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Performance and Emission Characteristics of B0 and BxxDxx Alternative Fuels for Diesel Generator Applications under Sustainable Energy Transition

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A B S T R A C T

The transition toward sustainable energy systems requires the development of alternative fuels with favorable combustion characteristics and reduced environmental impact. This study analyzes the physicochemical properties of diesel fuel (B0), biodiesel (B100), and various biodiesel-hydrotreated vegetable oil (HVO) blends (BxxDxx) and discusses their potential implications for diesel generator applications. Fuel properties including cetane number, sulfur content, flash point, lubricity, total acid number (TAN), fatty acid methyl ester (FAME) content, and particulate contamination were evaluated in accordance with ASTM standard methods. The analyzed properties were subsequently discussed in relation to combustion characteristics, fuel system cleanliness, engine durability, and emission tendencies based on established combustion theory and previous studies. The results indicate that fuels with higher cetane numbers and lower sulfur content may contribute to improved combustion quality and reduced particulate-related emissions. Meanwhile, high FAME content fuels exhibit potential advantages in cleaner combustion but may also increase oxidation tendency and deposit formation due to their higher viscosity and lower oxidation stability. Among the tested blends, B30D20 demonstrated balanced fuel characteristics with promising potential for sustainable diesel generator applications. This study provides an analytical understanding of biodiesel-HVO fuel behavior and highlights the importance of optimizing fuel properties to support cleaner and more sustainable diesel energy systems in Indonesia.

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1. INTRODUCTION

The transition toward sustainable energy systems has become a global priority in response to increasing concerns over climate change, environmental degradation, and the depletion of fossil fuel resources. Diesel generators continue to play a crucial role in providing energy, particularly in remote areas and as backup power systems. However, their dependence on conventional fossil-based diesel fuel (B0) significantly contributes to greenhouse gas emissions, including carbon dioxide (CO_2), sulfur oxides (SOx), and particulate matter (PM),

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which pose serious environmental and health risks (Agarwal 2007; Atabani et al. 2013).

To address these challenges, alternative fuels such as biodiesel and hydrotreated vegetable oil (HVO) have emerged as promising solutions due to their renewable origin, lower sulfur content, and improved combustion characteristics (Agarwal et al. 2015; Indonesian Ministry of Energy and Mineral Resources 2019; Knothe 2010). Biodiesel, commonly produced from vegetable oils or animal fats, contains oxygenated compounds that enhance combustion efficiency and reduce emissions of carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (Agarwal 2007; Agarwal et al. 2015). However, biodiesel also presents several limitations, including higher viscosity, oxidative instability, and the potential to increase nitrogen oxides (NOx) emissions under certain operating conditions (Atabani et al. 2013; Knothe 2010).

Hydrotreated vegetable oil (HVO), on the other hand, offers superior fuel properties, such as higher cetane number, excellent oxidative stability, and near-zero sulfur content, making it an attractive alternative for diesel engines (Alptekin & Canakci 2009; Indonesian Ministry of Energy and Mineral Resources 2019). Previous studies have demonstrated that HVO and its blends with diesel can improve combustion characteristics and support cleaner combustion behavior, particularly under high-load conditions (Hossain & Davies 2010; Kalnes, Marker & Shonnard 2007). Therefore, combining biodiesel and HVO in blended fuels (BxxDxx) has the potential to balance their respective advantages while minimizing their individual drawbacks.

In Indonesia, the implementation of biodiesel policies such as B30 has significantly contributed to reducing dependence on fossil fuels and promoting renewable energy adoption (Heywood 2018; Hoekman & Robbins 2012). However, challenges remain regarding fuel stability, engine compatibility, and emission characteristics, particularly under tropical operating conditions where temperature and humidity can influence fuel behavior and combustion performance (Atabani et al. 2013; Knothe 2010).

Despite the increasing number of studies on alternative fuels, most existing research focuses on single fuel types or limited blending ratios and often evaluates performance or emissions separately. Furthermore, there is still a lack of comprehensive studies that simultaneously analyze multiple fuel properties, such as cetane number, sulfur content, total acid number (TAN), lubricity, and particulate contamination, and their potential implications for combustion behavior, fuel stability, and fuel system durability (Knothe, Van Gerpen & Krahl 2010; Rakopoulos, Antonopoulos & Rakopoulos 2006). This gap is particularly relevant for real-world diesel generator applications in tropical regions like Indonesia.

