to oxidative degradation during storage. Biodiesel containing higher concentrations of unsaturated fatty acid methyl esters (FAME) is inherently more susceptible to oxidation than conventional petroleum diesel. Consequently, oxidation stability directly influences the formation of degradation products that subsequently affect viscosity, density, acid number, and overall fuel quality.

Among all physicochemical parameters evaluated in this study, oxidation stability exhibited the greatest sensitivity to oxygen ultrafine bubble (UFB) treatment. Immediately after oxygen injection, all UFB-treated samples showed lower oxidation stability than untreated B35 biodiesel, and the reduction became progressively greater as bubbling duration increased. The UFB-30 sample consistently exhibited the shortest oxidation induction time, whereas the untreated control maintained the highest oxidation stability throughout the entire storage period. These observations clearly indicate that increasing dissolved oxygen concentration accelerated the susceptibility of biodiesel to oxidative reactions. The variation in oxidation stability during the seven-week storage period is presented in Fig. 7.

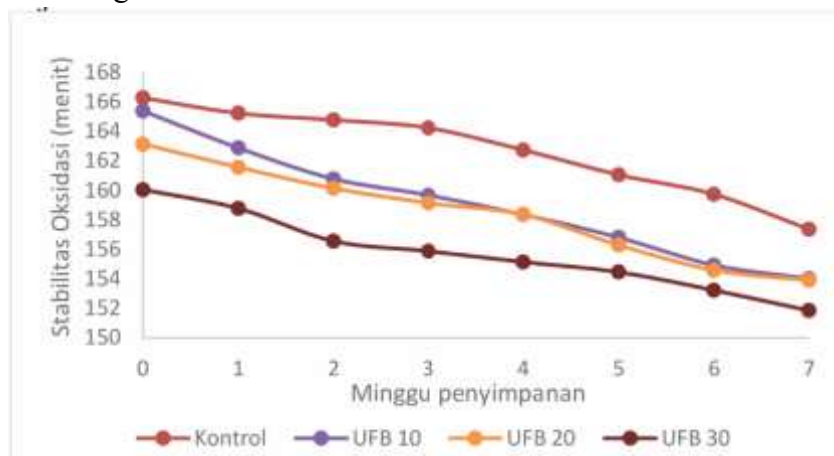


Figure 7. Changes in oxidation stability of untreated and oxygen UFB-treated B35 biodiesel during seven weeks of storage.

The reduction in oxidation stability can be explained by the role of oxygen as the primary oxidizing agent in biodiesel degradation. Ultrafine bubbles possess an extremely large gas-liquid interfacial area, allowing oxygen to dissolve more efficiently into the fuel than conventional bubbling methods. The elevated dissolved oxygen concentration facilitates free-radical initiation

reactions involving unsaturated FAME molecules, thereby accelerating the formation of hydroperoxides during the early stage of oxidation. Although these primary oxidation products do not immediately alter the acid number, they reduce the oxidation induction period measured by accelerated oxidation tests, indicating that the fuel becomes more susceptible to further degradation during storage. Similar oxidation mechanisms have been described by Knothe (2006) and Hartikka et al. (2013), who reported that oxygen availability strongly influences biodiesel oxidation kinetics.

As illustrated in Fig. 7, oxidation stability decreased continuously throughout the storage period for all experimental groups. The untreated biodiesel (Control) consistently maintained the highest oxidation stability, whereas the UFB-treated samples exhibited progressively lower values with increasing bubbling duration. Among the treated fuels, the UFB-30 sample showed the lowest oxidation stability throughout the investigation, indicating that prolonged oxygen UFB treatment increased the susceptibility of biodiesel to oxidative degradation. Nevertheless, all measured oxidation stability values remained substantially higher than the Indonesian minimum specification of 45 min, demonstrating that the treated biodiesel maintained acceptable oxidative resistance during the seven-week storage period.

Storage duration further reduced oxidation stability for all experimental groups. This trend reflects the continuous oxidation of FAME molecules during storage, where hydroperoxides gradually decompose into aldehydes, ketones, organic acids, and polymeric compounds. As oxidation proceeds, the antioxidant capacity naturally present in biodiesel is progressively consumed, shortening the oxidation induction period. The present findings therefore demonstrate that oxidation stability is governed by two simultaneous processes: the immediate increase in dissolved oxygen caused by UFB treatment and the natural aging process occurring during storage.

An interesting observation is that the difference between treated and untreated fuels remained relatively constant throughout the storage period. Although oxidation stability continuously decreased in all samples, oxygen UFB treatment did not appear to accelerate degradation exponentially after storage began. Instead, oxygen injection primarily shifted the initial oxidation state of the fuel, while the subsequent degradation rate remained relatively similar among treatments. This behavior suggests that oxygen UFB influences the initial oxidative condition rather than fundamentally changing the oxidation pathway during storage.

From an engineering perspective, reduced oxidation stability represents the principal limitation associated with oxygen UFB technology. Nevertheless, even the lowest oxidation stability measured for the UFB-30 sample after seven weeks remained substantially higher than the minimum Indonesian specification of 45 min. Therefore, despite accelerating the initial oxidation process, oxygen UFB treatment did not compromise compliance with national fuel quality requirements during the investigated storage period.

