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Evaluation of Corrosion Effects in Diesel-Biodiesel and Diesel-Biodiesel-HVO Blends on Metals for Fuel Storage Systems

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Indonesia has implemented B35, as a mixture of 35% biodiesel and 65% diesel fuel. Considering the potential of higher biodiesel blends, it is important to explore the use of hydrotreated vegetable oil (HVO) in fuel blends. HVO can improve cetane number, heating value, sulfur content, and oxidation stability. However, further research is needed, particularly regarding compatibility of materials used in storage and distribution systems. Common materials include stainless steel, carbon steel, and brass. This study aimed to assess effects different fuel mixtures on corrosion rates of stainless steel 304, carbon steel SA 516 Gr.70, and brass immersed in B30, B30D10 (30% biodiesel, 60% diesel fuel, and 10% HVO), and B40. Corrosion rates were tested using ASTM G31 over 2160 hours at room temperature. Results showed that stainless steel 304 had the lowest corrosion rate, followed by carbon steel SA 516 Gr.70 and brass. However, brass led to fuel degradation, notably in cleanliness, water content, and oxidation stability, making it unsuitable for storing diesel-biodiesel and diesel-biodiesel-HVO blends. HVO positively influenced biodiesel-diesel blends, resembling diesel fuel and reducing total acid number and water content, thus lowering corrosion rates of metals.

Keywords: *Corrosion rate, Corrosion, Immersion, Biodiesel, HVO*

1. Introduction

Currently, vegetable fuel is an alternative liquid fuel to reduce dependence on fossil fuels. The utilization of vegetable fuel, specifically biodiesel and HVO, as diesel blends have increased. Biodiesel exhibits distinct characteristics from diesel fuel, as it is an oxygenated fuel. It is due to biodiesel being an ester compound produced through transesterification processes using short-chain alcohols like methanol, forming fatty acid methyl ester (FAME) [1]. As a renewable fuel, biodiesel presents several advantages, including reducing emissions without significantly affecting fuel consumption [2].

On the other hand, due to its ester compound nature, biodiesel exhibits higher hygroscopicity than diesel fuel and possesses solvent properties, which can present various technical challenges during practical applications and may affect the contacting materials [3,4]. Ensuring high-quality standards through specification improvements is a crucial requirement for the sustainable utilization of biodiesel blends, particularly about key parameters such as water content, monoglyceride content, and oxidation stability. To increase water content, careful technology selection is required, since certain processes, such as vacuum evaporation, might have a negative impact on oxidation stability and other characteristics [5].

On the other hand, HVO is a vegetable-based fuel with a chemical composition that is similar to diesel fuel,

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consisting of hydrocarbons derived from renewable sources. HVO exhibits distinct characteristics, such as a higher flash point and lower viscosity, compared to diesel fuel. Unlike diesel fuel, which primarily contains paraffinic, naphthalene, and aromatic components, HVO does not contain aromatics, which improves environmental air quality. HVO offers advantages in terms of cetane number, calorific value, sulfur-free content, aromatic-free content, glyceride-free content, and exhibits oxidation stability similar to diesel fuel [6,7].

In addition to improving the specifications of biodiesel, HVO, and their blends, proper storage and distribution systems play a vital role in maintaining quality by standards. It is crucial to select suitable materials for storing and delivering biodiesel, HVO, and their blends. Stainless steel, carbon steel, and brass are commonly used metallic materials in storage and distribution systems. Stainless steel is widely employed in biofuel facilities for reactors, process pipes, process pumps, storage tanks, and heat exchangers [8]. Carbon steel is utilized for B30 (30% biodiesel and 70% diesel) storage tanks [9]. Brass, a popular material consisting of copper, zinc, and lead (Cu-Zn-Pb), is commonly utilized in building plumbing systems and manufacturing various components for industrial and commercial purposes [10]. Stainless steel 304 offers high heat resistance, excellent mechanical processing properties, and superior corrosion resistance, making it extensively utilized across various sectors [11]. Carbon steel is one of the most widely used metal alloys in the world and it is frequently utilized in extreme industrial circumstances, particularly in oil/gas extraction and processing, rendering it susceptible to corrosion [12].

Compatibility tests on stainless steel, carbon steel, and brass are needed to examine the resistance of these metals to biodiesel and HVO as blends with diesel fuel, as well as their impact on the quality of the fuel mixture. According to Sorate and Bhale [13], Fazal *et al.* [14], and Hu *et al.* [15], biodiesel is more corrosive than diesel fuel. Biodiesel shows slightly higher corrosive properties towards copper and bronze than aluminum, brass, and stainless steel, while fuel properties such as the acid number and kinematic viscosity of biodiesel and diesel fuel did not change significantly [13]. Biodiesel is more corrosive to copper compared to brass, aluminum, cast iron, mild carbon steel, and stainless steel. The TAN (Total Acid Number) value of the fuel exceeded the standard limit after copper is exposed to biodiesel, while density and viscosity remained within acceptable ranges [14,15]Click or tap here to enter text.. Research on the influence of biodiesel-diesel fuel blends on metals was conducted by Alves *et al.* [16] (B7) and Kugelmeier *et al.* [17] (B7, B15, and B30). Methyl and ethyl esters had little influence on metal degradation. However, the release of metal ions from the surface of stainless steel during corrosion caused biodiesel oxidation, altering the fuel composition and quality, and reducing oxidation stability [16]. The fuel mixture had no significant effect on carbon steel, stainless steel, and aluminum, except for copper, which experienced intense corrosion attack, mass loss, and degradation in the fuel blend. Copper had a stronger impact on the stability of biodiesel oxidation [17].

Based on previous studies, the comprehensive investigation of high-ratio blends of biodiesel-diesel fuel and biodiesel-diesel fuel-HVO exceeding 30% has not been extensively explored. However, the current global trend of biodiesel utilization towards higher biodiesel blending ratio, such as implementing B35 (35% biodiesel and 65% diesel fuel) in Indonesia since February 2023. Indeed, conducting such studies is critical for understanding the characteristics of the fuel. It allows for appropriate implementation preparation, including recommended materials for fuel storage systems. Therefore, this study aims to analyze the corrosion effects on metals for fuel storage systems against palm-based biodiesel blends, specifically B30 (30% biodiesel and 70% diesel fuel), B30D10 (30% biodiesel, 60% diesel fuel, and 10% HVO), and B40 (40% biodiesel and 60% diesel fuel). The primary objective of this study is to determine the corrosion rate of stainless steel 304, carbon steel SA 516 Gr.70, and brass as commonly used metals in fuel storage systems. In this research, the effect of biodiesel and HVO on the materials was also compared. Additionally, it aims to assess the long-term impact on fuel quality after contact with these metals, leading to valuable recommendations for practical applications.

