International Journal of Engineering & Technology
ISSN: 3083-9114

Effect of Oxygenated Turpentine and Alpha-Pinene on Diesel Fuel Physicochemical Properties

Syazwana Sapee[1], Ahmad Fitri Yusop[1], Asep Kadarohman[2], Ratnaningsih Eko Sardjono[2]

[1]Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al Sultan Abdullah, 26600, Malaysia

[2]Department of Chemistry, Faculty of Mathematics and Science, Indonesia University of Education, Indonesia

Corresponding Author: syazwana.sapee@gmail.com

Abstract

The increasing demand for alternative fuels has led to extensive research on bio-additives to enhance fuel performance and reduce environmental impact. This study investigates the effect of turpentine and alpha-pinene, both in pure and oxygenated forms, on the physicochemical properties of diesel fuel. The fuel properties analyzed include density, kinematic viscosity, calorific value, and cetane number. The results indicate that adding bio-additives alters the fuel's characteristics significantly. The density of the test fuels increased compared to diesel (857.72 kg/m³), with the highest density observed in alpha-pinene diesel at 877.06 kg/m³. Kinematic viscosity decreased with the addition of bio-additives, with oxygenated alpha-pinene diesel showing the lowest value of 2.83 mm²/s, compared to 3.32 mm²/s for diesel. The calorific value of turpentine oxygenated diesel was the highest at 44.94 MJ/kg, while alpha-pinene oksigenasi had the lowest at 41.09 MJ/kg. The cetane number decreased in most test fuels, with the lowest value found in turpentine diesel at 63.78, while APD had the highest cetane number of 69.46, surpassing diesel (67.3). Gas chromatography-mass spectrometry analysis revealed significant compositional changes due to oxygenation, with α-pinene content reducing from 61.81% to 32.68% and new oxygenated compounds, such as α-pinene-oxide (6.15%) and trans-verbenol (6.66%), emerging. These findings suggest that turpentine and alpha-pinene bio-additives influence fuel properties differently, with turpentine-oxygenated diesel showing the highest calorific value and alpha pinene-diesel exhibiting the best cetane number. Further research is required to evaluate their impact on engine performance and emissions.

Article Info
Received: 23 March 2025
Revised: 18 April 2025
Accepted: 25 April 2025
Available online: 25 July 2025

Keywords
Bio-additives
Turpentine
Alpha-pinene
Diesel fuel
Physicochemical properties

1. Introduction

In recent decades, global energy security and environmental sustainability challenges have driven intensive research into developing more environmentally friendly alternative fuels. The high dependence on fossil fuels has accelerated the exploitation of non-renewable natural resources and contributed to increased greenhouse gas emissions and air pollution. Therefore, searching for cleaner and more efficient fuel solutions has become urgent in the transportation and industrial sectors. One promising approach is using bio-additives derived from renewable biomass sources, such as turpentine and alpha-pinene. These bio-additives can improve diesel fuel's combustion quality while reducing negative environmental impacts. However, further research is needed to fully understand their effects on the physicochemical properties of fuels and diesel engine performance to ensure their effectiveness and feasibility in practical applications.

Renewable energy is increasingly becoming a significant focus in alternative fuel research, significantly reducing dependence on fossil fuels and reducing greenhouse gas emissions (Bahagia, Nizar, Yasin, Rosdi, & Faisal, 2025; Gani et al., 2025; Holechek, Geli, Sawalhah, & Valdez, 2022). One approach that has attracted attention is using bio-additives based on turpentine and alpha-pinene in diesel fuel blends. These materials are known to have unique chemical properties, such as high volatility and oxygen content that contribute to combustion efficiency (Irhamni, Kurnianingtyas, Muhtadin, Bahagia, & Yusop, 2025; Kohse-Höinghaus, 2021; Muhtadin, Rosdi, Faisal, Erdiwansyah, & Mahyudin, 2025). Several previous studies have shown that bio-additive-based fuel blends can improve energy efficiency and reduce unavoidable pollutant emissions, although their effects on combustion characteristics and engine performance are still a topic that needs further study (Ghazali, Rosdi, Erdiwansyah, & Mamat, 2025; Iqbal, Rosdi, Muhtadin, Erdiwansyah, & Faisal, 2025; Jalaludin, Kamarulzaman, Sudrajad, Rosdi, & Erdiwansyah, 2025). In the past few decades, various studies have been conducted to evaluate bio-additives impact on fuels' physical and chemical properties. For example, turpentine has a higher density and viscosity compared to pure diesel, so that it can affect the fuel atomization pattern in the combustion chamber (Alenezi et al., 2021; S. M. M. Rosdi, Erdiwansyah, Ghazali, & Mamat, 2025; Rosli, Xiaoxia, & Shuai, 2025; Xiaoxia, Lin, & Salleh, 2025). Increasing the turpentine content in the fuel mixture can reduce viscosity and increase evaporation efficiency, which in turn affects combustion characteristics (Almardhiyah, Mahidin, Fauzi, Abnisa, & Khairil, 2025; Jeevanantham et al., 2020; Muzakki & Putro, 2025; NOOR, Arif, & Rusirawan, 2025). However, several other studies have shown that the use of bio-additives in diesel fuel can reduce the cetane number and affect the ignition time of the fuel (Alenezi, Erdiwansyah, Mamat, Norkhizan, & Najafi, 2020; Biodun, Fayomi, & Okeniyi, 2022; Pranoto, Rusiyanto, & Fitriyana, 2025).

This study examines the characteristics of bio-additive-based blended fuels, especially turpentine and alpha-pinene, in pure form and after undergoing oxygenation. Analysis was carried out on various physicochemical properties of the fuel, including density, viscosity, calorific value, and cetane number. This parameter plays a vital role in determining engine performance and combustion efficiency, so a more in-depth evaluation can provide insight into the potential of bio-additives in alternative fuel applications (Alli & Kotha, 2023; Erdiwansyah, Mamat, Sani, Sudhakar, et al., 2019; Mufti, Irhamni, & Darnas, 2025; S. M. Rosdi, Maghfirah, Erdiwansyah, Syafrizal, & Muhibbuddin, 2025). The results showed that adding bio-additives to diesel fuel caused significant changes in fuel characteristics. For example, the calorific value of the fuel mixture with turpentine increased compared to pure diesel, indicating that bio-additives can contribute to fuel energy efficiency (Fitriyana, Rusiyanto, & Maawa, 2025; Kurniawan, Setyaningsih, & Setiapraja, 2021; Muhibbuddin, Hamidi, & Fitriyana, 2025). On the other hand, the cetane number of the blended fuel tends to be lower than that of diesel, which can affect the ignition characteristics of the fuel in a diesel engine (Erdiwansyah et al., 2024; Erdiwansyah, Mamat, Sani, & Sudhakar, 2019; Khalisha, Caisarina, & Fakhrana, 2025; Labeckas, Slavinskas, & Kanapkienė, 2017).

