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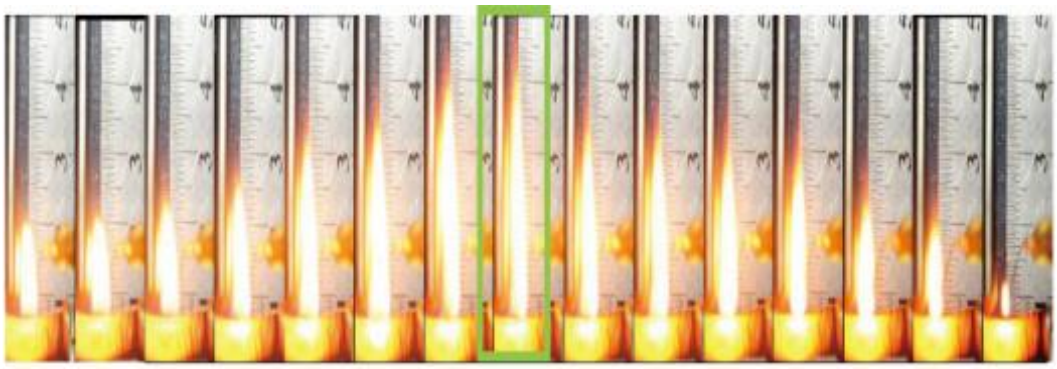
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Igniting the flame, maximizing energy: The effectiveness of nutmeg oil as a bioadditive in B20 droplet combustion

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Highlights:

- Nutmeg oil (Myristica fragrans) was introduced as a bioadditive to Biodiesel B20 fuel to improve ignition quality and combustion performance.
- The addition of nutmeg oil significantly reduced ignition delay and combustion duration, while increasing burning rate and peak flame temperature.
- GC–MS analysis confirmed the presence of oxygenated and volatile compounds (e.g., α-pinene and myristicin) that promoted more efficient combustion.
- Statistical analyses (ANOVA and Tukey HSD) verified the significance of the observed improvements, highlighting the potential of nutmeg oil–blended B20 for sustainable fuel applications.

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Abstract

This study aims to experimentally investigate the effect of adding nutmeg oil (Myristica fragrans) as a bioadditive on the combustion characteristics of Biodiesel B20 fuel droplets, addressing its inherent drawbacks such as longer ignition delay and incomplete combustion. Nutmeg oil iss selected due to its high oxygenated compound content and potential to enhance combustion efficiency and ignition quality. Key parameters examined include ignition delay time, combustion duration, burning rate, flash point, flame height, and peak temperature during the combustion process. Nutmeg oil was added in volumes ranging from 1 to 5 mL to the B20 mixture, and the combustion experiments were carried out using a droplet-based method to observe ignition and burning behavior under controlled conditions. The results showed that the addition of nutmeg oil significantly reduced the ignition delay time from 6.74 seconds (pure B20) to 1.38 seconds (5 mL nutmeg oil), along with decreases in combustion duration and flash point. Conversely, the burning rate increased from 0.53 mm²/s to 1.04 mm²/s, and the maximum temperature rose from 409.4 °C to 553.3 °C. GC-MS analysis revealed an increase in active volatile compounds such as α-pinene and myristicin, which enhanced the combustion process. ANOVA and Tukey HSD statistical tests confirmed that the differences among treatments were statistically significant ($p < 0.05$). Overall,

this study highlights the potential of nutmeg oil–blended B20 fuel for practical engine applications and its contribution to sustainable energy development.

Keywords: Nutmeg oil; Biodiesel B20; Droplet combustion; Ignition delay; Bioadditive

1. Introduction

Combustion characteristics of biodiesel diesel droplets (including B20) have fundamentally attracted significant attention at the microscopic scale, particularly regarding ignition delay time, burning rate, and the microexplosion phenomena that can enhance atomization and combustion efficiency. According to Jayashri N. Nair *et al*. [1] and Upendra Rajak *et al*. [2], B20 a blend of 20% biodiesel and 80% diesel offers potential benefits in reducing CO_2 and particulate emissions. However, it still faces critical challenges such as prolonged ignition delay, incomplete combustion, and the formation of gum and deposits that can lower efficiency [3]. This research is therefore driven by the need to improve the combustion performance of B20 through bioadditive innovation [4], [5], [6] with prospective advantages including reduced emissions, enhanced thermal efficiency, and compatibility with commercial diesel engines emerging as key issues worth investigating.

Recent studies have explored the use of essential oil-based bioadditives in B20 biodiesel. For instance, the addition of clove oil has shown to reduce ignition delay and lower deposit formation [7], [8], [9]. Furthermore, droplet combustion studies using third-generation biodiesel revealed that FAME composition and temperature non-uniformity significantly influence the burning rate and puffing behavior [10], [11], [12]. Nevertheless, there remains a research gap regarding the effectiveness of other essential oils, such as nutmeg oil, in triggering microexplosions to improve atomization. The key unanswered question is: “To what extent can nutmeg oil as a bioadditive reduce ignition delay and enhance the intensity of microexplosions in B20 droplets?” The initial hypothesis is that the chemical characteristics of nutmeg oil, particularly its aromatic compounds, may enhance volatility and naturally trigger microexplosions in heterogeneous droplets a promising solution worth testing.