2. Experimental Methods

2.1 Fuel for Immersion Testing

The fuel used for immersion testing included Biodiesel (B100) derived from palm oil, obtained from APROBI, as well as diesel fuel (B0) and HVO (D100) obtained from PT Kilang Pertamina Internasional. The fuels were blended to create different mixtures: B30 (30% biodiesel and 70% diesel fuel), B30D10 (30% biodiesel, 60% diesel fuel, and 10% HVO), and B40 (40% biodiesel and 60% diesel fuel). The biodiesel, diesel fuel, and HVO (Hydrotreated Vegetable Oil) comply with the specifications enforced in Indonesia [18-20]. The fuels used for immersion testing were tested to clarify that the fuels within the specification according to Director General of Oil and Gas Decree No. 185.K/HK.02/DJM/2022, as shown in Table 1.

2.2 Preparation of Coupons

The metallic materials used for corrosion testing were stainless steel 304 (C: 0.037%, Mn: 0.933%, Si: 0.501%, S: 0.009%, P: 0.015%, Cr: 18.53%, Ni: 8.00%), carbon steel SA 516 Gr.70 (C: 0.23%, Si: 0.28%, Mn: 0.94%, P: 0.009%, S: 0.005%), and brass (Cu: 57.2%, Zn: 40.2%). All of the materials were obtained from the local market. Stainless steel 304 and brass came in round bars, while carbon steel SA 516 Gr.70 came in a sheet plate. The chemical composition of the metals was analyzed using Bruker Q4 Tasman Optical Emission Spectroscopy (OES). Coupons of stainless steel 304 (diameter 24.9 mm, thickness 5.5 mm, hole diameter 2.9 mm) and brass (diameter 24.9 mm, thickness 5.5 mm, hole diameter 2.9 mm) were prepared using cutting machines, lathe machines, and drilling machines (to create holes for coupon support). The carbon steel SA 516 Gr.70 coupon (diameter 24.9 mm, thickness 5.5 mm, hole diameter 2.9 mm) was prepared using Electrical Discharge Machining (EDM), cutting machines, and drilling machines. The coupon temperature was carefully controlled throughout the preparation process to avoid structural changes in the metals. All metal surfaces were smoothed using silicon carbide abrasive paper (ranging from grade 400 to 1200) and finally polished with 0.3 μm alumina. Subsequently, the coupons were cleaned with acetone and dried using a heat gun. The weight of each coupon was measured with a scale that had a precision of four decimal places. Prior to immersion testing, the coupons were stored in a desiccator to protect them from exposure to ambient air.

2.3 Immersion Test and Data Processing

The corrosion testing of metals was conducted by ASTM G31, with an immersion period of 2160 hours (3 months) at room temperature (25 ± 2ºC). Three duplicate coupons were used for each test solution (B30, B30D10, and B40). The volume of the test solution was calculated based on the minimum ratio to the coupon's surface area, which was 0.20 mL/mm^2. Following the immersion test, the coupons were cleaned with acetone to ensure no residual solution remained and weighed. Any corrosion deposits on the coupons were carefully removed using 0.3 μm alumina without altering the original surface, followed by another round of cleaning with acetone and dried with a heat gun. The coupons were then weighed to determine the weight loss, which was calculated by subtracting the initial weight of the coupon before exposure to the test solution from its final weight after exposure. The corrosion rate for each coupon was calculated using Equation 1. The morphological changes on the metal surfaces were examined using a JEOL 2300 Series Scanning Electron Microscopy (SEM) to identify the type of corrosion observed after the immersion test.

Table 1. The results of fuel testing for metal immersion

Parameter	Method	B30	B30D10	B40
FAME Content (% v/v)	ASTM D7371	30.73	30.35	40.83
Total Acid Number (mg KOH/g)	ASTM D664	0.19	0.18	0.22
Water Content (ppm)	ASTM D6304	299.98	276.08	339.46
Density at 15ºC (kg/m^3)	ASTM D4052	852.1	864.4	855.5
Viscosity at 40ºC (mm^2/s)	ASTM D445	3.012	3.058	3.206
Cloud Point (ºC)	ASTM D2500	1.4	2.3	2.2
Color (No. ASTM)	ASTM D1500	1.3	1.2	1.3
Oxidation Stability (hour)	EN 15751	>35	>35	>35

$$Corrosion\ rate\ (\mu m/y) = \frac{K \cdot W}{A \cdot T \cdot D} \quad (1)$$

where:
K = constant (8.76×10^7)
W = weight loss (g)
A = metal area (cm^2)
T = immersion time (hours)
D = density (g/cm^3)

After the immersion, the test solutions were examined to determine the following parameters: fatty acid methyl esters (FAME) content, acid number, water content, density, viscosity, cloud point, color, cleanliness, and oxidation stability. Since water content and acid number become the most affected characteristic in long term storage of biodiesel [21], a blank fuel which also kept for 2160 hours without any coupon was also tested for acid number and water content. The quality analysis of the fuel was conducted by comparing the test results with the relevant specifications outlined in Director General of Oil and Gas Decree No. 185.K/HK.02/DJM/2022.

3. Results and Discussion

3.1 Visual Analysis of Specimen Surfaces

The visual surface analysis of stainless steel 304, carbon steel SA 516 Gr.70, and brass specimens after a 2160-hour immersion test in the B30, B30D10, and B40 solutions is presented in Fig. 1. Before the visual examination, the specimens underwent a treatment process involving immersing them in acetone for 10 seconds to remove the immersion solution, followed by drying with a heat gun. On the surfaces of stainless steel 304 and carbon steel SA 516 Gr.70, corrosion appeared as spots and dark-colored points in various areas. In the case of brass, corrosion was observed as dark green patches covering the surface, evident in all immersion solutions (B30, B30D10, and B40), as shown in the accompanying figure. The presence of green patches is consistent with the findings of Fazal *et al.* [14] for copper-based alloys,