In addition, this study also observed changes in the chemical composition of turpentine before and after the oxygenation process using gas chromatography-mass spectrometry (GC-MS) techniques. The analysis showed that the oxygenation process produced new oxygenated compounds that could increase the reactivity of the fuel in the combustion process. This aligns with previous studies showing that adding oxygenating compounds to fuel can improve combustion efficiency and reduce unavoidable exhaust emissions, such as unburned hydrocarbons and carbon monoxide (Liu et al., 2021). This study aims to comprehensively evaluate the effect of turpentine and alpha-pinene addition on the physicochemical characteristics of fuel and its implications on engine performance and exhaust emissions. The novelty of this study lies in the in-depth analysis of the effect of oxygenation on the chemical composition of bio-additives, which has not been widely explored in previous studies. Thus, this study provides a new contribution to the development of bio-additive-based fuels with the potential to improve combustion efficiency and reduce environmental impacts.

2. Experimental engine test setup

This section outlines the methodologies employed to evaluate the performance, combustion characteristics, and exhaust emissions of the test fuels in a diesel engine. It details the experimental engine test setup, including engine specifications, installed systems, key equipment, measurement techniques, and instruments utilized for data collection. A thorough explanation of sensor integration and the data acquisition system is provided. The section also includes a schematic representation of the experimental engine setup, specifications, components, and measurement approaches. The engine test rig was assembled as depicted in the schematic diagram in **Fig. 1**. The experiment was carried out at the Engine Performance Laboratory, Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang, Pekan, Pahang.

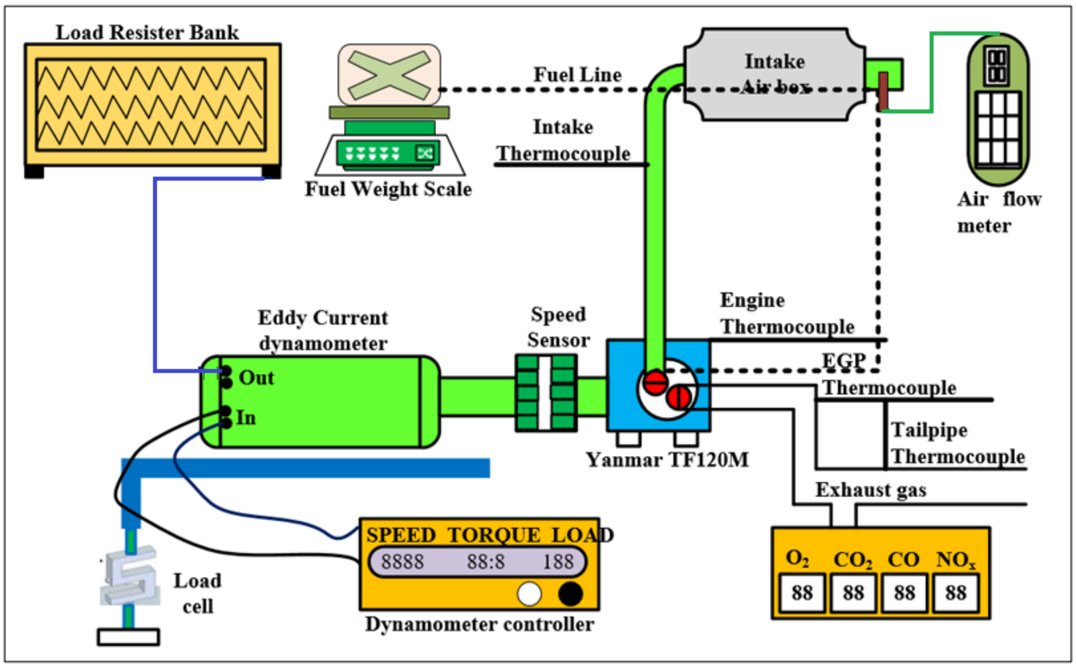

Fig. 1. Diagrammatic representation of the diesel engine test setup

Table 1 presents the specifications of the Yanmar TF120M diesel engine, a horizontal, four-stroke, single-cylinder engine that operates with a direct injection system. This engine was manufactured in 2016 with a capacity of 0.638 litres and has a bore × stroke size of 92 mm × 96 mm. In terms of performance, this engine produces a continuous output power of 7.82 kW at 2,400 rpm, while the rated output power reaches 8.94 kW at 2,400 rpm. In addition, under 1 hour of operation, the engine can produce 12.0 hp (9.0 kW) at 2,400 rpm, with a rated continuous power of 10.5 hp (7.8 kW) at 2,400 rpm. The maximum torque of this engine is 43.35 N m at 1,800 rpm. The fuel consumption efficiency of the engine is indicated by the figure of 169 gr/hp.h in its specific fuel consumption specifications. The engine ignition system uses a manual (hand) starting method, with water-cooled cooling and a natural aspiration system. This engine has a compression ratio 17.7 and a fuel injection angle of 17° before TDC. The Power Take-Off (PTO) position is located on the flywheel side, with the direction of rotation of the crankshaft counterclockwise when viewed from the flywheel side. These specifications indicate that the Yanmar TF120M engine is designed for reliable and efficient performance in agricultural or small industrial applications.