To address these limitations, this study presents a comprehensive evaluation of diesel fuel (B0), pure biodiesel (B100), and various biodiesel-HVO blends (BxxDxx) for diesel generator applications under tropical operating conditions. The analysis integrates physicochemical fuel properties with their potential implications for combustion behavior, fuel system cleanliness, engine durability, and emission tendencies based on established combustion principles and findings reported in previous studies (Heywood 2018; Knothe 2010).

To the best of the authors' knowledge, no prior study has comprehensively evaluated biodiesel-HVO blends across multiple physicochemical fuel properties and their potential implications for diesel generator applications under tropical operating conditions. Therefore, this research aims to provide a holistic understanding of fuel behavior and to identify optimal blending strategies that can support cleaner and more sustainable diesel energy systems. The findings are expected to support Indonesia's energy transition roadmap and contribute to global efforts in sustainable fuel development (Knothe, Van Gerpen & Krahl 2010; Rakopoulos, Antonopoulos & Rakopoulos 2006).

2. LITERATURE REVIEW

The increasing global emphasis on reducing greenhouse gas (GHG) emissions and reliance on fossil fuels has driven the exploration of alternative fuels such as biodiesel, hydrotreated vegetable oil (HVO), and their blends. Biodiesel, typically produced through transesterification of vegetable oils or animal fats, offers environmental benefits, including a significant reduction in carbon monoxide (CO), particulate matter (PM), and unburned hydrocarbons (HC). Additionally, its renewable nature and compatibility with existing diesel engines make it a promising candidate for achieving sustainable energy goals (Agarwal 2007; Agarwal et al. 2015).

In Indonesia, the implementation of B30 biodiesel under government mandates has marked significant progress in reducing the nation's dependency on imported fossil fuels (Indonesian Ministry of Energy and Mineral Resources 2019). However, challenges such as oxidative instability, higher NOx emissions, and cold flow properties have raised concerns regarding long-term applicability and fuel stability under varying operating conditions (Atabani et al. 2013; Knothe 2010).

HVO, on the other hand, offers superior oxidative stability, higher cetane numbers, and lower sulfur content compared to biodiesel, making it an attractive alternative for blending with diesel and biodiesel (Alptekin & Canakci 2009; Indonesian Ministry of Energy and Mineral Resources 2019). Research has shown that HVO-diesel blends can improve combustion characteristics and support cleaner combustion behavior, particularly in engines operating under high-load conditions (Hossain & Davies 2010; Kalnes, Marker & Shonnard 2007).

Despite these advantages, studies have highlighted that the optimal blend ratios for biodiesel and HVO are still underexplored, particularly in tropical climates like Indonesia. Moreover, the compatibility of these fuels in existing engines, their long-term impact on fuel system durability, and their combustion-related characteristics under varying operational conditions require further investigation (Knothe, Van Gerpen & Krahl 2010; Rakopoulos, Antonopoulos & Rakopoulos 2006).

2.1. NOVELTY

This study addresses critical gaps in existing literature by providing a comprehensive and integrated evaluation of biodiesel-HVO diesel blends based on physicochemical fuel properties and their potential implications for diesel generator applications.

1. A multi-dimensional analysis integrating physicochemical fuel properties with their potential implications for combustion characteristics, fuel stability, fuel system durability, and emission tendencies.
2. A systematic evaluation of a wide range of fuel blends (B0, Bxx, BxxDxx, Dxx, and B100), enabling identification of optimal blending strategies.
3. Discussion of biodiesel-HVO fuel characteristics in the context of practical diesel generator applications under tropical operating conditions.
4. Investigation under tropical operating conditions, where temperature and humidity significantly influence fuel behavior, which remains underexplored in existing studies.
5. Identification of promising blend compositions (e.g., B30D20) with balanced physicochemical characteristics for sustainable diesel fuel applications in Indonesia.

3. METHODOLOGY

This study evaluates the physicochemical properties of diesel fuel (B0), biodiesel (B100), and biodiesel-HVO blends (BxxDxx) and discusses their potential implications for diesel generator applications.