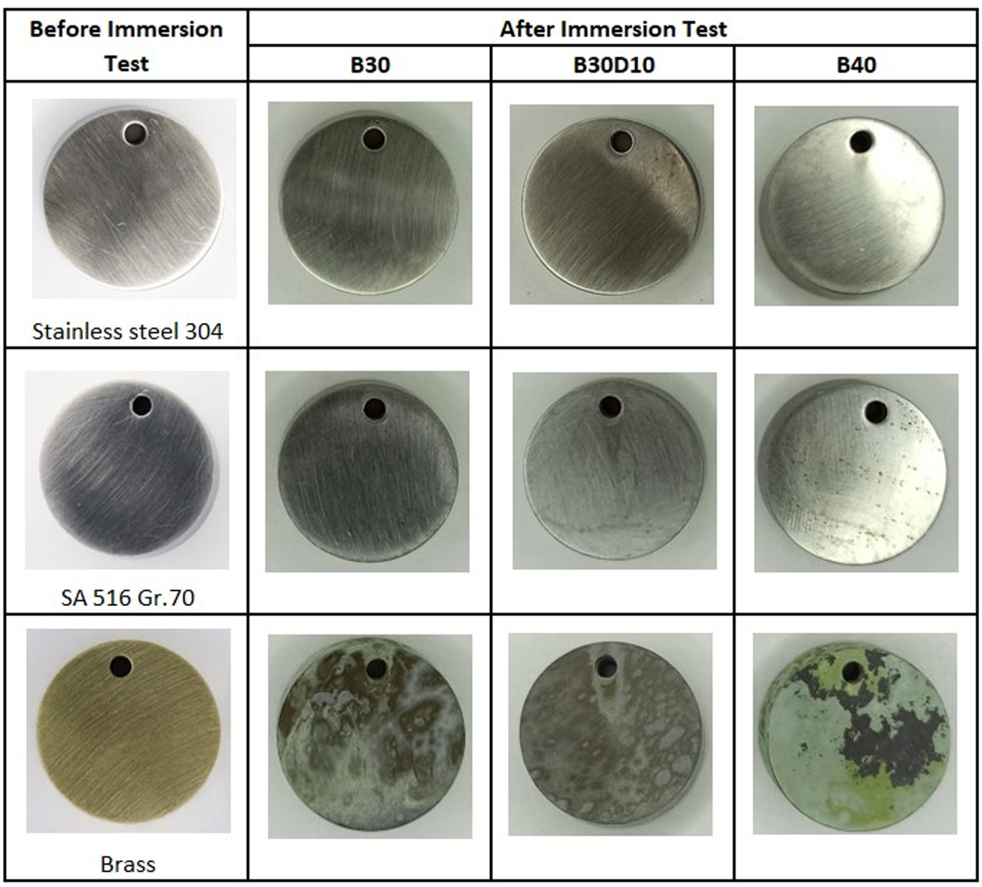


Fig. 1. Metal Surface Before and After Immersion Test

including brass, where the dominant compound formed in biodiesel immersion solutions is green-colored $CuCO_3$. The occurrence of dark green patches on brass also aligns with the research conducted by Aquino *et al.* [22], which highlights the characteristic formation of CuO. Corrosion on stainless steel 304 was more pronounced in B40 than in specimens immersed in B30 and B30D10.

Similarly, carbon steel SA 516 Gr.70 exhibited more extensive corrosion in B40 than in B30 and B30D10. Regarding brass, the corrosion layer formed in B40 was thicker and wider than in B30 and B30D10. Mass loss measurements were conducted to determine the corrosion rate, and SEM analysis was performed to identify the type of corrosion.

The main corrosion reaction is oxidation of the metal. Based on research conducted by Fazal *et al.* [14], the corrosion reaction that occurs on Cu and Zn metals which are the main constituents of brass materials produces ZnO, CuO, $CuCO_3$, $Cu(OH)_2.H_2O$, and $CuCO_3.Cu(OH)_2$. Meanwhile, the corrosion reaction on Fe metal, which is the main component of stainless steel 304 and carbon steel SA 516 Gr.70, produces $Fe(OH)_2$, Fe_2O_3, Fe_2O_3, $Fe_2(OH)_2CO_3$, and $FeCO_3$. Although X-Ray Diffraction analysis was not carried out in this study to find out in detail the compounds formed, visually the corrosion products show characteristics that are in accordance with the research of Fazal *et al.* [14], for example the formation of a green crust on brass which is the formation of $CuCO_3$.

3.2 Metal Corrosion Rate Analysis

The corrosion rates of stainless steel 304, carbon steel SA 516 Gr.70, and brass after a 2160-hour immersion in B30, B30D10, and B40 solutions are shown in Fig. 2. The corrosion rates of stainless steel 304, carbon steel SA 516 Gr.70, and brass in B30 were 0.576 µm/year, 1.226 µm/year, and 5.940 µm/year, respectively. In B30D10, the corrosion rates of stainless steel 304, carbon steel SA 516 Gr.70, and brass were 0.640 µm/year, 1.386 µm/year, and 4.403 µm/year, respectively. Meanwhile, in B40, the corrosion rates of stainless steel 304, carbon steel SA 516 Gr.70, and brass were 0.646 µm/year, 1.442 µm/year, and 7.546 µm/year, respectively. Stainless steel 304 had the lowest corrosion rate, followed by carbon steel SA 516 Gr.70, and brass, respectively. These results are consistent with the findings of Hu *et al.* [15], who discovered that biodiesel is more corrosive to carbon steel than stainless steel, and the study conducted by Sorate and Bhale [13], which indicated that biodiesel is also more corrosive to brass than stainless steel. This correlation aligns with the galvanic series, which ranks metal elements' ease of oxidation and reduction. The galvanic series follows the order shown in Table 2 [23].

Based on Table 2, metals located towards the left side exhibit lower reduction potentials, indicating higher susceptibility to oxidation. As we move toward the right side, metals become more oxidation-resistant [23].

According to the composition data of the metals and the galvanic series, it can be understood that brass, with a zinc concentration of 40%, is more prone to oxidation compared to stainless steel 304 and carbon steel SA 516 Gr.70. This is because stainless steel 304 and carbon steel SA 516 Gr.70 are predominantly composed of iron (Fe) and other metals with higher reduction potentials than zinc (located to the right of zinc), making them less susceptible to oxidation.