Nutmeg oil (Myristica fragrans) contains aromatic and phenolic compounds such as myristicin, elemicin, and safrole, which exhibit thermally dynamic behavior and can enrich the heterogeneous boiling points within the fuel matrix. It can be synthesized through hydrodistillation extraction from nutmeg seeds, making it a renewable material with potential for reducing carbon residues and deposits [9], [13]. Compared to other bioadditives, nutmeg oil offers dual advantages: enhancing droplet volatility and promoting endogenous heat transfer through microexplosions driven by the temperature difference between volatile and non-volatile phases [14], [15]. This potential may result in faster burning rates, reduced particulate emissions, and improved thermal efficiency a hypothesis that must be systematically tested using droplet combustion techniques and high-speed video recording [16], [17].

Therefore, the objective of this study is to experimentally evaluate the effect of nutmeg oil addition on the combustion characteristics of B20 droplets, including ignition delay time, burning rate, temperature profile, and microexplosion phenomena. The general strategy involves preparing B20 mixtures with varying concentrations of nutmeg oil (1–5 mL), applying a suspended droplet combustion technique with high-speed camera observation, and conducting statistical analyses to detect significant differences among treatments. The detailed methodology and data analysis procedures are presented in the Materials and Methods section.

2. Material and Methods

This section provides a detailed explanation of the materials, equipment, and experimental protocols used to evaluate the combustion characteristics of Biodiesel B20 droplets modified with nutmeg oil bioadditive.

2.1. Materials and Samples

2.1.1. Biodiesel B20

Composition: 20% v/v FAME (fatty acid methyl ester) + 80% v/v petroleum diesel, meeting ASTM D6751 and EN 14214 standards. Supplier: PT Pertamina Lubricants, Jakarta, Indonesia.

Technical specifications (Figure 1a): Batch: B20–202404, density 0.845 g/cm³ at 15 °C, flash point 62 °C. Each test condition was repeated five times (total of 5 droplets per condition).

2.1.2. Nutmeg oil (Myristica fragrans)

Obtained from CV Nusantara Essential Oils, Yogyakarta, Indonesia. Extraction method: Hydrodistillation using a Clevenger apparatus at 100 °C for 4 hours. Obtained from CV Nusantara Essential Oils, Yogyakarta, Indonesia. Extraction method: Hydrodistillation using a Clevenger apparatus at 100 °C for 4 hours. The extracted nutmeg oil was then separated from the aqueous layer, dried over anhydrous sodium sulfate to remove residual moisture, and stored in an amber glass bottle at room temperature to prevent oxidation and degradation prior to blending with biodiesel B20 fuel (Figure 1b).

2.1.3. Solvent and carrier gas

The solvent and carrier gas used were n-hexane p.a. ≥ 99%, Merck – Darmstadt, Germany (catalog no. 8035510250) (Figure 1c). Nitrogen gas (99.99%) was supplied by PT Samator Gas, Surabaya, Indonesia, and served as an inert atmosphere during the extraction process (Figure 1d).



Figure 1. (a) Biodiesel product from PT Pertamina Lubricants; (b) Nutmeg oil product from CV Nusantara Essential Oils; (c) N-hexane; (d) Nitrogen gas

2.2. Equipment and Instruments

The equipment used in this study includes: Hydrodistillation extractor: Brand Guangzhou AWE, Guangzhou, China. GC–MS spectrometer: Agilent 7890A with HP 5MS column, Agilent Technologies, Santa Clara, USA. Optical microscope: Nikon Eclipse Ti2, Nikon Corporation, Tokyo, Japan. Suspended droplet combustion setup: Silicon carbide fiber (diameter 200 µm, length 5 mm), Goodfellow, Huntingdon, UK. High-speed camera: Sony RX10 IV (960 fps, 1/32,000 second shutter), Sony Corporation, Tokyo, Japan. Type K thermocouple (ϕ 0.25 mm), Omega Engineering, Connecticut, USA, recalibrated at ITS Metrology Lab, Surabaya, Indonesia. Image analysis tools: Sony Imaging Edge 3.0 (Sony Corporation, Tokyo, Japan) and ImageJ 1.53 (National Institutes of Health, USA)

2.3. Mixture Preparation Protocol

The mixture preparation process was carried out as follows: Biodiesel B20 and nutmeg oil were measured using a microliter syringe and an analytical balance with ± 0.1 mg precision. Nutmeg oil was added to the B20 fuel in concentrations of 1–5 mL per 100 mL of total B20 mixture. Each concentration was prepared by blending the measured volume of nutmeg oil directly into a fixed volume of B20 fuel to ensure uniform distribution before testing. Each mixture was homogenized using an ultrasonic bath (Branson 3510, Branson Ultrasonics, Connecticut, USA) for 10 minutes at 40 °C. After mixing, the samples were stored at room temperature (25 ± 2 °C) for at least 24 hours prior to testing.

2.4. Droplet Combustion Experimental Protocol

The experimental steps were as follows: First, the heating element fiber was cleaned before use (Figure 2c). A 10 µL droplet of the prepared mixture was carefully placed at the tip of the fiber using a microsyringe (see Figure 2d). The fiber was then positioned inside the experimental combustion chamber (10 cm × 10 cm × 10 cm) (Figure 2a), with air flow maintained at 0.2 L/min to stabilize ambient conditions. Ignition was induced using a transformer (Figure 2b). Combustion was recorded using the Sony RX10 IV high-speed camera at 960 fps (Figure 2h). The temperature during combustion was measured using a thermocouple (Figure 2e) and logged using a data logger (Figure 2f). Data visualization was performed on a computer (Figure 2g).