3.1. FUEL SAMPLE PREPARATION

Fifteen fuel samples were prepared to evaluate the characteristics of diesel fuel, biodiesel, hydrotreated vegetable oil (HVO), and their blended fuels. The tested fuels consisted of pure diesel fuel (B0), pure biodiesel (B100), pure HVO (D100), and various biodiesel-HVO-diesel blends (BxxDxx).

The biodiesel used in this study was produced from palm oil methyl ester (FAME), while the HVO was obtained through hydrotreatment processes of vegetable oil feedstocks. Fuel blending was carried out volumetrically under controlled laboratory conditions to ensure mixture homogeneity.

The composition of each fuel blend evaluated in this study is presented in Table 1. All fuel samples were properly labeled and stored in sealed containers under controlled ambient conditions prior to testing to minimize oxidation, moisture absorption, and particulate contamination, thereby ensuring consistency and reliability during the experimental measurements.

Table 1. Composition of fuel blends used in this study.

No.	Fuel formula	Biodiesel (%)	Diesel (%)	HVO (%)
1	B0	0	100	0
2	B30	30	70	0
3	B35	35	65	0
4	B30D5	30	65	5
5	D35	0	65	35
6	B40	40	60	0

No.	Fuel formula	Biodiesel (%)	Diesel (%)	HVO (%)
7	B35D5	35	60	5
8	B30D10	30	60	10
9	D40	0	60	40
10	B50	50	50	0
11	B35D15	35	50	15
12	B30D20	30	50	20
13	D50	0	50	50
14	D100	0	0	100
15	B100	100	0	0

B represents biodiesel content, while D represents hydrotreated vegetable oil (HVO) content in the fuel blends.

3.2. LABORATORY TESTING AT LEMIGAS

The physicochemical properties of all fuel samples were analyzed at the Research and Development Center for Oil and Gas Technology (LEMIGAS), Indonesia, in accordance with internationally recognized ASTM testing standards.

The evaluated parameters included cetane number, sulfur content, flash point, carbon residue, distillation characteristics, fatty acid methyl ester (FAME) content, lubricity, particulate contamination, and total acid number (TAN). The testing procedures and corresponding ASTM methods used in this study are summarized in Table 2.

Table 2. Test parameters and methods used.

Parameter	Standard Method	Purpose
Cetane Number	ASTM D613	Determines ignition quality and combustion characteristics
Sulfur Content	ASTM D4294	Measures sulfur concentration related to emission formation
Flash Point	ASTM D93	Evaluates fuel flammability and handling safety
Carbon Residue	ASTM D4530	Indicates deposit formation tendency after combustion
Distillation Range (T90)	ASTM D86	Assesses fuel volatility and evaporation behavior
Fatty Acid Methyl Ester	ASTM D7806	Determines biodiesel concentration in fuel blends
Lubricity (HFRR)	ASTM D6079	Evaluates wear protection capability of fuel
Particulate Contaminants	ASTM D6217	Measures solid contaminant level in fuel samples
Total Acid Number (TAN)	ASTM D664	Indicates acidity and potential corrosion tendency

Each parameter was measured in triplicate, and the average values were reported to ensure reliability and reproducibility of the experimental data.

3.3. ANALYTICAL APPROACH

The physicochemical properties obtained from laboratory testing were comparatively analyzed to evaluate the potential influence of each fuel blend on combustion characteristics, fuel system cleanliness, engine durability, and emission tendencies in diesel generator applications.

The discussion and interpretation of the results were conducted based on established combustion principles and supported by findings reported in previous studies related to biodiesel, hydrotreated vegetable oil (HVO), and diesel fuel applications.

4. RESULTS AND DISCUSSION

4.1. EFFECT OF CETANE NUMBER ON COMBUSTION CHARACTERISTICS

Figure 1 shows the variation of cetane number for different fuel blends evaluated in this study. Cetane number is an important fuel property that influences ignition delay and combustion quality in compression ignition engines. Fuels with higher cetane numbers generally exhibit shorter ignition delay, resulting in more stable and efficient combustion processes (Agarwal 2007; Alptekin & Canakci 2009).