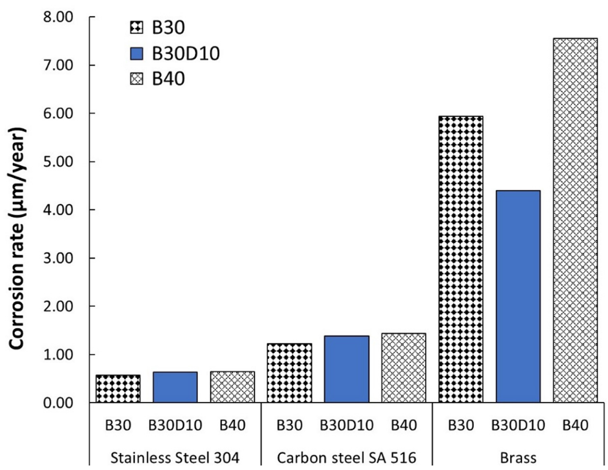


Fig. 2. Corrosion Rates of Stainless Steel 304, Carbon Steel SA 516 Gr.70, and Brass after immersion testing in B30, B30D10, and B40 for 2160 hours

Table 2. Galvanic series

Lower (tends to oxidize) ← Reduction potential → Higher (difficult to oxidize)
Li – K – Ba – Ca – Na – Mg – Al – Mn – Zn – Cr– Fe – Cd – Ni – Sn – Pb – H – Sb – Bi – Cu – Hg– Ag – Pt – Au

Among the three metals examined, the immersion test results for stainless steel 304 did not reveal significant differences in corrosion rates among the fuel samples, similar to the findings for carbon steel SA 516 Gr.70. However, during the brass immersion test, it became evident that the lowest corrosion rate was achieved when immersed in B30D10, followed by B30 and B40. Despite the similarities between B30 and B30D10, as D10 shares the properties of diesel fuel [6,7], the initial characteristics of the respective fuel samples differ, specifically in terms of total acid number and moisture content, thereby influencing the corrosion rate on brass. Notably, B30, with a higher acid number and moisture content, exhibits a higher corrosion rate than B30D10. In addition, the better characteristics of HVO compared to diesel oil can reduce the corrosive nature of the fuel, because it has higher purity, where HVO is sulfur-free, aromatic-free, glyceride-free, and shows oxidation stability similar to diesel oil [6,7].

By evaluating the mentioned corrosion rate values, the relative corrosion resistance of stainless steel 304, carbon steel SA 516 Gr.70, and brass against B30, B30D10, and

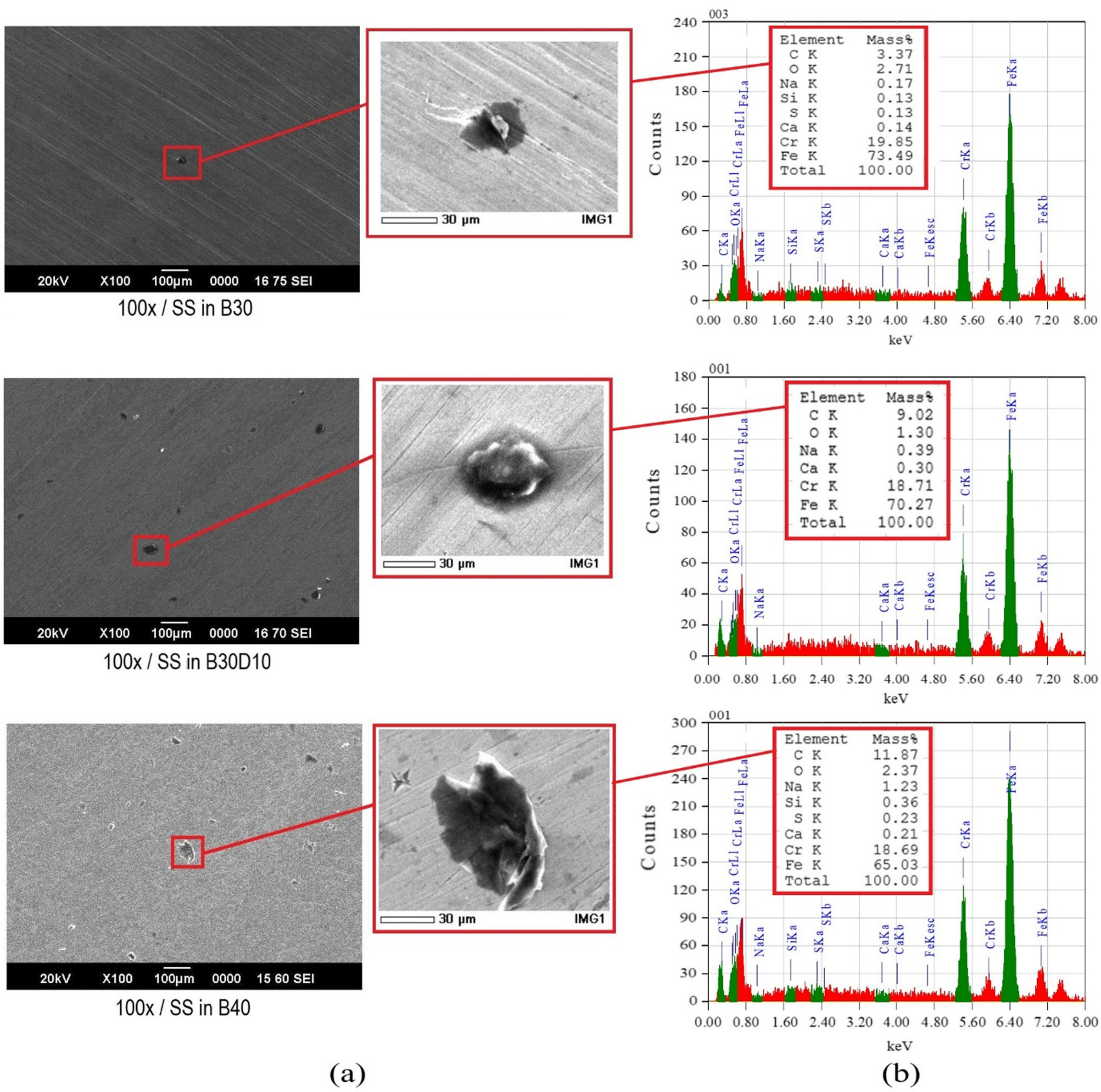
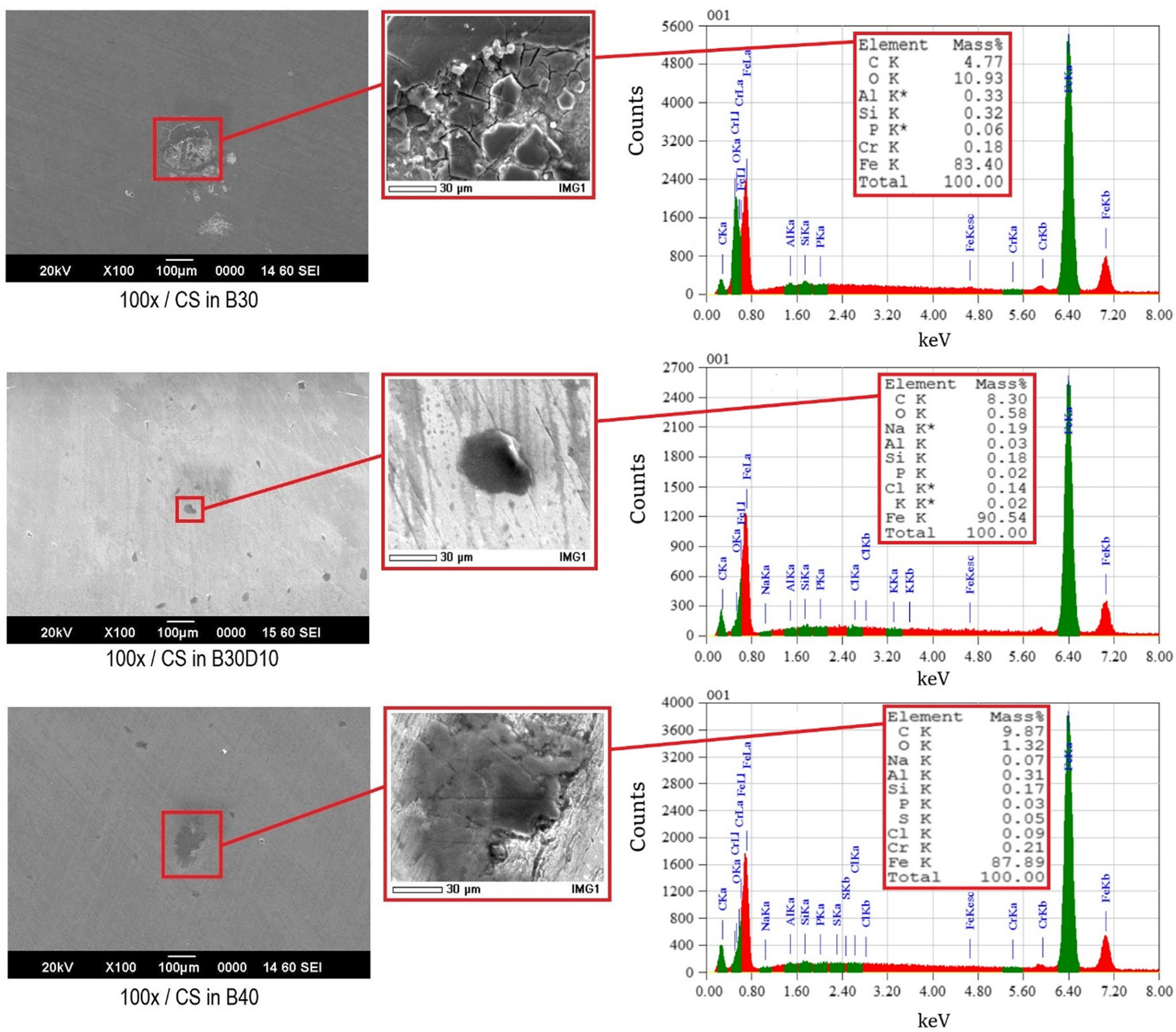