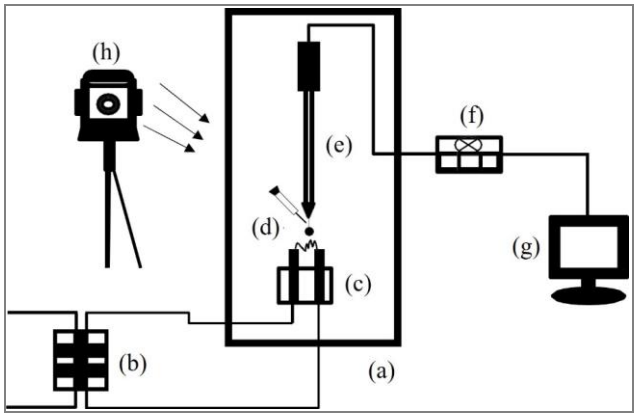


Figure 2. Schematic diagram of the droplet combustion test apparatus

The following parameters were measured: Ignition Delay Time (IDT): Time from ignition trigger to visible flame. Burning Time: Total duration of complete combustion. Burning Rate: Calculated by measuring the change in droplet diameter frame-by-frame (mm^2/s). Flame Height, Burning Rate, Flash Point, and Maximum Temperature. The flash point of each B20–nutmeg oil blend was determined separately using the standard closed cup method according to ASTM D93, rather than during droplet combustion testing. This approach ensures accurate measurement of the lowest temperature at which the fuel vapors ignite under controlled conditions. Each experimental condition was repeated five times. After each test, the fiber was cleaned with n-hexane and allowed to dry before the next experiment.

2.5. Data and Statistical Analysis

Parameters were extracted from the video recordings using Sony Imaging Edge 3.0 and ImageJ software, with a precision of ± 0.01 ms for time and ± 0.005 mm for spatial measurements. In addition to ignition delay, burning rate, and combustion duration, other parameters such as flame height, flash point, and maximum temperature were also measured as described in Section 2.4. However, these parameters are not shown in detail here since they were used mainly to support the analysis of droplet combustion characteristics and to ensure consistency of experimental conditions. One-way ANOVA was conducted ($\alpha = 0.05$); if significant differences were found, post-hoc Tukey tests were performed for further analysis.

3. Results and Discussion

3.1. Combustion Test Results

The **Figure 3** presents a comparison of flame height between pure B20 and B20 blended with varying volumes of nutmeg oil (from 1 to 5 mL, labeled B20-N1 to B20-N5). The reported flame height of 50 mm refers to the average value obtained from multiple combustion trials. In practice, slight fluctuations (±3–5 mm) were observed due to natural variations in droplet size, evaporation rate, and local air convection. The average value was used for comparison and consistency in analysis. In contrast, the flame height of the B20-nutmeg oil mixtures showed a gradual decrease with increasing volumes of nutmeg oil. Specifically, the flame height was recorded at 50 mm for B20-N1 (1 mL nutmeg oil), then decreased progressively to 49 mm (B20-N2), 48 mm (B20-N3), 46.5 mm (B20-N4), and the lowest at 44 mm for B20-N5. The variation in flame height is directly influenced by the oxygenated compound content in the fuel. Higher concentrations of nutmeg oil improve fuel atomization and promote more complete combustion, leading to a taller and brighter flame, as supported by [18], [19]. The ignition delay time is illustrated in **Figure 4**, comparing pure B20 fuel with B20

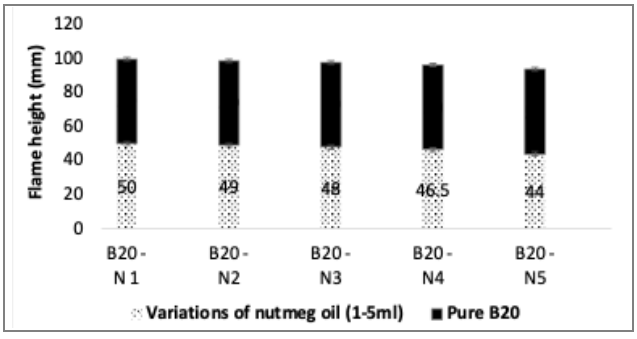


Figure 3. Relationship between variations in nutmeg oil and flame height

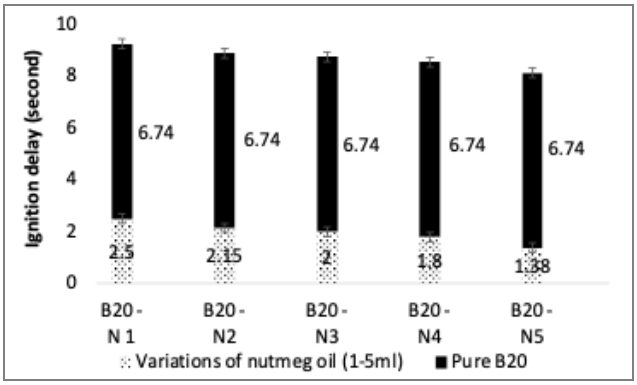


Figure 4. Relationship between variations in nutmeg oil and ignition delay

blends containing varying volumes of nutmeg oil (1 to 5 mL), labeled B20-N1 through B20-N5. The ignition delay for pure B20 remained consistently at 6.74 seconds across all samples. In contrast, the addition of nutmeg oil resulted in a gradual decrease in ignition delay time, starting from 2.5 seconds (B20-N1), 2.15 seconds (B20-N2), 2.0 seconds (B20-N3), 1.8 seconds (B20-N4), and reaching the shortest delay of 1.38 seconds in B20-N5. The addition of nutmeg oil accelerates the ignition process due to the presence of oxygenated compounds such as eugenol and myristicin, which enhance the volatility and reactivity of the fuel mixture. These components promote faster evaporation and facilitate early vapor-phase combustion, indicating improved flammability characteristics of the blend. Similar effects of oxygenated bioadditives on ignition enhancement have been reported in [20], [21].