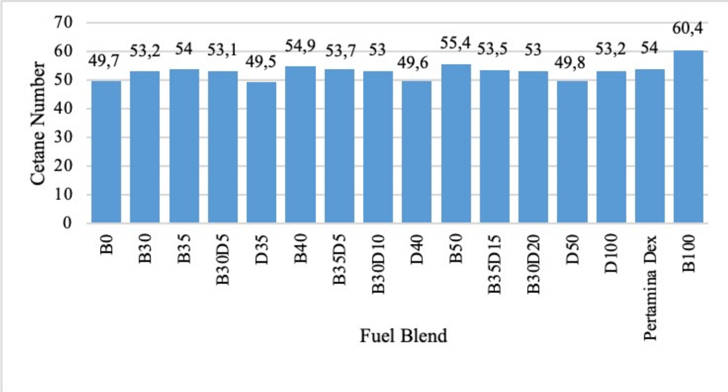

Figure 1. Variation of cetane number for different fuel blends.

As presented in Figure 1, B100 exhibited the highest cetane number (60.4), followed by several blended fuels with cetane values above 53. Higher cetane fuels are expected to promote more complete combustion, which may contribute to lower unburned hydrocarbon (UHC) and particulate matter (PM) emissions. In contrast, fuels with lower cetane numbers, such as B30 and D100, may experience relatively longer ignition delay, potentially leading to incomplete combustion and higher combustion-related emissions (Atabani et al. 2013; Knothe 2010).

In addition to combustion quality, cetane number also influences combustion smoothness and engine operability. Higher cetane fuels typically provide more stable ignition behavior and reduced combustion fluctuations, particularly under varying engine operating conditions (Knothe, Van Gerpen & Krahl 2010). However, excessively rapid combustion associated with very high cetane fuels may also contribute to slightly higher combustion temperatures, which can potentially increase nitrogen oxide (NOx) formation (Agarwal et al. 2015).

Overall, the trend observed in Figure 1 indicates that cetane number plays an important role in determining combustion characteristics and emission tendencies of biodiesel-HVO fuel blends. Therefore, optimization of cetane number is essential in achieving balanced combustion performance and environmental sustainability.

4.2. EFFECT OF SULFUR CONTENT ON COMBUSTION CLEANLINESS AND EMISSION TENDENCIES

Sulfur content is an important fuel parameter associated with combustion cleanliness, deposit formation, and sulfur oxide (SOx) emissions in diesel combustion systems. Fuels containing high sulfur concentrations tend to produce sulfur dioxide (SO_2) and sulfur trioxide (SO_3) during combustion, which may subsequently react with water vapor to form acidic compounds such as sulfuric acid (H_2SO_4) (Alptekin & Canakci 2009; Knothe 2010).

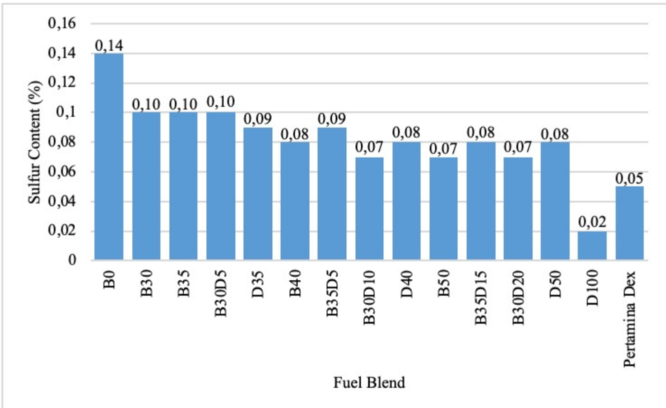

Figure 2. Variation of sulfur content for different fuel blends.

Figure 2 shows the sulfur content of the evaluated fuel blends. As observed in Figure 2, D100 and Pertamina

Dex exhibited significantly lower sulfur content compared to several biodiesel-containing blends. Lower sulfur fuels are generally associated with cleaner combustion conditions and reduced risks of corrosion, injector fouling, and deposit accumulation in fuel system components (Knothe 2010; Knothe, Van Gerpen & Krahl 2010).

In contrast, fuels with relatively higher sulfur content, such as B0 and B30, may contribute to increased sulfur oxide emissions and deposit formation during prolonged engine operation. Sulfur-related deposits and acidic compounds can potentially affect injector cleanliness and combustion chamber conditions, leading to increased maintenance requirements and reduced fuel system durability (Atabani et al. 2013; Rakopoulos, Antonopoulos & Rakopoulos 2006).