Fig. 3. Stainless steel 304 after immersion testing in B30, B30D10, and B40 for 2160 hours (a) SEM images (b) EDS analysis

B40 can be classified from the lowest to the highest values as unacceptable, poor, fair, good, excellent, and outstanding, respectively [24]. With corrosion rates < 25 μm/yr, the corrosion resistance falls into the category of outstanding. However, it is also necessary to analyze its impact on fuel quality, which will be discussed in the subsequent section on fuel analysis.

3.3 Analysis of Specimen Morphology after Immersion Test

The cleaned coupon surfaces were subjected to SEM analysis for further investigation. This step refers to the research conducted by Sorate and Bhale [13]. The morphologies of stainless steel 304, carbon steel SA 516 Gr.70, and brass after a 2160-hour immersion in B30, B30D10, and B40 solutions can be observed in Fig. 3a – 5a. SEM images at 100x magnification reveal the presence of pitting corrosion in all the metals. Apart from dark spots and patches, stainless steel 304 and carbon steel SA 516 Gr.70 also exhibit pitting corrosion in specific areas. Similarly, in brass, in addition to dark green patches covering the surface, pitting corrosion is observed in several areas. The intensity of pitting corrosion is slightly higher in the metals exposed to B40 than those immersed in B30 and B30D10. Some of the pitting corrosion formations on stainless steel 304, carbon steel SA 516 Gr.70, and brass exceed a size of 10 μm, thus not falling



(a) (b)

Fig. 4. Carbon steel SA 516 Gr. 70 after immersion testing in B30, B30D10, and B40 for 2160 hours (a) SEM images (b) EDS analysis

into the category of micro pitting, which typically ranges from 5 to 10 μm [25]. In the study conducted by Alves *et al.* [16], micro-pitting corrosion was observed, possibly due to the influence of more corrosion-resistant metals, different characteristics of the immersion solution, and varying testing conditions. Based on Fig. 3a – 5a, visually, the surfaces of stainless steel 304 and carbon steel SA 516 Gr.70 exhibit more instances of pitting corrosion compared to brass. However, based on corrosion rate analysis, brass demonstrates the highest corrosion rate. This phenomenon is attributed to the formation of corrosion products on the brass surface, which detach from the metal surface during the cleaning process.

The presence of carbon and oxygen can be seen in the EDS analysis of stainless steel 304 (Fig. 3b) and carbon steel SA 516 Gr.70 specimens (Fig. 4b) after 2160 hours of immersion testing in B30, B30D10, and B40 solutions, which is related with the formation of corrosion products. This result is similar with the studies conducted by Hu *et al.* [15] and Kugelmeier *et al.* [17]. Carbon and oxygen are also present in brass (Fig. 5b), as reported by Fazal *et al.* [14]. The high oxygen content indicates a higher concentration of oxygenated compounds that adhere to the metal surface. Pitting can occur on the metal surface due to corrosion attacks on the base metal and the rupture of oxygenated compounds [14].