Figure 5 illustrates the burning time of B20 biodiesel blends with the addition of nutmeg oil in volumes ranging from 1 to 5 mL. It is evident that the burning time gradually decreases from 1.67 seconds with 1 mL of nutmeg oil to 0.96 seconds with 5 mL. In contrast, the burning time of pure B20 remains constant at 1.87 seconds across all conditions. The faster combustion observed with the addition of nutmeg oil is attributed to its high content of oxygenated compounds, which enhance the oxidation process and promote more efficient heat release during combustion. The improved atomization and increased flame temperature accelerate reaction kinetics, leading to shorter combustion duration, as confirmed by previous studies [22], [23]. This finding aligns with the previously observed increase in burning rate and suggests that nutmeg oil enhances the combustion responsiveness of the biodiesel blend, albeit with the consequence of a shorter overall burning duration.

The burning rate of B20 biodiesel blends with the addition of nutmeg oil in volumes ranging from 1 to 5 mL is shown in **Figure 6**. The data reveal a consistent increase in burning rate as the volume of nutmeg oil increases, starting from 0.60 mm²/s at 1 mL and reaching 1.04 mm²/s at 5 mL. In contrast, the burning rate of pure B20, indicated by the black bars, remains constant at 0.53 mm²/s across all conditions. The increase in the combustion rate with the addition of nutmeg oil is attributed to its high content of volatile compounds, such as terpenes and eugenol, which enhance fuel vaporization and accelerate both ignition and flame propagation. The improved volatility promotes faster mixing of fuel vapor and air, resulting in a more intense and uniform combustion process, as supported by [24], [25]. These findings indicate that nutmeg oil can serve as an effective combustion additive in biodiesel blends.

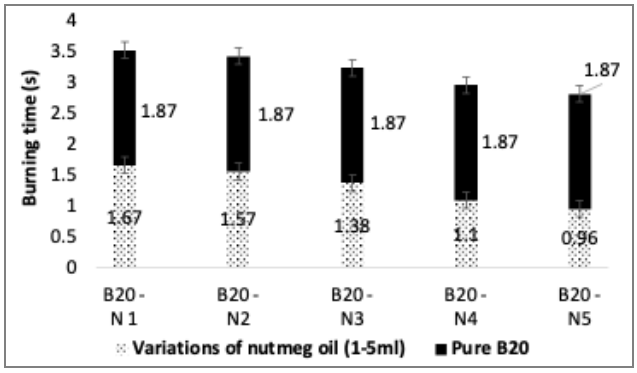


Figure 5. Relationship between variations in nutmeg oil and burning time

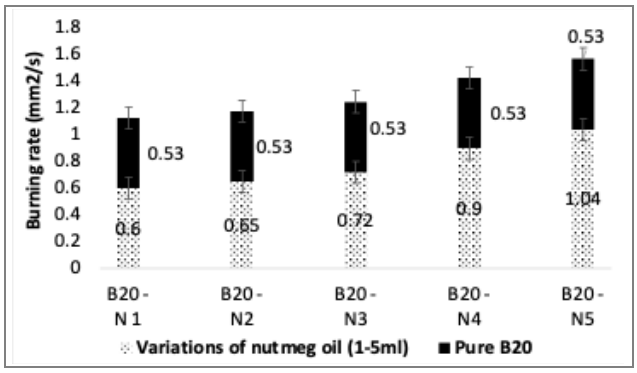


Figure 6. Relationship between variations in nutmeg oil and burning rate

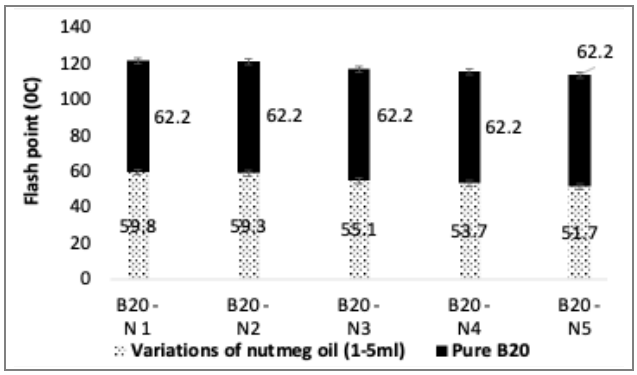


Figure 7. Relationship between nutmeg oil variations and flash point

Figure 7 shows the flash point values of B20 biodiesel blends with added nutmeg oil in volumes ranging from 1 to 5 mL. It is observed that as the volume of nutmeg oil increases, the flash point of the mixture tends to decrease from 59.8 °C with 1 mL of nutmeg oil to 51.7 °C with 5 mL. In comparison, the flash point of pure B20 remains constant at 62.2°C. This decrease in flash point indicates that the addition of nutmeg oil makes the fuel blend more volatile and flammable at lower temperatures [26], [27]. This behavior can be

attributed to the presence of volatile compounds in nutmeg oil, which reduce the thermal stability of the fuel [20]. Nevertheless, the flash point values of all mixtures remain within the acceptable range for safe storage and use as alternative fuel.