Table 1: Specification of Yanmar TF120M diesel engine

Description	Specification
Engine model	YANMAR TF120M
Engine year	2016
Engine type	Horizontal, four-cycle, four-stroke, diesel engine
Number of cylinders	1
Continuous power output (kW)	7.82 kW at 2,400 rpm
Rated power output (kW)	8.94 kW at 2,400 rpm
Bore × Stroke (mm)	92 × 96
Displacement (L)	0.638
Maximum torque (kgf.m/rpm)	43.35 N.m / 1,800 rpm
At 1-hr. rated output (hp/rpm, kW)	12.0 hp / 2,400 rpm (9.0 kW)
Rated continuous output (hp/rpm, kW)	10.5 hp / 2,400 rpm (7.8 kW)
Specific fuel consumption (gr/hp.h)	169 gr/hp.h
Injection timing	17°bTDC
Compression ratio	17.7
Combustion system	Direct injection
Aspiration	Natural aspiration
Cooling system	Water-cooled
Starting system	Manual (hand) starting.
Position of PTO	Flywheel side
The direction of crankshaft rotation	Counterclockwise viewed from the flywheel.

Fig. 2 shows the main parts of the Yanmar TF120M diesel engine, which consists of several components essential for engine operation. The exhaust pipe functions to remove combustion gases from the combustion chamber. The radiator plays a role in the engine cooling system by helping to reduce the engine temperature during operation. The flywheel is a flywheel that stores kinetic energy and helps maintain stable engine speed. The fuel filter filters dirt and particles from the fuel before entering the combustion system, while the fuel line flows fuel from the tank to the engine. Fuel oil is the fuel used in this engine to generate power. The throttle controls the amount of fuel entering the combustion chamber, affecting the engine's speed and power. The starter is a component used to start the engine, while the oil port is where the oil is filled to lubricate the inside to reduce friction and increase engine life. These parts work together to ensure the engine operates efficiently and optimally.

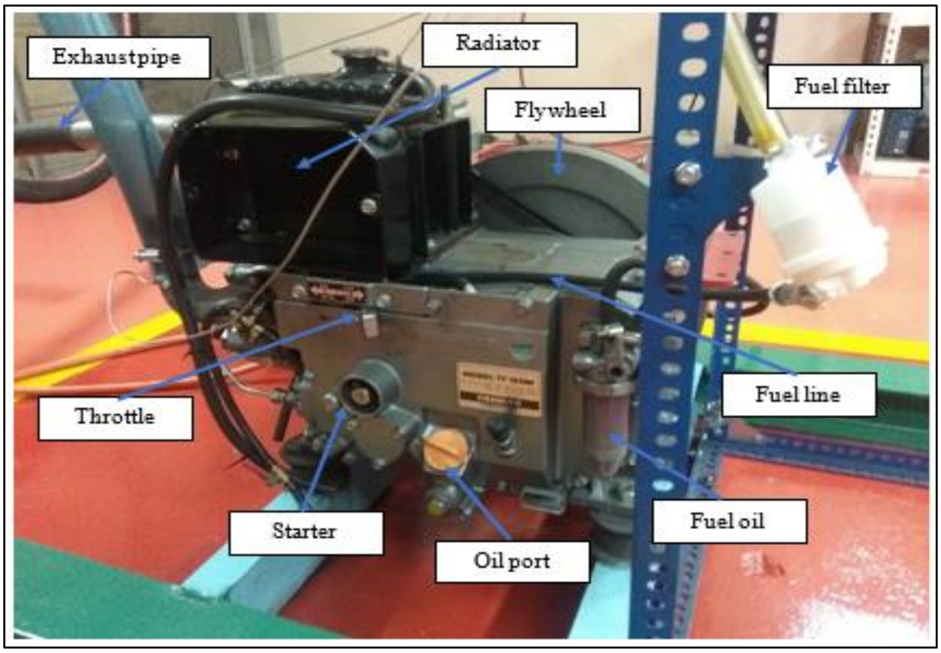

Fig. 2. Yanmar TF120M engine parts

3. Result & Discussion

Analysis of the physicochemical properties of test fuels

The test fuels are diesel blended with four different bio-additive types: turpentine, alpha-pinene, oxygenated turpentine, and oxygenated alpha-pinene. The properties of each blended fuel are presented in this chapter. The physicochemical properties of all test fuels (diesel (D), turpentine-diesel (TD), alpha pinene-diesel (APD), oxygenated turpentine-diesel (OTD), and oxygenated alpha pinene-diesel (OAPD) play a crucial role in determining engine performance, combustion, and emission characteristics. Therefore, these properties must be evaluated first before further study on the test fuels. These properties are essential in understanding the character of each test fuel before associating them with any findings, such as the engine characteristics. The analysed physicochemical properties include density, viscosity, calorific value, and cetane number. All measurements of fuel properties were carried out following ASTM standards.

Bio-additive chemical composition observation

Table 2. shows the measured fuel parameters of the test fuels. The measured fuel properties were compared with the baseline and ASTM D975 fuel standard specification for diesel fuel oils. The standard was referred to avoid the complication of fuel usage in a diesel engine. The chemical contents in diesel, turpentine, and oxygenated turpentine were detected, quantified, and identified using gas chromatography-mass spectrometry (GC-MS). The results were compared to the baseline diesel fuel. Gas chromatography-mass spectrometry was used to obtain detailed information on the chemical composition of the fuel. Each chemical compound discovered in the fuel is represented by a peak produced by the gas chromatogram. The number of peaks in the fuel samples reflects the number of chemical compositions that have been isolated. The individual peaks' position shows each chemical composition's retention time. Table presents the chemical constituents' composition of diesel, turpentine, and oxygenated turpentine. Figure 4.1 shows a chromatogram of diesel fuel, turpentine, and oxygenated turpentine, illustrating the chemical components and composition. Details of the chromatogram peak report of turpentine and oxygenated turpentine using mass spectrum data are attached in Appendix G and Appendix H, respectively.