The trend presented in Figure 2 indicates that reducing sulfur content is beneficial for minimizing combustion-related contamination and supporting cleaner diesel combustion systems. Therefore, low-sulfur fuel blends offer significant potential for improving environmental sustainability and maintaining long-term engine cleanliness.

4.3. EFFECT OF TOTAL ACID NUMBER (TAN) ON FUEL STABILITY AND CORROSION TENDENCY

Total Acid Number (TAN) is an important indicator of fuel acidity and oxidation stability. Elevated TAN values generally indicate the presence of acidic compounds formed during fuel oxidation and degradation processes, which may contribute to corrosion and deposit formation in fuel system components (Hoekman & Robbins 2012; Knothe 2010).

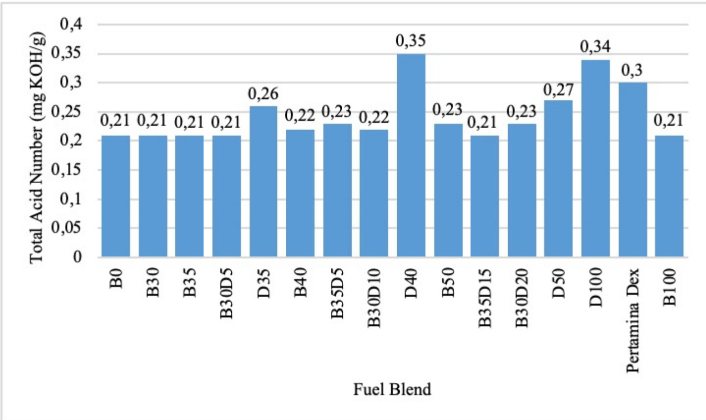

Figure 3. Variation of total acid number (TAN) for different fuel blends.

Figure 3 presents the variation of TAN values for different fuel blends evaluated in this study. As shown in Figure 3, D40 and D100 exhibited relatively higher TAN values compared to other tested fuels. Higher acidity levels may accelerate corrosion processes in metallic fuel system components, particularly in injectors, pumps, and fuel storage systems (Hoekman & Robbins 2012; Knothe, Van Gerpen & Krahl 2010).

In addition to corrosion tendency, acidic compounds formed during fuel oxidation may also promote the formation of insoluble oxidation products and deposits within fuel delivery systems. These deposits can potentially affect injector cleanliness and fuel spray characteristics during combustion (Atabani et al. 2013; Rakopoulos, Antonopoulos & Rakopoulos 2006).

Conversely, fuels with lower TAN values, such as B0 and B30, demonstrated lower acidity levels, indicating better resistance to oxidation-related degradation and lower risks of corrosive effects during storage and utilization.

The trend observed in Figure 3 suggests that controlling fuel acidity is important for maintaining fuel stability, minimizing corrosion tendency, and supporting long-term durability of diesel fuel systems. Therefore, optimization of TAN values should be considered in the development of biodiesel-HVO fuel blends for sustainable diesel applications.

4.4. EFFECT OF LUBRICITY ON FUEL SYSTEM PROTECTION AND COMBUSTION STABILITY

Lubricity is an important fuel property associated with friction reduction and wear protection in diesel fuel injection systems. Adequate lubricity helps maintain protective fuel films between moving metallic components, thereby minimizing wear in fuel pumps and injectors during engine operation (Alptekin & Canakci 2009; Knothe, Van Gerpen & Krahl 2010).

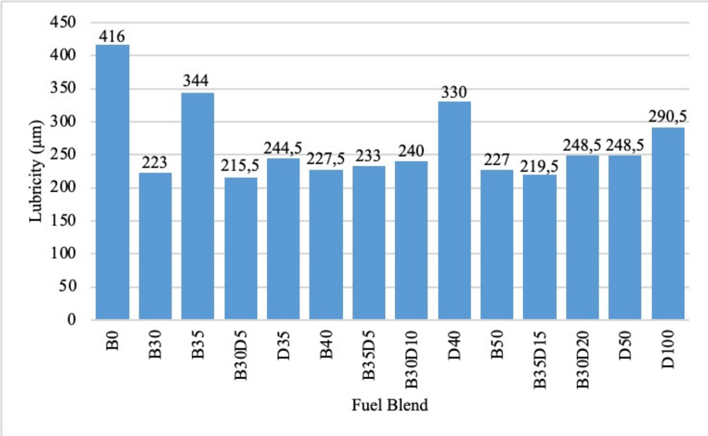

Figure 4. Variation of lubricity for different fuel blends.