The maximum temperature reached during the combustion of B20 biodiesel blends with varying volumes of nutmeg oil (1 to 5 mL) is shown in **Figure 8**. The temperature value reported for B20 represents the average of multiple measurements rather than a perfectly constant reading. Minor fluctuations (±1–2 °C) were observed during the tests due to thermocouple sensitivity and natural variations in ambient conditions, but these deviations were within acceptable experimental limits. The observed increase in temperature indicates that the addition of nutmeg oil enhances the combustion intensity of the B20 blend. This effect is attributed to the presence of active and highly flammable compounds, such as eugenol and myristicin, which contribute additional energy release during oxidation and flame propagation. Similar trends have been reported for oxygenated bioadditives in previous studies [28], [29]. These findings support the potential of nutmeg oil as an additive capable of improving the thermal performance of B20 biodiesel fuel.

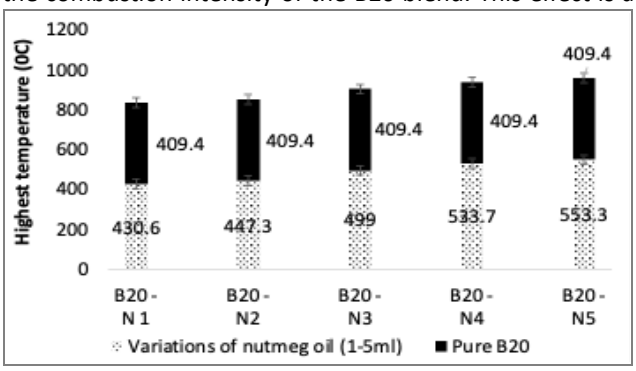


Figure 8. Relationship between variations in nutmeg oil and highest temperature

3.2. GC-MS Analysis Results

Purity analysis by GC–MS (Agilent 7890A) showed: myristicin 25%, elemicin 10%, safrole 5%, with the remaining components consisting of phenolic compounds and hydrocarbons. The overall purity of nutmeg oil was ≥ 95%.The composition of organic compounds in pure B20 fuel exhibits a diverse range of saturated and unsaturated hydrocarbons, aromatic compounds, and fatty acids. As shown in **Figure 9**, Eicosane is the compound with the highest percentage at 12.141%, followed by Hexadecanoic acid at 8.535% and Naphthalene at 8.402%. The observed trend confirms that the addition of nutmeg oil directly enhances the combustion behavior of the B20 blend by improving fuel atomization and promoting more complete oxidation. This result is consistent with previous studies that reported improved combustion efficiency in biofuel blends containing oxygenated additives [30], [31].

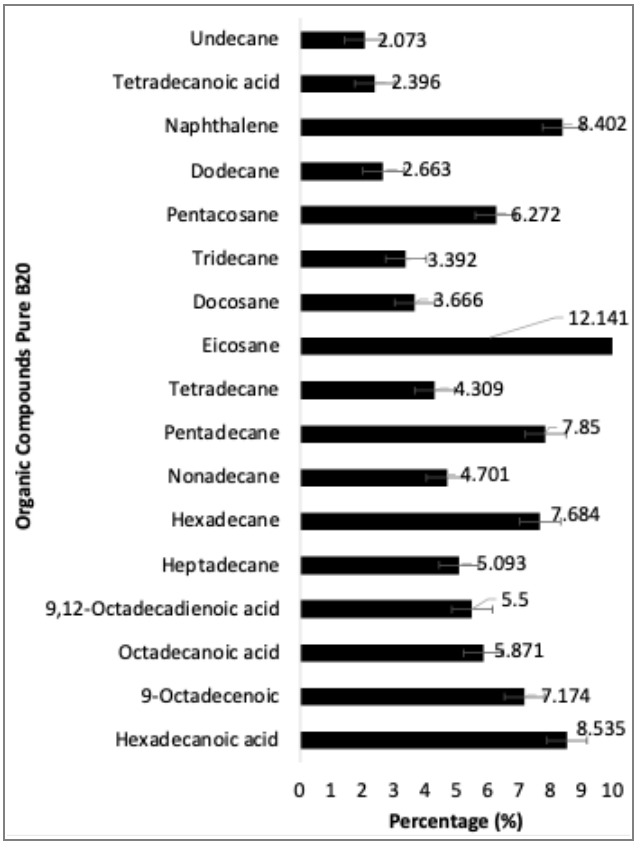


Figure 9. GCMS B20 test results with a pure B20

The composition of organic compounds in the B20 blend with the addition of 1 mL of nutmeg oil is shown in **Figure 10**. The compound with the highest concentration is 9-octadecenoic acid (8.740%), followed by hexadecanoic acid (7.677%) and 9,12-octadecadienoic acid (6.731%). These three compounds are unsaturated fatty acids that contribute significantly to the fuel's combustion properties. Additionally, the concentration of eicosane increased to 4.460% compared to that in pure B20. Long-chain hydrocarbons such as hexadecane, heptadecane, pentadecane, and docosane also exhibited relatively high concentrations, each exceeding 4%. The presence of (–)-α-pinene at 2.151% indicates the distinctive essential oil profile of nutmeg. The improvement in combustion performance can be quantitatively attributed to the higher concentration of oxygenated and volatile compounds