Table 2. Chemical constituents' composition of diesel, turpentine, and oxygenated turpentine fuels

Compound	Molecular Formula	Diesel (wt.%)	Turpentine (wt.%)	Oxygenated Turpentine (wt.%)
Pentadecane	$C_{15}H_{32}$	5.27	-	-
2,6,10,14-Tetramethylpentadecane (pristane)	$C_{19}H_{40}$	2.44	-	-
Hexadecane (n-cetane)	$C_{16}H_{34}$	10.67	-	-
n-Octadecane	$C_{18}H_{38}$	7.47	-	-
n-Nonadecane	$C_{19}H_{40}$	5.37	-	-
n-Heneicosane	$C_{21}H_{44}$	4.84	-	-
n-Docosane	$C_{22}H_{46}$	4.81	-	-
n-Tricosane	$C_{23}H_{48}$	4.07	-	-
α-Pinene	$C_{10}H_{16}$	-	61.81	32.68
Camphene	$C_{10}H_{16}$	-	2.25	2.94
β-Pinene	$C_{10}H_{16}$	-	4.80	4.44
δ-3 Carene	$C_{10}H_{16}$	-	19.70	5.77
dl-Limonene	$C_{10}H_{16}$	-	3.58	1.93
α-Terpinolene	$C_{10}H_{16}$	-	2.49	-
α-Pinene oxide	$C_{10}H_{16}O$	-	-	6.15
α-Campholene aldehyde	$C_{10}H_{16}O$	-	-	3.59
Trans-verbenol	$C_{10}H_{16}O$	-	-	6.66

Compound	Molecular Formula	Diesel (wt.%)	Turpentine (wt.%)	Oxygenated Turpentine (wt.%)
Verbenone	$C_{10}H_{14}O$	-	-	3.11
Patchoulane	$C_{15}H_{26}$	-	-	8.29

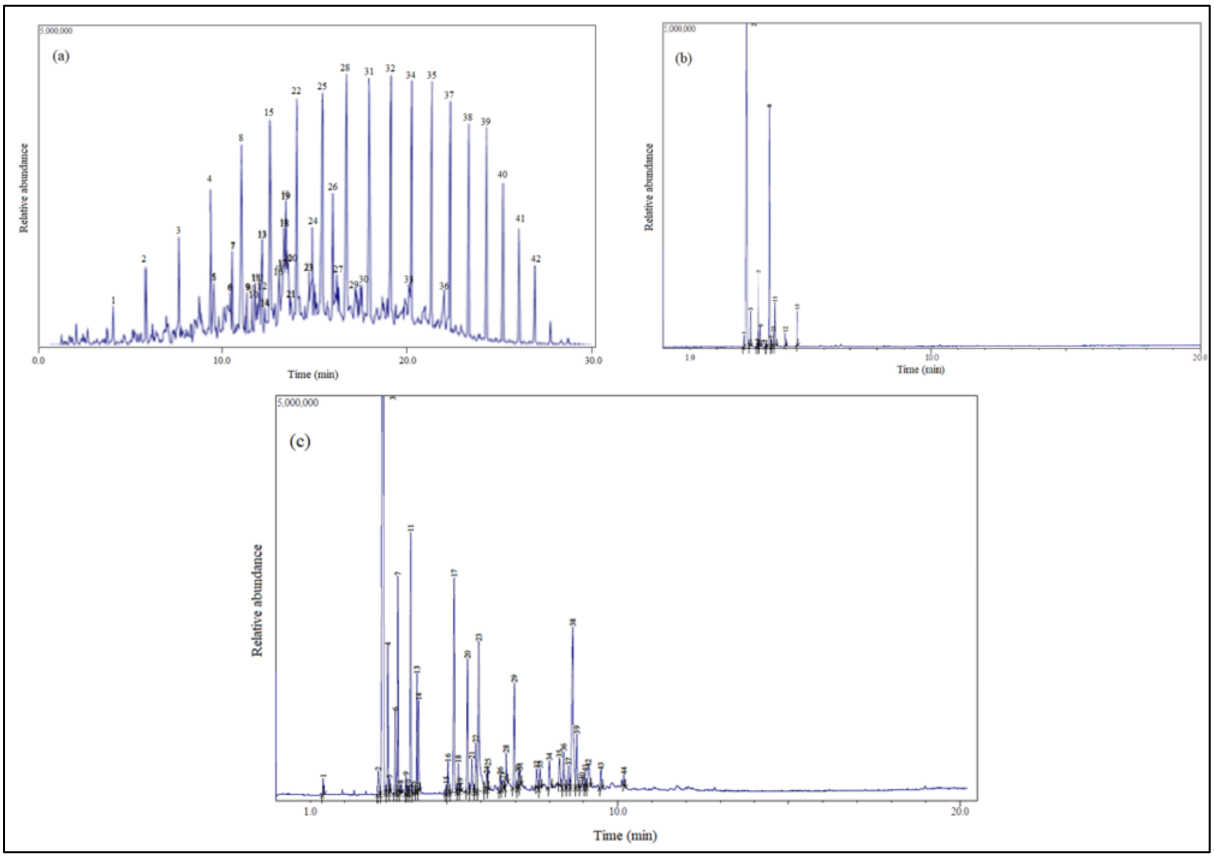

Fig. 3. Gas chromatogram of (a) diesel fuel, (b) turpentine, and (c) oxygenated turpentine

Referring to **Fig. 3** (a–c), the chemical compositions of diesel fuel were traced at the beginning of the retention period until the procedure was nearly complete in 30 min. On the other hand, the situation for turpentine and oxygenated turpentine is quite different. As for turpentine, chemical compositions were traced at the beginning of the retention period, and the procedure was nearly complete at the retention time of 4.993 min. Meanwhile, the chemical compositions of oxygenated turpentine were traced at the beginning of the retention period (1.385 min), and the procedure was nearly complete at the retention time of 10.175 min. The results showed that the chemical compositions of turpentine and oxygenated turpentine were identified at the start of the retention period.

In contrast, the chemical compositions of diesel fuel were detected during the retention period. Thus, the early detection of the chemical compositions of turpentine and oxygenated turpentine reveals that both fuels contain chemical compounds with high volatility. On the other hand, the late detection of the chemical compounds of diesel fuel suggests that diesel fuel contains chemical compounds with low volatility. The chemical compound's volatility directly influences the flash point of the fuel. This finding is consistent with the mass spectrometer observation of diesel fuel due to the low molecular weight components; thus, diesel fuel is more volatile than turpentine and oxygenated turpentine.