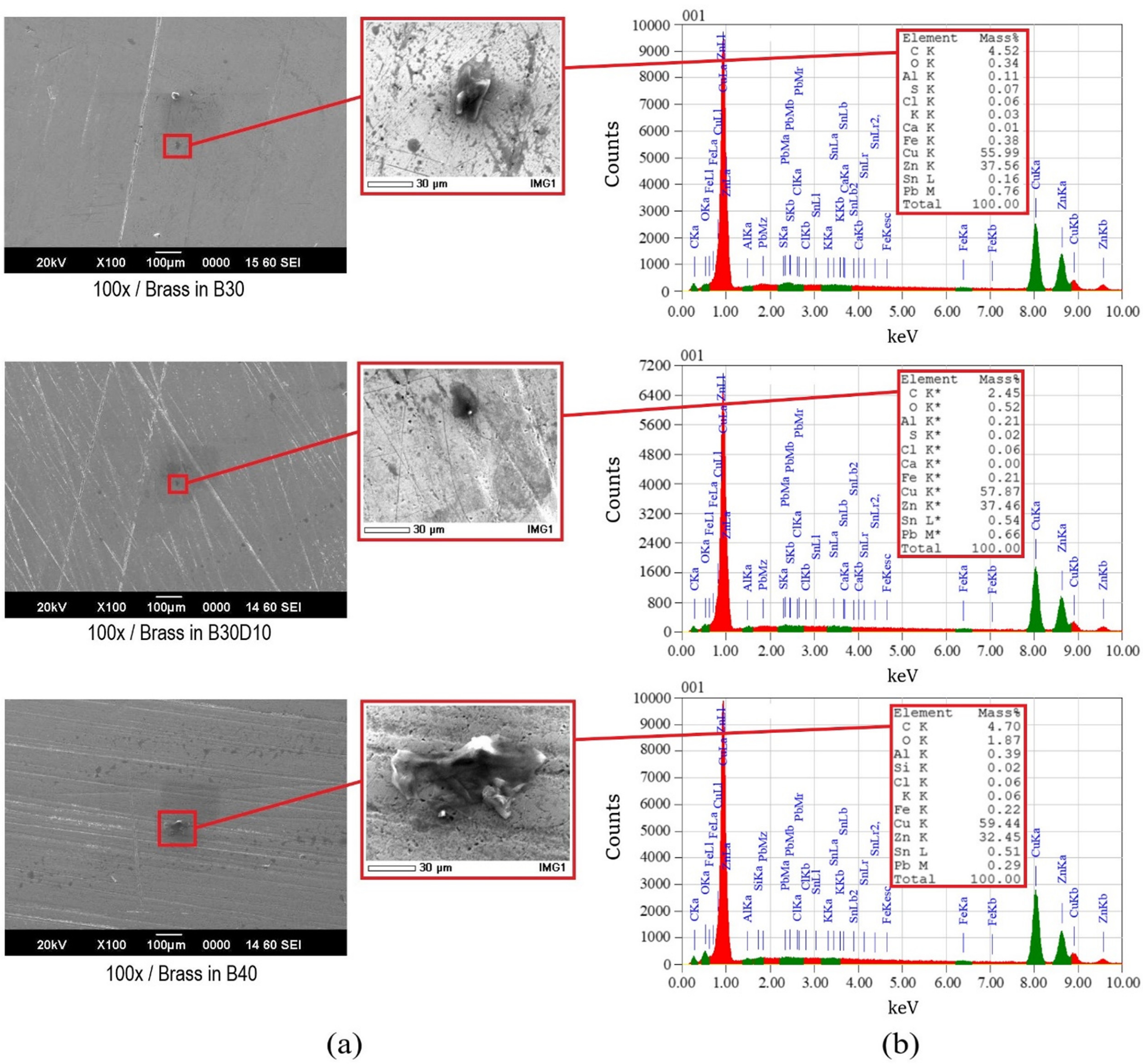


Fig. 5. Brass after immersion testing in B30, B30D10, and B40 for 2160 hours (a) SEM images (b) EDS analysis

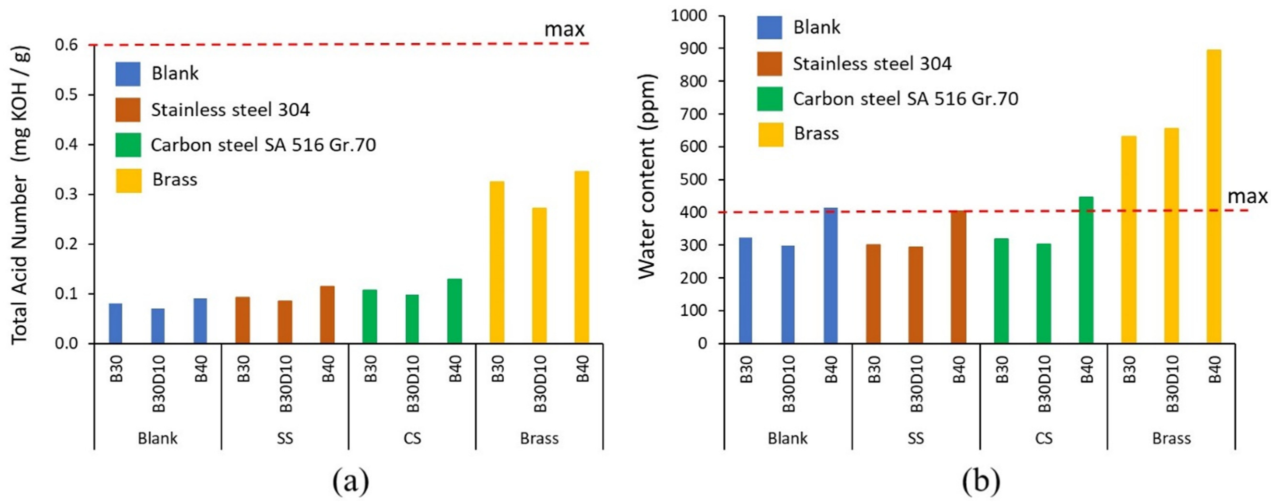


Fig. 6. Quality analysis of immersion fuel (a) total acid number and (b) water content after 2160 hours

3.4 The Immersion Fuel Analysis

The quality of the fuel was tested after being used to immerse the metal for 2160 hours to investigate the effect of metal contact with fuel. The tested fuel quality parameters included total acid number, water content, color, cleanliness, cloud point, and oxidation stability. The test metal's effect on each fuel's quality is presented in Figs. 6-8.