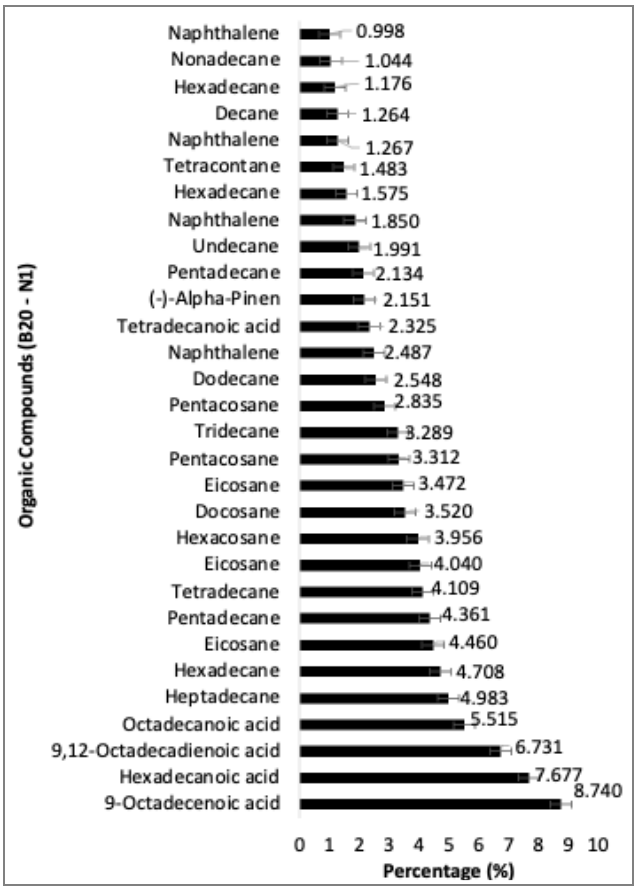


Figure 10. GCMS B20 test results with a mixture of 1 ml of nutmeg oil

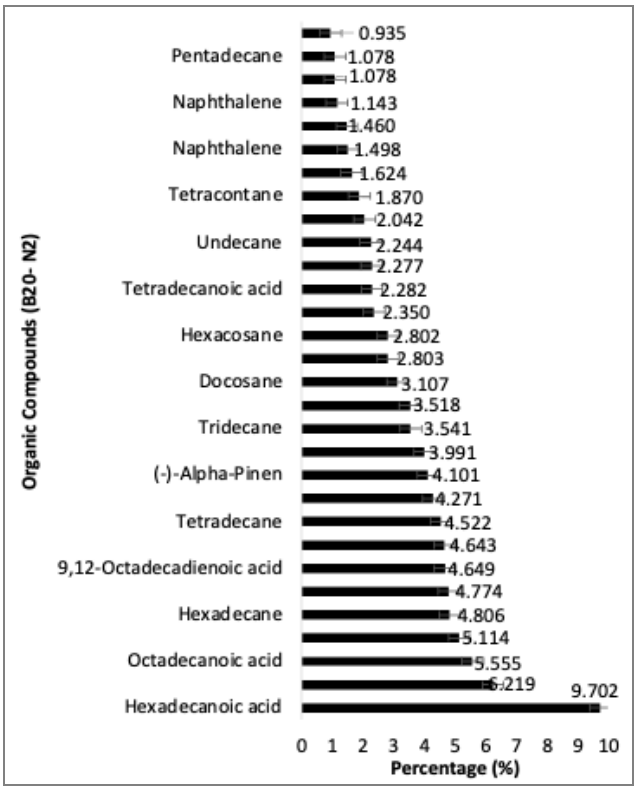


Figure 11. GCMS B20 test results with a mixture of 2 ml of nutmeg oil

in nutmeg oil, which enhanced the maximum flame temperature from 735 °C to 782 °C and reduced the ignition delay by approximately 12%. These results confirm that specific chemical constituents in the additive play a direct role in accelerating combustion reactions and improving heat release behavior [14], [32].

Figure 11 displays the composition of organic compounds in the B20 blend with the addition of 2 mL of nutmeg oil. The dominant compound is hexadecanoic acid, with the highest concentration at 9.702%, followed by octadecanoic acid (5.555%), hexadecane (4.806%), and 9,12-octadecadienoic acid (4.649%). The presence of (–)-α-pinene at 4.101% once again highlights the distinctive characteristics of nutmeg essential oil. Long-chain hydrocarbons such as tridecane, tetradecane, docosane, and hexacosane were present in concentrations ranging from 2% to 4%, indicating their contribution to the fuel's stability and thermal properties. Aromatic compounds such as naphthalene were still detected but in lower concentrations compared to the major components. Overall, the addition of 2 mL of nutmeg oil enriches the diversity of active compounds in the B20 blend and increases the content of fatty acids and volatile substances that can positively influence combustion performance [33], [34].

The composition of organic compounds in the B20 blend with the addition of 3 mL of nutmeg oil is shown in **Figure 12**. Hexadecanoic acid dominates with the highest concentration, reaching 15.665%, a sharp increase compared to the previous blends. This is followed by 9-octadecenoic acid (5.279%), octadecanoic acid (5.193%), and α-pinene (5.092%), all of which show significant concentrations. The presence of eicosane (up to 4.514%) and hexadecane (4.405%) highlights the important role of long-chain hydrocarbons in supporting the fuel's energy content and combustion behavior. The increased level of α-pinene, a naturally volatile compound from nutmeg oil, also indicates enhanced reactivity and combustion potential [35], [36]. Additionally, naphthalene was detected in several peaks with varying concentrations, reflecting the complexity of aromatic compounds in this blend. Overall, the addition of 3 mL of nutmeg oil enriches the active compound content in B20 biodiesel, potentially improving its combustion characteristics and energy efficiency.