Figure 4 presents the lubricity characteristics of the evaluated fuel blends based on HFRR measurements. In HFRR analysis, lower wear scar diameter values indicate better lubricating performance. As shown in Figure 4, several biodiesel-containing blends exhibited relatively lower wear scar values, indicating improved lubricity characteristics compared to conventional diesel fuel.

The improved lubricity of biodiesel-containing fuels is mainly attributed to the presence of oxygenated compounds and polar molecular structures, which enhance surface film formation and reduce metal-to-metal contact within the fuel injection system (Hoekman & Robbins 2012; Knothe 2010). Improved lubricity may contribute to reduced injector wear, more stable fuel spray characteristics, and improved long-term fuel system durability.

Conversely, fuels with poorer lubricity characteristics may accelerate wear processes in injectors and fuel pumps, potentially affecting fuel atomization and combustion consistency during prolonged operation (Atabani et al. 2013; Rakopoulos, Antonopoulos & Rakopoulos 2006). Overall, the trend observed in Figure 4 suggests that lubricity plays an important role in maintaining fuel system reliability and combustion stability. Therefore, optimization of lubricity characteristics is essential in the development of sustainable biodiesel-HVO fuel blends for diesel engine applications.

4.5. EFFECT OF FLASH POINT ON FUEL VOLATILITY AND HANDLING CHARACTERISTICS

Flash point is an important fuel property related to fuel volatility and ignition safety during storage, transportation, and handling. Fuels with higher flash points generally exhibit lower volatility and reduced risks of accidental ignition under ambient conditions (Alptekin & Canakci 2009; Kalnes, Marker & Shonnard 2007).

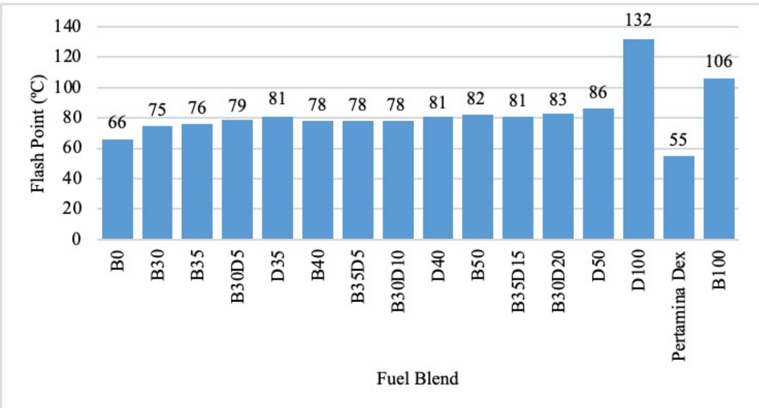

Figure 5. Variation of flash point for different fuel blends.

Figure 5 presents the flash point values for different fuel blends evaluated in this study. As shown in Figure 5, D100 and B100 exhibited significantly higher flash point values compared to conventional diesel fuel and several blended fuels. The higher flash point characteristics of biodiesel-containing fuels are commonly associated with the presence of heavier molecular components and lower volatile fractions (Hoekman & Robbins 2012; Knothe 2010).

Higher flash point fuels generally provide safer handling and storage characteristics due to their lower evaporation tendency. In contrast, fuels with relatively lower flash point values exhibit higher volatility, which may increase evaporative losses and ignition sensitivity during fuel handling processes (Atabani et al. 2013; Knothe 2010).

In combustion applications, flash point may also influence fuel evaporation behavior prior to ignition. However, flash point is primarily considered a safety and storage parameter rather than a direct indicator of combustion efficiency or engine performance (Knothe, Van Gerpen & Krahl 2010).