Fig. 6a shows that the acid number of the immersion fuel increased compared to the blank fuel. The increase in fuel acid number is similar to the corrosion rate, where stainless steel 304 with the lowest corrosion rate results in a relatively stable fuel acid number (compared to blank fuel) with a total acid number of 0.09 - 0.11 mg KOH/gram sample. It is followed by carbon steel SA 516 Gr.70 immersion fuel with an acid number of 0.10 - 0.13 mg KOH/gram sample, and brass immersion causing the highest acid number reaching up to 0.35 mg KOH/gram sample. These results are consistent with the predicted behavior, where material corrosion increases the acid number due to oxidation [16,26]. The three fuels used show a similar trend among the four variables, including blank, stainless steel 304 immersion, carbon steel SA 516 Gr.70 immersion, and brass immersion. B30D10 has the lowest acid number, followed by B30 and B40, respectively. These results are not surprising as the components of the fuel blends have different acid numbers, where according to standard specifications, HVO has the lowest acid number limit, followed by biodiesel and diesel (based on specification tables). Although all samples still meet the quality standard of BXX (B35) currently commercialized in Indonesia, the significantly high acid number of brass immersion fuel needs attention, especially if fuel-metal contact occurs for more than 2160 hours.

The water content in the fuel after a 2160-hour immersion shows a similar pattern to the acid number, where the stainless steel 304 and carbon steel SA 516 Gr.70 immersion fuels are relatively similar to the blank fuel, while the brass immersion fuel has a higher water content as indicated in Fig. 6b. In the case of the blank, stainless steel 304 immersion, and carbon steel SA 516 Gr.70 immersion, the B40 fuel has exceeded the maximum water content limit of BXX in Indonesia, which is 400 ppm. However, all brass immersion fuels have surpassed the maximum limit, with a water content reaching 893 ppm in B40.

Overall, the higher corrosivity of biodiesel relative to diesel fuel is due to its higher hygroscopicity, higher electrical conductivity, higher polarity, and higher solubility compared to diesel fuel. The presence of water and oxygen in biodiesel stimulates microbial growth, and ultimately, biodiesel auto-oxidation leads to the formation of monocarboxylic acids, intensifying the corrosion process [27]. Therefore, the corrosion rate is highly dependent on water content, acid number, oxidation stability, and cleanliness.

The cleanliness parameter of the immersion fuel is expressed in the number of particles per mL of the sample, commonly also converted into ISO 4406 standards. The cleanliness of the immersion fuel follows a similar trend to the corrosion rate, where the stainless steel 304 immersion fuel has the lowest value (highest quality), followed by the carbon steel SA 516 Gr.70 immersion fuel, and the brass immersion fuel has the most noticeable value as indicated in Fig. 7a. Although the cleanliness parameter is not currently a quality standard for BXX fuel in Indonesia, it is crucial to consider it as a high particle content can interfere its application, such as accelerating fuel filters and injector blockages. Most fuel applications recommend cleanliness limits according to ISO 18/16/13, which means having particle content of ≥ 4 μm ranging from 1301-2500 particles/mL (ISO 18), ≥ 6 μm ranging from 321-640 particles/mL (ISO 14), and ≥ 14 μm ranging from 41-80 particles/mL (ISO 13) [28].

Oxidation stability is one of the most important parameters in fuel quality. Fig. 7b shows how the three immersed metals in the fuel differ in their influence on fuel oxidation stability. Stainless steel 304 performs the best, with a fuel oxidation stability of 36 hours, surpassing the minimum limit of 35 hours as required by BXX standards in Indonesia. In the case of carbon steel SA 516 Gr.70 immersion, the fuel oxidation stability falls below the minimum limit, especially in the case of brass immersion, where the oxidation stability is only around 0.05 hours. The decrease in oxidation stability is attributed to the corrosion-induced degradation of the metal, resulting in the release of metal ions that subsequently dissolve in the fuel [16]. By observing Fig. 2 and Fig. 7b, it can be noted that high corrosion rates are accompanied