Considering these findings, oxygen UFB technology appears suitable for applications involving short-term fuel utilization, where improved combustion performance is prioritized over prolonged storage. However, if oxygen-enriched biodiesel is intended for long-term storage, the incorporation of antioxidant additives may be considered to suppress oxidation reactions and preserve fuel stability, as previously suggested in biodiesel oxidation studies (Schober & Mittelbach, 2004).

3.7 Compliance with Indonesian Fuel Standards and Practical Implications

An important objective of this study was to determine whether oxygen ultrafine bubble treatment alters the storage performance of B35 biodiesel sufficiently to exceed the quality limits

established by Indonesian fuel regulations. Although oxygen UFB modified several physicochemical properties, all measured parameters remained within the specification limits established by the Directorate General of Oil and Gas (Decree No. 170.K/HK.02/DJM/2023) throughout the seven-week storage period.

The highest kinematic viscosity recorded in this study remained considerably lower than the maximum allowable value of $5.0 \text{ mm}^2 \text{ s}^{-1}$, while the measured densities were well within the specified range of $815\text{--}880 \text{ kg m}^{-3}$. Likewise, water content never exceeded the regulatory limit of 400 ppm, despite the gradual moisture absorption observed during storage. The total acid number also remained substantially below the maximum allowable value of $0.60 \text{ mg KOH g}^{-1}$, indicating that oxidation had not progressed sufficiently to produce excessive acidic degradation products. Furthermore, oxidation stability remained more than three times higher than the minimum specification of 45 min, even for the UFB-30 treatment, demonstrating that oxygen-enriched biodiesel maintained an adequate resistance to oxidative degradation throughout the experimental period.

These results demonstrate that oxygen ultrafine bubble treatment modifies the physicochemical characteristics of biodiesel without compromising compliance with national fuel quality standards during short-term storage. From a practical perspective, this finding is significant because previous studies primarily focused on the combustion advantages of oxygen UFB technology, including increased engine power, reduced specific fuel consumption, and lower exhaust emissions. The present study complements those investigations by demonstrating that such performance improvements are not accompanied by unacceptable deterioration of fuel quality during storage.

Nevertheless, several practical considerations should be addressed before large-scale implementation. The continuous decline in oxidation stability indicates that oxygen-enriched biodiesel is more susceptible to oxidative degradation than untreated fuel. Therefore, prolonged storage beyond the period investigated in this study may require additional stabilization strategies, including antioxidant additives, controlled storage temperature, moisture management, or oxygen-limiting storage systems. Such preventive measures are particularly relevant for biodiesel distribution networks where storage periods may exceed several months.

Another important implication concerns fuel management practices. The gradual increases in water content and total acid number observed during storage highlight the importance of minimizing air exchange within storage tanks to reduce moisture ingress and microbial contamination. Maintaining storage tanks under sealed conditions and avoiding unnecessary opening during storage may contribute to preserving biodiesel quality regardless of oxygen UFB treatment.

Overall, the present findings demonstrate that oxygen ultrafine bubble technology represents a promising approach for enhancing diesel fuel applications while maintaining acceptable physicochemical stability during short-term storage. The results provide experimental evidence supporting the feasibility of applying oxygen UFB technology to commercial B35 biodiesel under practical storage conditions. Future investigations should extend the storage duration beyond seven weeks, evaluate the effectiveness of antioxidant additives, and examine the combined influence of oxygen UFB treatment and long-term storage on engine durability and fuel performance under real operating conditions.

Conclusions

This study evaluated the influence of oxygen ultrafine bubble (UFB) treatment on the physicochemical properties and storage stability of commercial B35 biodiesel during seven weeks of storage. Oxygen UFB treatment immediately modified several fuel properties by increasing kinematic viscosity and density while reducing water content and oxidation stability. In contrast, the total acid number remained essentially unchanged immediately after oxygen injection, indicating that the initial oxidation process had not yet progressed to the formation of acidic degradation products. During storage, all fuel samples exhibited gradual physicochemical changes characterized by increasing viscosity, density, water content, and total acid number, accompanied by decreasing oxidation stability. These trends were consistent with the natural oxidative aging of biodiesel and were slightly more pronounced in oxygen UFB-treated fuels. Nevertheless, all measured parameters remained well within the quality limits specified by the Indonesian Directorate General of Oil and Gas (Decree No. 170.K/HK.02/DJM/2023) throughout the seven-week storage period, demonstrating that oxygen UFB treatment did not compromise compliance with national fuel quality standards during short-term storage. The findings demonstrate that oxygen ultrafine bubble technology can be applied to commercial B35 biodiesel without causing unacceptable deterioration of fuel quality during short-term storage. Although oxygen enrichment slightly reduced oxidation stability, the overall physicochemical characteristics remained suitable for practical application. These results provide new experimental evidence regarding the storage behaviour of oxygen UFB-treated biodiesel and support the feasibility of integrating ultrafine bubble technology into diesel fuel systems where improved combustion performance is desired. Future research should investigate longer storage periods, evaluate the effectiveness of antioxidant additives in mitigating oxidation, and examine the combined effects of oxygen ultrafine bubble treatment on long-term fuel stability, engine durability, and real-world operating performance.

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