Fig. 3 (a) shows that diesel fuel comprises saturated hydrocarbons (HCs) like regular paraffin and cycloparaffins. The primary components of diesel fuel include hexadecane (n-cetane), pristane (2,6,10,14-tetramethylpentadecane), and bowls of paraffin (Rosner & Organization, 1996). Turpentine, on the other hand, contains at least 12 compounds, as shown in **Fig. 3** (b), with the most abundant being α-pinene (61.61%), δ-care (19.70%), β-pinene (4.8%), limonene (3.58%), and camphene (2.25%), with retention times of 3.127 min, 3.950 min, 3.568 min, 4.712 min, and 3.267 min, respectively. These findings are consistent with prior research (Jonsson, Hallquist, & Ljungström, 2006). The oxidation process has significantly changed the chemical components and composition of turpentine. **Table 2** shows the chemical components of oxygenated turpentine, where GC-MS discovered at least 44 compounds, as presented in **Fig. 3** (c). The oxidation of turpentine produces new compounds of varied compositions. The composition of key turpentine components was significantly reduced after oxidation. For instance, α-pinene (32.68%; reduced from previously 61.61%), δ-care (5.77%; reduced from previously 19.70%), β-pinene (4.44%, reduced from previously 4.8%), and limonene (1.93%; reduced from previously 3.58%). New oxygenated compounds with significant compositions, such as α-pinene-oxide, patchcoulane, trans-verbenol, verbenone, and α-champholene aldehyde, were discovered with retention times of 5.213 min, 8.684 min, 5.932 min, 6.974 min, and 5.604 min, respectively. More oxygen-related functional groups, such as hydroxyl (-OH), aldehyde (-HC=O), and ketone (-C=O), are present in oxygenated products. These findings demonstrated the effectiveness of specific turpentine oxidation processes, and the major oxygenated molecules derived from the oxidation of α-pinene and δ-carene are the two most essential elements of turpentine.

In general, the energy content of a fuel may be predicted based on the HC chain length. An increased HC chain length results in higher energy density, higher boiling points, and lower volatility (Bacha, Freel, Gibbs, Gibbs, & Hemighaus, 2007). In contrast, fuel containing common alkane HCs provides the best ignition quality, which improves with increasing chain length. The diesel fuel was mainly made up of paraffin (alkane) and aromatic families, based on the gas chromatography results in **Table 2**. Diesel fuel has an outstanding ignition quality due to the presence of the alkane family. Moreover, the aromatic family's presence contributes to the diesel fuel's high energy content per unit volume (Pulkrabek, 2000). Meanwhile, turpentine and oxygenated turpentine properties are predicted to have a poorer ignition quality and energy content due to the lack of alkane and aromatic components.

Furthermore, the number of atoms in the molecular structure significantly impacts the fuel's boiling temperature. The boiling temperature increases as the number of atoms in the molecular structure increases. As a result, fuels with fewer atoms in their molecular structure are more volatile (Ganesan, 1994). When comparing the chemical composition of diesel fuel with turpentine and oxygenated turpentine, it was discovered that the significant alkane HC in diesel fuel has a carbon (C) atom count of 14–32. Meanwhile, turpentine and oxygenated turpentine were mainly made up of α-pinene and δ-carene with 10 C atoms. Therefore, the lower number of atoms in both fuels causes them to boil at lower temperatures, making them more volatile.

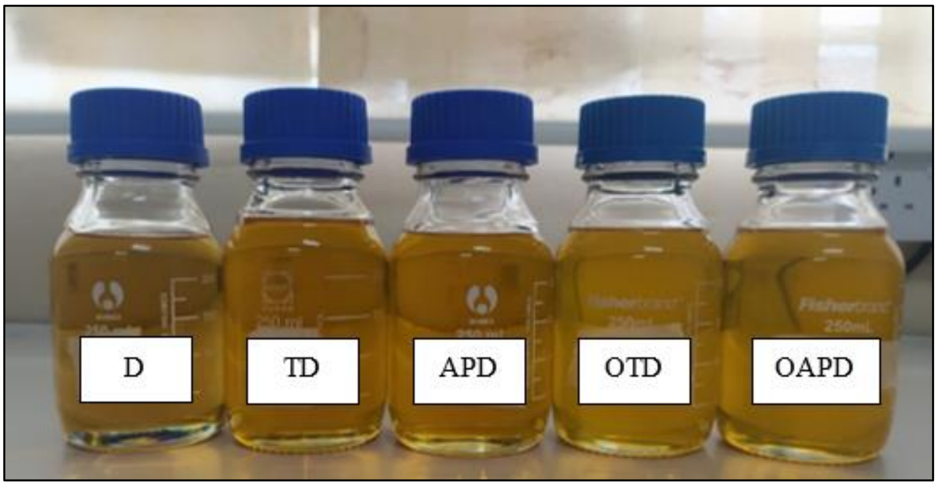

Fig. 4. Samples of test fuels

In contrast, due to the more significant number of atoms in the molecular structure of diesel fuel, the boiling temperature and volatility are supposed to be higher and less volatile. In addition, the hydrogen (H2) ratio to C atoms is directly related to the calorific value. Hydrogen has a higher calorific value than C. The calorific value increases typically as the molecule's H2 to C atoms increase (Ganesan, 2012). According to the findings in **Table 2**, diesel fuel has a higher proportion of H_2 to C atoms than turpentine and oxygenated turpentine. Hence, the calorific value of diesel fuel is higher than that of turpentine and oxygenated turpentine. **Fig. 4** shows the samples of test fuels after blending with diesel fuel. After mixing, one of the most critical processes is stability analysis. The analysis must be performed before further testing the test fuels. The long-term stability of the bio-additives blended with diesel fuel can be accomplished by using a suitable procedure to prepare test fuels.