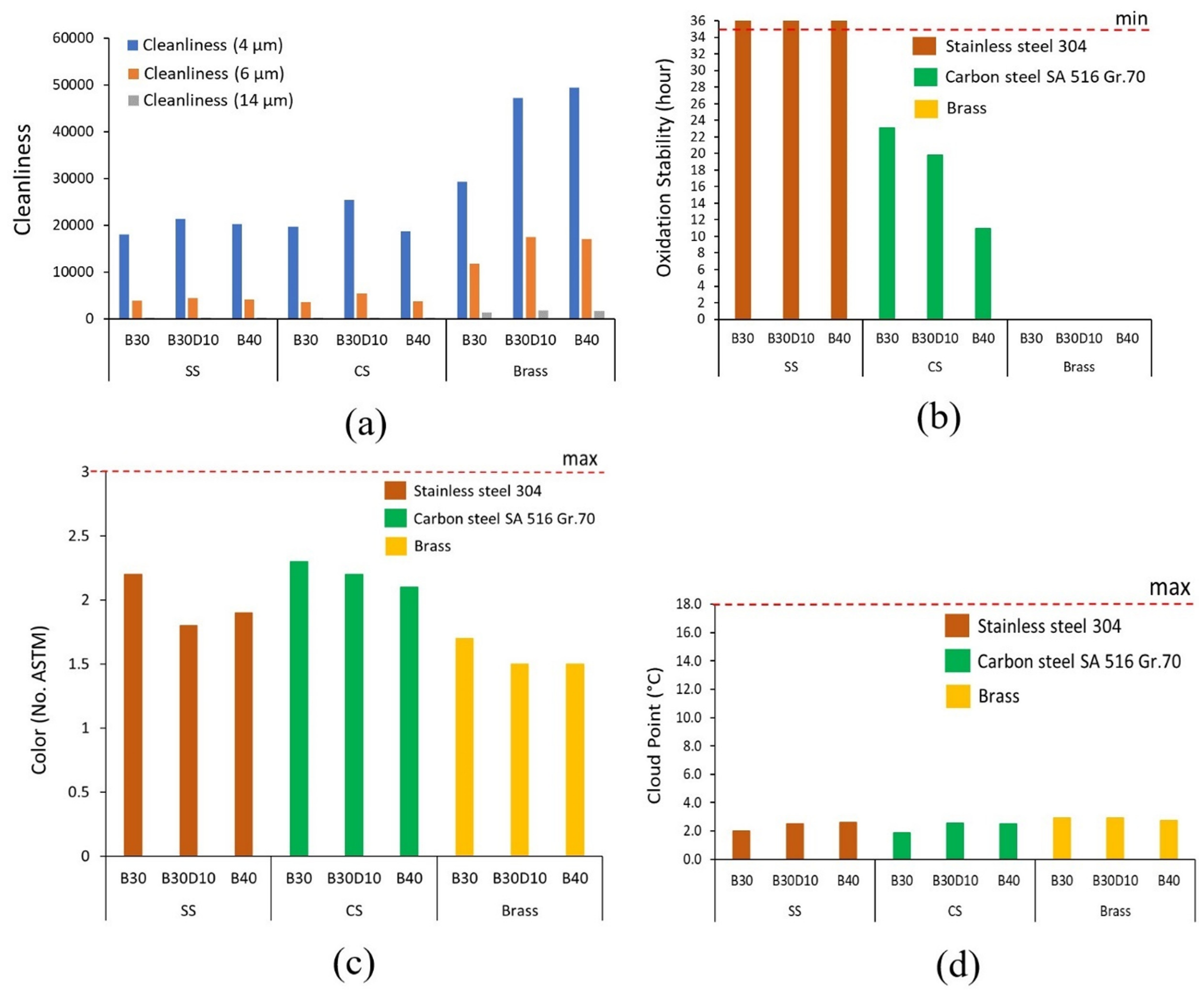


Fig. 7. Quality analysis of immersion fuel (a) cleanliness, (b) oxidation stability, (c) color, and (d) cloud point after 2160 hours

by low oxidation stability.

Fig. 7c and Fig. 8 show that the color of all fuel samples falls within the range of 1.5-2.3, which is still in accordance with the B35 standard in Indonesia, with a maximum of 3. Among all variables, the B30 fuel has the highest color value (lowest quality), while the brass immersion fuel has the lowest color value (highest quality), followed by the stainless steel 304 and carbon steel SA 516 Gr.70 immersion fuels in that order. Fig. 8 shows that the color of the immersion fuel of brass appears brighter than the immersion fuel of stainless steel 304 and carbon steel SA 516 Gr.70. It is due to the tendency of brass corrosion products to produce sediment, which accumulates at the bottom of the liquid, while the corrosion products of stainless steel 304 and carbon steel SA 516 Gr.70 remain dissolved in the fuel, impacting the fuel color [27,29].

The cloud point value of the fuel needs to be tested to represent its performance at low temperatures. The longer the carbon chain of the alcohol component, the better the performance of biodiesel at low temperatures. According to the study by Wang *et al.* [29], a longer carbon chain of the alcohol component and a more irregular structure of the oleate molecule result in better performance of biodiesel at low temperatures. In this study, various metal compounds and transition metals were used as immersed materials, which have the potential to catalytically break down the alcohol and oleate chain components into smaller and simpler chains [30]; this can decrease the performance of the fuel at low temperatures, as indicated by an increase in the cloud point. Based on Fig. 7d, the cloud point of all fuel samples falls within the range of 1.9-2.9 ºC, while the maximum cloud point limit according to the BXX standard in Indonesia is 18 ºC. Among the three metal variations, there is no significant difference in the cloud point parameter, although brass has a higher cloud point than the others.

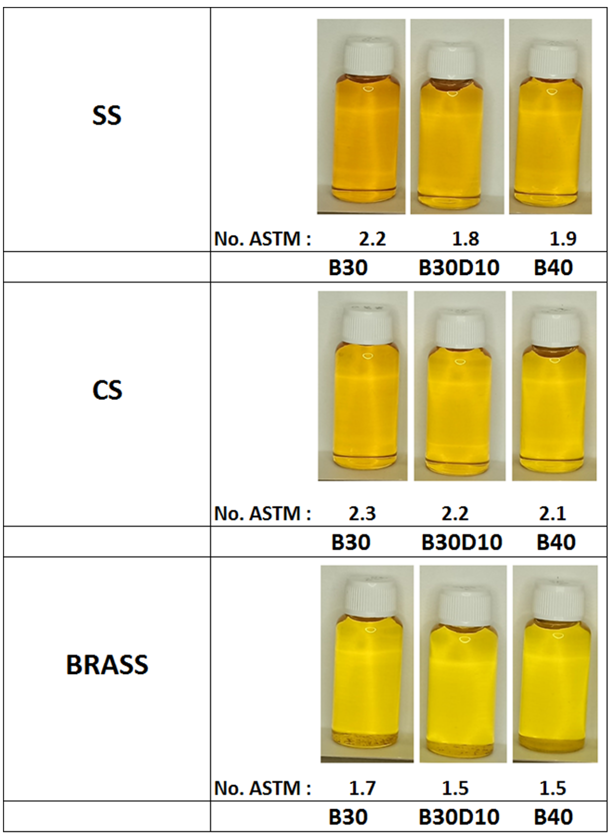


Fig. 8. Fuel appearance after immersion test for 2160 hours

4. Conclusions

This study was conducted to provide recommendations for implementing higher ratio vegetable-based fuel blends (above 30%). The study focused on analyzing the compatibility of common materials, such as stainless steel 304, carbon steel SA 516 Gr.70, and brass, in long-term direct contact with biodiesel-diesel and biodiesel-diesel-HVO blends. The study findings led to the following conclusions:

The lowest corrosion rate was observed in stainless steel 304, followed by carbon steel SA 516 Gr.70 and brass, respectively. Among the three metals examined, the immersion test results for stainless steel 304 did not reveal significant differences in corrosion rates among the fuel samples, similar to the findings for carbon steel SA 516 Gr.70. However, during the brass immersion test, it became evident that the lowest corrosion rate was achieved when immersed in B30D10, followed by B30 and B40. Based on the corrosion rate values, the relative corrosion resistance falls into the outstanding category, indicating a corrosion rate of less than 25 μm/year.

Despite the very low corrosion rate, based on the testing conducted on the fuel used for immersion, brass causes degradation of the fuel, particularly in terms of total acid number, moisture content, cleanliness, and oxidation stability parameters. Therefore, using brass as a material in contact with B30, B30D10, or B40 fuel is not recommended to be used for fuel storage systems of diesel-biodiesel and diesel-biodiesel-HVO blends.

HVO provides a good effect on the quality of the fuel mixture, including the parameters of water content, acid number, sulfur content, and oxidation stability, which influence the rate of metal corrosion. The use of HVO makes the corrosion rate of B30D10 lower than B40 and even than B30.

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