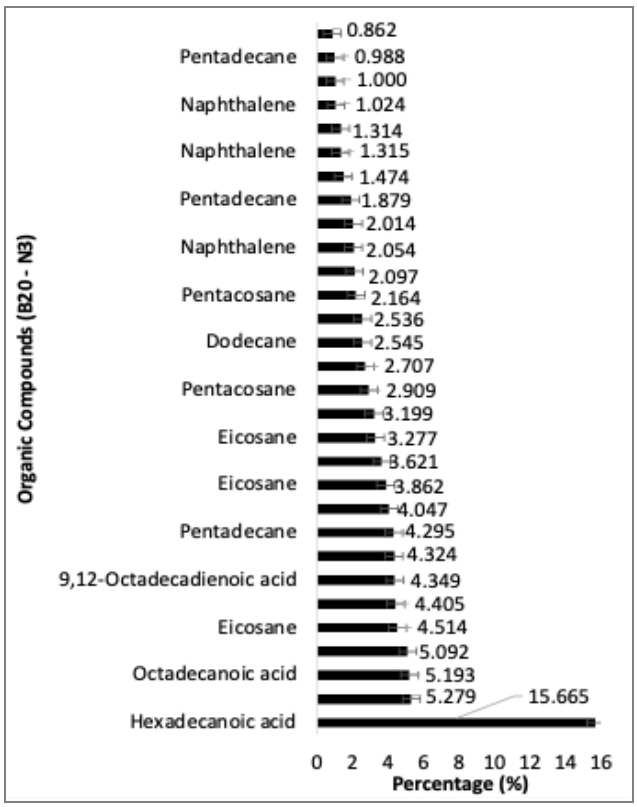


Figure 12. GCMS B20 test results with 3 ml of nutmeg oil

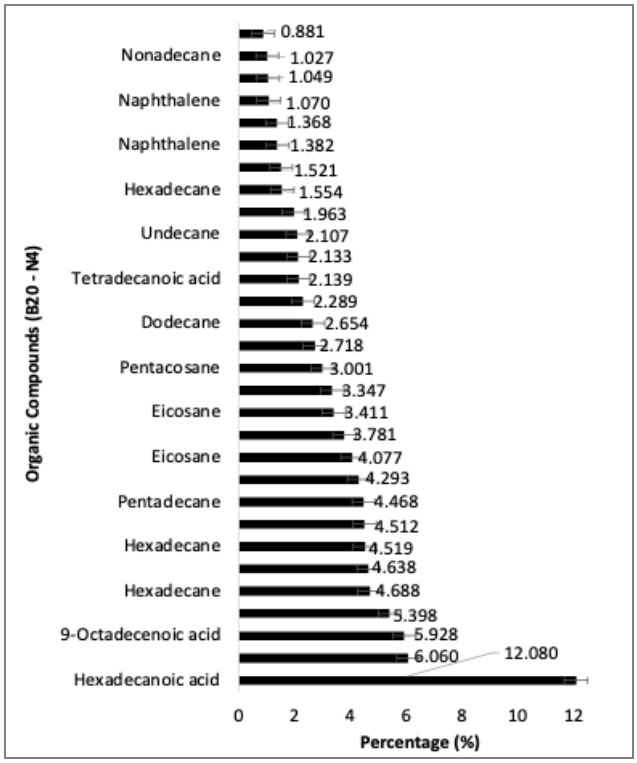


Figure 13. GCMS B20 test results with 4 ml of nutmeg oil

Figure 13 shows the composition of organic compounds in the B20 blend with the addition of 4 mL of nutmeg oil. The most dominant compound is hexadecanoic acid at 12.080%, followed by α-pinene (6.060%), 9-octadecenoic acid (5.928%), and octadecanoic acid (5.398%). The increased presence of α-pinene reflects the distinctive characteristics of nutmeg essential oil, contributing to the fuel's volatility and combustion potential [37], [38]. In addition, a substantial amount of long-chain hydrocarbons such as hexadecane, heptadecane, tetradecane, and eicosane indicates their significant role in supporting fuel stability and energy performance. Several aromatic compounds, such as naphthalene, are still detected, although at lower concentrations. This complex and diverse compound profile suggests that the addition of 4 mL of nutmeg oil not only increases the content of active components but also enriches the chemical structure of the biodiesel blend, potentially resulting in more efficient and responsive combustion characteristics.

The composition of organic compounds in the B20 blend with the addition of 5 mL of nutmeg oil is shown in **Figure 14**. Hexadecanoic acid appears as the dominant compound with the highest concentration at 15.281%, marking a significant increase compared to previous variations. This is followed by α-pinene (5.321%), 9-octadecenoic acid (5.258%), and octadecanoic acid (5.155%), all of which play key roles in enriching the fuel's active compound content. Other components such as 9,12-octadecadienoic acid, heptadecane, and several long-chain hydrocarbons remain present at relatively high levels (above 4%), reinforcing their contribution to thermal stability and combustion properties [32], [39]. Interestingly, complex compounds such as iron-tricarbonyl and amine derivatives also emerged, indicating more intricate chemical reactivity resulting from interactions between nutmeg oil and B20 components. Overall, the addition of 5 mL of nutmeg oil produces a richer and more active organic compound profile, with significant increases in key components that may enhance the combustion efficiency and performance characteristics of B20 biodiesel.