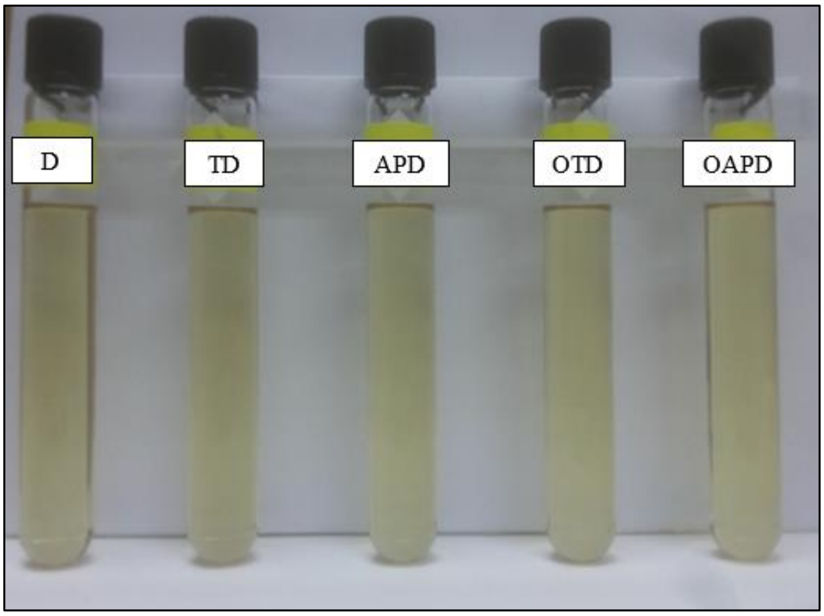

Fig. 5. Test fuels in conical plastic tubes for stability test

A visual separation method was used in this study, as shown in **Fig. 5**. The Visual separation method was done by taking pictures over a period while waiting for the additives to settle to the bottom or the top of the test tube without being disturbed. The appearance of any separating layer was continuously monitored. After blending, the observation was recorded for up to 30 days. The samples were well-blended if the additives were soluble in diesel fuel. This is because bio additives are soluble in diesel. After 30 days of stability analysis, there was no separating layer for all the test fuels. In addition, the specific gravity of the test fuels was monitored and determined every 3 days until 30 days. All the test fuels were ensured to obtain constant specific gravity before further testing.

Density

Fig. 6 presents the effect of additives and oxygenated additives on the density of test fuels. As shown in **Table 3**, the density of the test fuels used in this study ranged from 857.72 kg/m^3 to 877.06 kg/m^3. The lowest density is D (857.72 kg/m^3). The density of test fuels increased compared to D for TD, OTD, APD, and OAPD with the values of 866.79 kg/m^3 (1.06%), 867.92 kg/m^3 (1.19%), 877.06 kg/m^3 (2.25%), and 866.62 kg/m^3 (1.04%), respectively. Adding additives increased the density of test fuels. This is because the density of turpentine and alpha-pinene oil is higher than that of diesel. Notably, APD has the maximum density, which is 2.25% higher than the density of diesel. The density of OTD increased slightly while the density of OAPD decreased when oxygenated, with a 1.19% increment and a 1.04% decrement, respectively. These data support the idea that various additives can alter the density of diesel fuel. This is primarily due to the higher density of additives than diesel fuel by 0.47–1.4% (Jeevanantham et al., 2020). According to previous research, increased density affected the advanced injection timing, resulting in considerable engine performance degradation and increased exhaust emissions (Torres-Jimenez et al., 2011). However, this constraint can be overcome by minor modifications of injection timing at the engine (Kegl, 2006).

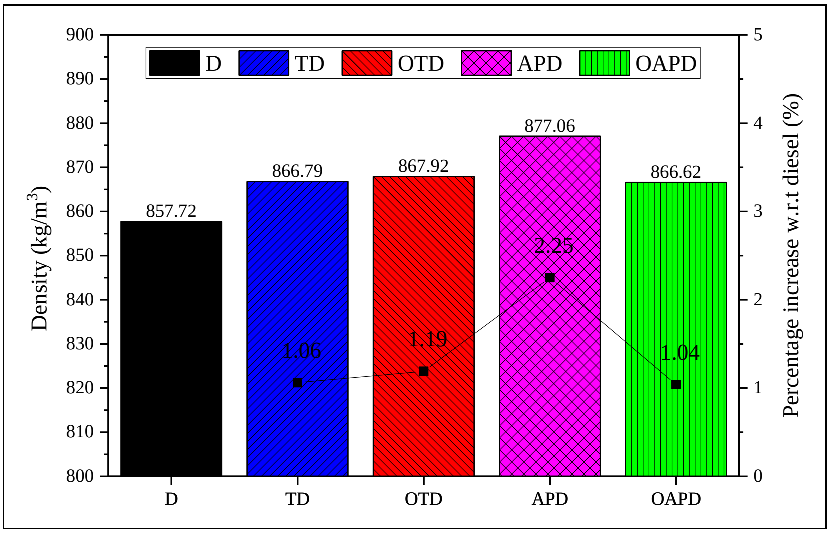

Fig. 6. Effect of additives and oxygenated additives on the density of test fuels

Kinematic viscosity

Fig. 7 shows the effect of additives and oxygenated additives on test fuels' kinematic viscosities @ 40°C. The kinematic viscosity of additive-diesel fuel blends ranged from 2.83 mm^2/s to 3.32 mm^2/s. D has the highest kinematic viscosity, while OAPD has the lowest. From **Fig. 7**, D has the highest viscosity of 3.32 mm^2/s, followed by OTD, TD, APD, and OAPD with viscosities of 3.18 mm^2/s, 3.08 mm^2/s, 2.94 mm^2/s, and 2.83 mm^2/s, respectively. Furthermore, when compared to diesel fuel, the viscosity difference between diesel fuel with TD, OTD, APD, and OAPD is 7.23%, 4.22%, 11.45%, and 14.76%, respectively. Notably, diesel fuels with additive blends have a lower viscosity than diesel. This is due to the lower viscosity of pure additive oil than diesel fuel; hence, the viscosity of test fuels decreases. Many studies have proved the significant role of fuel viscosity in injection systems.