Overall, the trend observed in Figure 5 indicates that biodiesel-HVO fuel blends exhibit varying volatility and handling characteristics depending on blend composition. Therefore, optimization of flash point properties is important for maintaining both operational safety and fuel stability in diesel fuel applications.

4.6. EFFECT OF FAME CONTENT ON COMBUSTION CHARACTERISTICS AND FUEL STABILITY

Fatty Acid Methyl Ester (FAME) content is an important parameter influencing combustion behavior, fuel stability, and physicochemical characteristics of biodiesel-containing fuels. The oxygenated nature of FAME promotes cleaner combustion by enhancing oxidation reactions during the combustion process, which may contribute to reduced soot and particulate matter formation (Agarwal 2007; Hoekman & Robbins 2012).

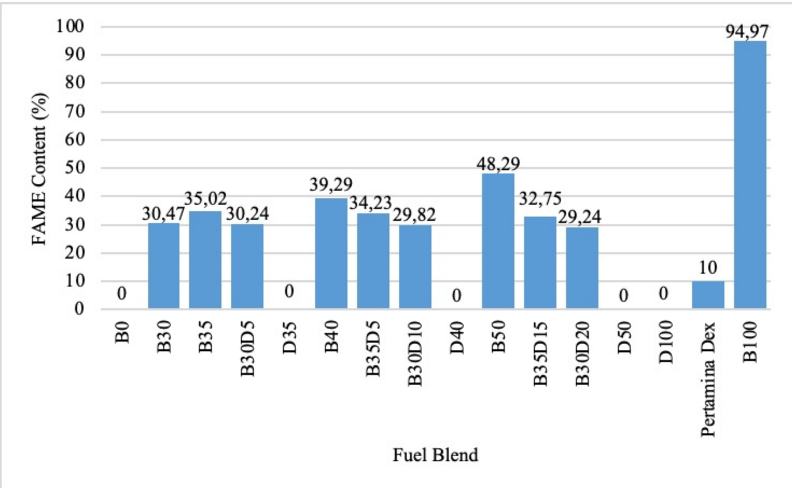

Figure 6. Variation of FAME content for different fuel blends.

Figure 6 presents the variation of FAME content for different fuel blends evaluated in this study. As shown in Figure 6, B100 exhibited the highest FAME concentration, followed by several biodiesel-containing blends such as B50 and B35. Higher FAME content generally increases oxygen availability during combustion, potentially improving combustion completeness and reducing carbonaceous emission tendencies (Atabani et al. 2013; Knothe 2010).

However, elevated FAME concentrations are also associated with higher viscosity and stronger oxidation tendencies compared to conventional diesel fuel (Hoekman & Robbins 2012; Knothe, Van Gerpen & Krahl 2010). These characteristics may contribute to deposit formation, injector fouling, and reduced storage stability during prolonged fuel utilization. In addition, biodiesel fuels containing high FAME concentrations tend to absorb moisture more easily, which may accelerate fuel degradation and microbial contamination within fuel storage systems (Rakopoulos, Antonopoulos & Rakopoulos 2006; UNFCCC 2021).

Conversely, fuels with lower FAME concentrations generally exhibit better oxidation stability and lower risks of storage-related degradation, although their oxygen contribution to combustion is comparatively lower. The trend observed in Figure 6 indicates that optimization of FAME concentration is important in balancing combustion cleanliness, fuel stability, and long-term fuel system reliability in biodiesel-HVO fuel applications.

4.7. EFFECT OF PARTICULATE CONTAMINATION ON FUEL SYSTEM CLEANLINESS

Particulate contamination is an important parameter associated with fuel cleanliness and the long-term reliability of diesel fuel systems. The presence of solid contaminants in fuel may contribute to abrasive wear, injector fouling, and fuel filter blockage, which can potentially affect fuel delivery consistency and combustion stability (Alptekin & Canakci 2009; Knothe 2010).