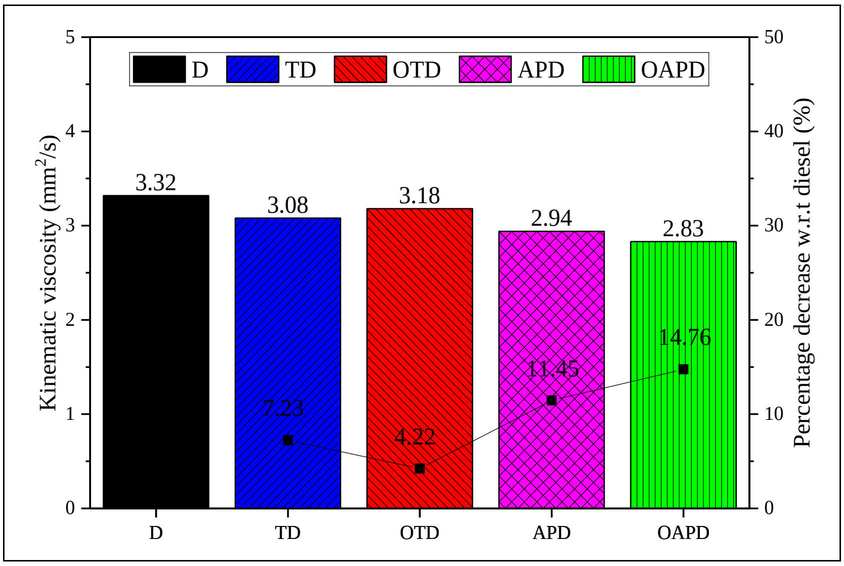

Fig. 7. Effect of additives and oxygenated additives on the kinematic viscosity of test fuels

Higher viscosity fuels have inferior atomisation and affect the fuel injector, resulting in incomplete combustion, low engine performance, severe engine damage, and the deposit of solid, unburnt particles. However, low-viscosity fuels do not lubricate the pump and injector, and too low viscosity may reduce fuel delivery due to leakage. Therefore, optimal viscosity is required. Hence, ASTM D975 limits the acceptable range of fuel viscosity from 1.3 m^2/s to 4.5 m^2/s. Fuel viscosity also affects the combustion chamber's atomisation process and spray pattern. As the viscosity decreases, it is expected that fuel atomisation is enhanced when additives are added to diesel fuel, resulting in a direct improvement in engine power output. Low fuel viscosity leads to smaller droplet size in spray, thus increasing the droplet surface area, enhancing evaporation, and improving combustion. The kinematic viscosity of the test fuels is similar to that of a previous study, where the kinematic viscosity of diesel fuel-turpentine blends decreased with the addition of turpentine in diesel (Dubey & Gupta, 2016). The kinematic viscosity of the oxygenated additive-diesel fuel blends is similar to that of (Yoshimoto, Kinoshita, Shanbu, & Ohmura, 2013).

Calorific value

Fig. 8 shows the effect of additives and oxygenated additives on the calorific value of test fuels. OTD has the highest calorific value (44.94 MJ/kg), while OAPD (41.09 MJ/kg) is the lowest. OAPD has the lowest calorific value (41.09 MJ/kg), followed by D, TD, APD, and OTD with the calorific values of 42.43 MJ/kg, 42.63 MJ/kg, 42.71 MJ/kg, and 44.94 MJ/kg, respectively. Furthermore, the calorific value difference between diesel fuel with TD, OTD, APD, and OAPD is 0.47%, 5.92%, 0.66%, and -3.16%, respectively. It is noted that the calorific value of additive-diesel blends is higher than that of diesel fuel. Thus, adding additives to blended fuels increases the calorific value of the fuel blends compared to diesel. This is primarily due to the higher calorific value of additive oil, which is significantly higher than diesel fuel by 4.0–5.4% (Jeevanantham et al., 2020; Raman, Sivasankaralingam, Dibble, & Sarathy, 2016). The findings are consistent with previous researchers (Dubey & Gupta, 2018; Loganathan & Manoharan, 2017), who found that adding turpentine to fuel blends improved the calorific value. Besides, oxygenated fuel shows improvement in calorific value. This aligns with OTD's calorific value data, which significantly increased to 5%. In contrast, the calorific value of OAPD decreased. This is due to the reactivity of alpha-pinene being oxygenated, as explained by the researchers who studied the oxidation and degradation of pinene (Liu et al., 2021).

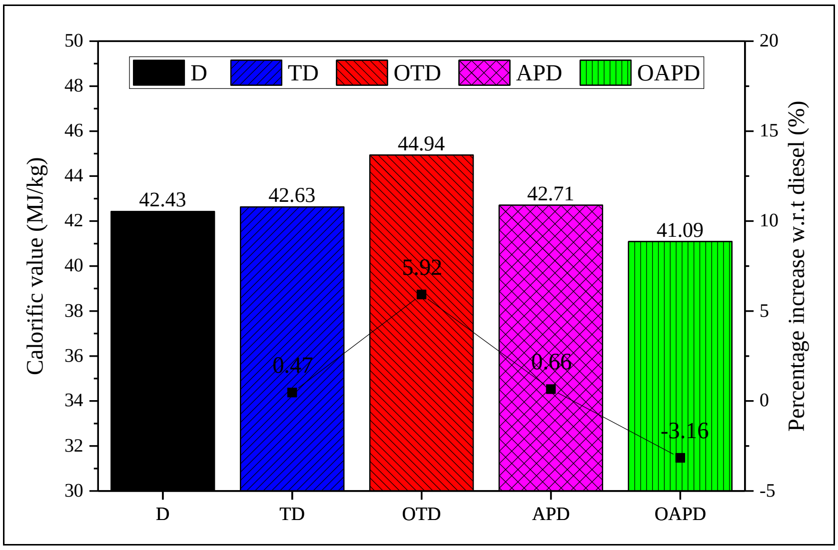

Fig. 8. Effect of additives and oxygenated additives on the calorific value of test fuels

Cetane number

Fig. 9 shows the effect of additives and oxygenated additives on the cetane number of test fuels. It reveals that the cetane number of test fuels ranged from 63.78 to 69.46. The values of cetane number of D, TD, OTD, APD, and OAPD are 67.3, 63.78, 64.17, 69.46, and 66.01, respectively. Most test fuels with additives showed lower cetane numbers than diesel. The percentages of reduction of cetane number concerning D for TD, OTD, APD, and OAPD are 5.23%, 4.65%, -3.2%, and 1.92%. This is due to the lower cetane number of turpentine (38) than the cetane number of diesel (53) (Jeevanantham et al., 2020). However, it is notable that APD has the highest cetane number of 69.46, which is greater than diesel fuel with a cetane number of 67.3. The significant component in the alpha-pinene composition is responsible for the higher cetane number. According to Jose and Anand (Jose & Anand, 2016), most biofuels have higher cetane numbers than diesel fuel because biofuels are mostly made up of long-chain HC groups. Furthermore, increased saturated fatty acids and oxygen (O_2) content in the fuel composition lead to a higher cetane number of biofuels (Bhuiya et al., 2016; Mosarof et al., 2015). Because APD has a higher cetane number, less fuel is consumed during premix combustion and more fuel is burned during diffusion combustion. This circumstance causes the pressure rate to rise in the cylinder and slow down, potentially resulting in a lower in-cylinder temperature.