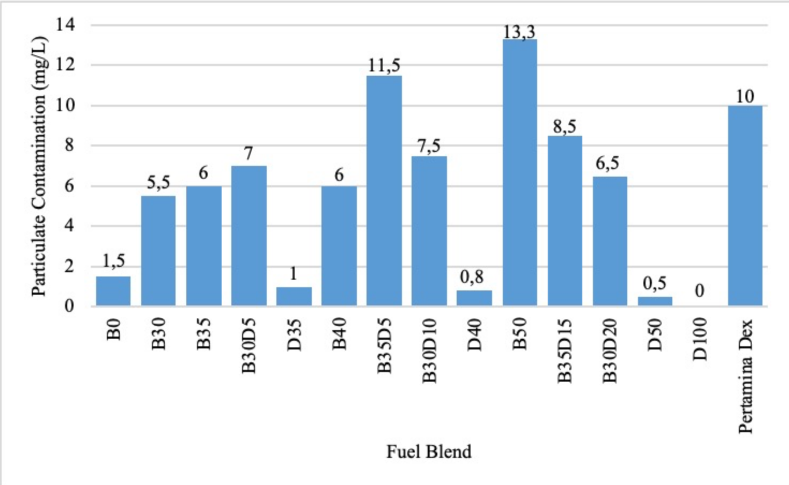

Figure 7. Variation of particulate contamination for different fuel blends.

Figure 7 presents the particulate contamination levels for different fuel blends evaluated in this study. As shown in Figure 7, several biodiesel-containing blends exhibited higher particulate contamination levels compared to D100 and Pertamina Dex. In contrast, D100 and Pertamina Dex demonstrated relatively lower contamination levels, indicating cleaner fuel characteristics.

Elevated particulate contamination may increase the risk of deposit accumulation within injectors and fuel delivery systems. Solid contaminants and oxidation-related residues can interfere with fuel atomization processes and potentially contribute to unstable combustion behavior during prolonged operation (Atabani et al. 2013; Rakopoulos, Antonopoulos & Rakopoulos 2006).

In addition, high particulate concentrations may accelerate fuel filter blockage and increase maintenance frequency in diesel fuel systems (Hossain & Davies 2010; Knothe, Van Gerpen & Krahl 2010). Cleaner fuels with lower particulate contamination levels generally support improved fuel system cleanliness and more stable fuel flow characteristics.

Overall, the trend observed in Figure 7 indicates that controlling particulate contamination is important for maintaining injector cleanliness, minimizing abrasive wear, and supporting long-term operational reliability in biodiesel-HVO fuel applications.

5. CONCLUSIONS

This study evaluated the physicochemical properties of diesel fuel (B0), biodiesel (B100), hydrotreated vegetable oil (HVO), and various biodiesel-HVO fuel blends (BxxDxx) and discussed their potential implications for diesel generator applications. The results indicate that fuel properties such as cetane number, sulfur content, lubricity, total acid number (TAN), flash point, FAME content, and particulate contamination play important roles in influencing combustion characteristics, fuel stability, fuel system cleanliness, and emission tendencies.

Fuels with higher cetane numbers and lower sulfur content demonstrated favorable characteristics for cleaner combustion and reduced contamination risks. Biodiesel-containing blends exhibited improved lubricity and oxygenated combustion characteristics, although higher FAME concentrations may increase oxidation tendency, deposit formation, and storage-related degradation. In contrast, fuels with lower particulate contamination and lower acidity levels showed better potential for maintaining long-term fuel system cleanliness and durability.

Among the evaluated fuel blends, several biodiesel-HVO blends demonstrated balanced physicochemical characteristics with promising potential for sustainable diesel fuel applications. Overall, the findings highlight the importance of optimizing fuel blend composition to achieve a balance between combustion quality, fuel stability, operational reliability, and environmental sustainability in diesel generator systems.

Future studies are recommended to include direct engine performance measurements and exhaust emission testing under controlled operating conditions to further validate the combustion and emission implications discussed in this study.

AUTHOR CONTRIBUTIONS

Lalu Wahyu Alam: Conceptualisation, Methodology, Investigation, Data Curation, Formal Analysis, Writing - Original Draft. **Nur Cahyo**: Supervision, Validation, Writing - Review and Editing. **Berkah Fajar T.K**: Supervision, Methodology, Writing - Review and Editing. **Ariyana Dwiputra Nugraha**: Data Curation, Investigation. **Muchamad**: Investigation, Data Analysis. **Paryanto**: Supervision, Review and Editing.

COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of the paper.

DATA ACCESSIBILITY

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

ETHICAL APPROVAL

This study does not involve human participants or animals.

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