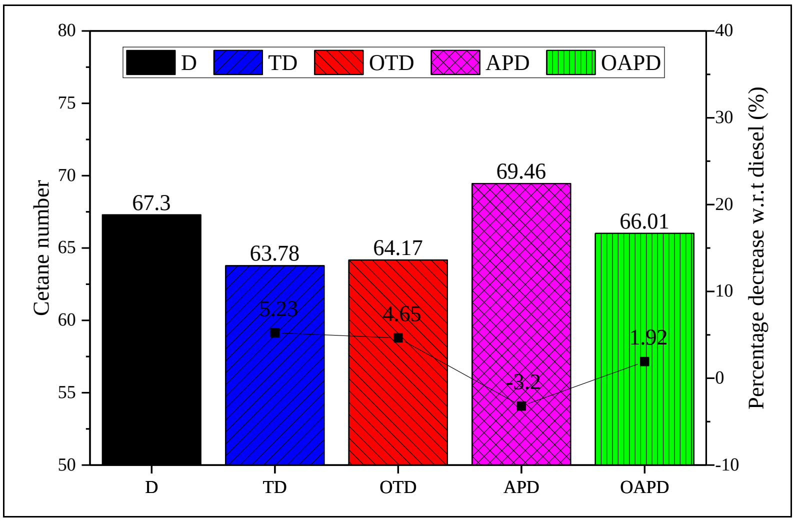

Fig. 9. Effect of additives and oxygenated additives on the cetane number of test fuels

The physicochemical properties of fuel play a crucial role in determining engine combustion, performance, and emissions. Therefore, these physicochemical properties must be determined first before further studying the mixed fuels. These parameters are critical in understanding the character of each test fuel before associating them with any findings, such as the engine characteristics. Identifying the effect of adding pure turpentine alpha-pinene oil and oxygenated oil in fuel blends is significant for describing the trend of fuel properties. Density, viscosity, calorific value, and cetane number are all test fuel properties evaluated in this study. All measurements of fuel qualities were carried out following ASTM standards. **Table 3** presents the measured fuel physicochemical properties of the test fuels.

Table 3. The physicochemical properties of test fuels

Property	ASTM D975		D	TD	OTD	APD	OAPD
	Test No.	Limits					
Density @ 15 °C (kg/m^3)	ASTM D4052	-	857.72	866.79	867.92	877.06	866.62
Kinematic viscosity @ 40 °C (mm^2/s)	ASTM D445	1.9 – 4.1	3.32	3.08	3.18	2.94	2.83
Calorific value (MJ/kg)	ASTM D240	-	42.43	42.63	44.94	42.71	41.09
Cetane number	ASTM D613	Min. 40	67.3	63.78	64.17	69.46	66.01

4. Conclusion

This study evaluated the effect of bio-additives turpentine and alpha-pinene, both in pure form and after undergoing the oxygenation process, on the physicochemical properties of diesel fuel. The results showed that adding bio-additives significantly affected the fuel's density, viscosity, calorific value, and cetane number. The density of the blended fuel increased compared to pure diesel (857.72 kg/m³), with the highest value in the alpha pinene-diesel blend of 877.06 kg/m³. This increase in density indicates a change in fuel composition that can affect atomization and combustion in the engine. In terms of viscosity, adding bio-additives decreased the viscosity value of the fuel compared to pure diesel (3.32 mm²/s). The blend with oxygenated alpha-pinene had the lowest viscosity of 2.83 mm²/s, while the blend with oxygenated turpentine showed a viscosity of 3.18 mm²/s. This decrease in viscosity can improve the quality of fuel atomization, which contributes to more efficient combustion.

The calorific value of the blended fuels showed an increase in some formulations compared to pure diesel (42.43 MJ/kg). The oxygenated turpentine blend had the highest calorific value of 44.94 MJ/kg, indicating the potential for increasing fuel energy efficiency. In contrast, the oxygenated alpha-pinene blend had the lowest calorific value of 41.09 MJ/kg, indicating that the oxygenation process can affect the energy content of the fuel differently depending on the type of bio-additive used.

Cetane number analysis showed that most of the bio-additive blends experienced a decrease in cetane number compared to pure diesel (67.3). The turpentine-diesel blend had the lowest cetane number of 63.78, while the alpha pinene-diesel blend had the highest cetane number of 69.46, which exceeded pure diesel's cetane number. This increase in cetane number indicates that some formulations of bio-additives can improve the ignition performance of the fuel in diesel engines. In addition, gas chromatography-mass spectrometry analysis showed significant changes in chemical composition after oxygenation. The main compounds in turpentine, such as α-pinene (61.81%) and δ-carene (19.70%), were reduced to 32.68% and 5.77% after oxygenation, while new compounds such as α-pinene-oxide (6.15%) and trans-verbenol (6.66%) appeared after oxygenation. These changes indicate that oxygenation can increase bio-additives oxygen content, potentially improving combustion efficiency and reducing exhaust emissions. Overall, this study shows that turpentine and alpha-pinene bio-additives can be used as components in diesel fuel with varying impacts on the physicochemical properties of the fuel. Turpentine oxygenation has the highest calorific value, which has the potential to improve energy efficiency, while alpha pinene-diesel shows the highest cetane number, which can improve combustion efficiency. These findings provide new insights into the development of bio-additive-based fuels, although further research is needed to evaluate their impacts on engine performance and exhaust emissions fully.

Acknowledgement

The authors fully funded this research and did not receive any specific grant from public, commercial, or not-for-profit funding agencies. The authors would like to express their sincere gratitude to all individuals and institutions that provided moral and technical support throughout this study.

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