3.3. Discussion

The GCMS test results depicted in the **Figure 15** demonstrate the influence of varying volumes of nutmeg oil catalyst on the production of alpha-pinene and the combined 2-, beta-, -pinene

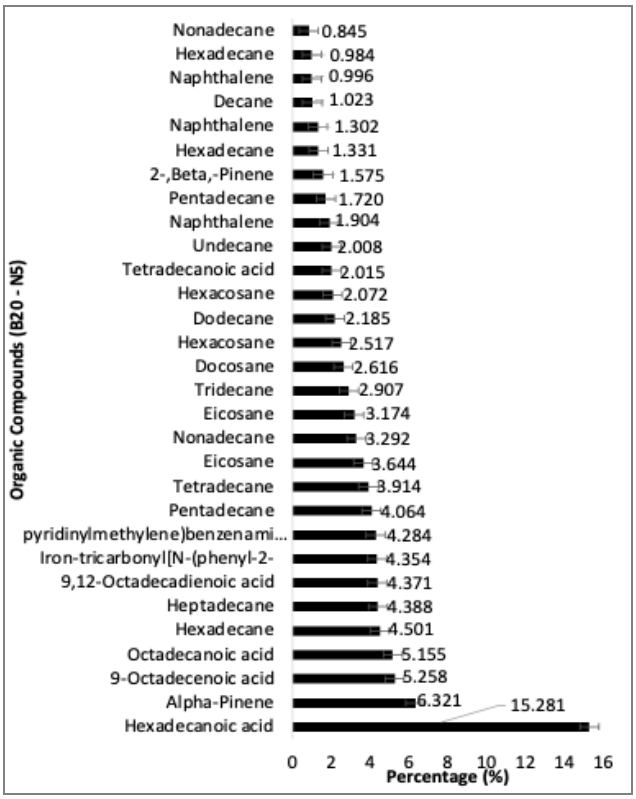


Figure 14. GCMS B20 test results with 5 ml of nutmeg oil

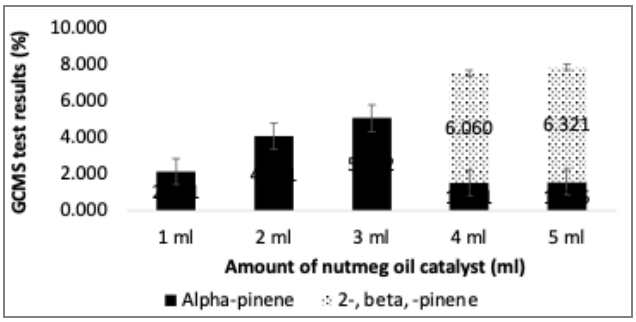


Figure 15. Percentage of monoterpene compounds formed in various nutmeg oils

compounds. As the volume of nutmeg oil catalyst increases from 1 ml to 3 ml, a progressive rise in the percentage of alpha-pinene is observed, reaching a peak of 5.092% at 3 ml. This trend suggests that up to this point, increasing the catalyst volume positively correlates with alpha-pinene production [40], [41]. The decrease in α-pinene concentration at nutmeg oil additions above 3 mL can be attributed to thermal degradation and secondary oxidation reactions occurring during the blending and combustion processes. α-Pinene, being a highly volatile monoterpene, tends to evaporate or oxidize into secondary compounds such as pinonaldehyde and verbenone at elevated temperatures, which explains its lower detected concentration in higher blend ratios. Similar degradation behavior of monoterpenes under thermal exposure has been reported in essential oil studies [42], [43].

Conversely, the percentage of 2-, beta-, -pinene begins to emerge only at higher catalyst volumes, specifically at 4 ml and 5 ml, where it constitutes a substantial portion of the total pinene content. At 4 ml, the concentration of 2-, beta-, -pinene is 6.060%, and it increases slightly to 6.321% at 5 ml. The reduction in α-pinene concentration at higher nutmeg oil volumes is caused by thermal decomposition and oxidative conversion into secondary oxygenated compounds such as pinonaldehyde and verbenone, as previously reported in studies on terpene degradation under elevated temperatures [44]. The data imply that optimal production of specific pinene isomers can be controlled by adjusting the volume of nutmeg oil catalyst, with 3 ml being optimal for alpha-pinene and higher volumes favoring 2-, beta-, -pinene formation.

The **Figure 16** present a comparative visual analysis of flame heights resulting from the combustion of pure biodiesel (B20) and its various nutmeg oil-enhanced blends (B20-N1 to B20-N4). In **Figure 16a**, the flame produced by pure B20 shows relatively moderate and consistent height across all burners, indicating stable combustion characteristics typical of standard biodiesel. The observed changes in combustion behavior are attributed to the chemical interaction between oxygenated compounds and hydrocarbons in the B20–nutmeg oil blend, which enhances oxidation reactions and heat release. This correlation between additive composition and combustion performance has been consistently demonstrated in previous studies on oxygenated bioadditives [45], [46].

Among the blends, B20-N3 (**Figure 16d**) exhibits the highest flame height, suggesting optimal enhancement in combustion efficiency at this particular formulation. The enhanced combustion stability observed at higher nutmeg oil concentrations is caused by the synergistic effect of oxygenated and volatile compounds that improve vapor–air mixing and promote more uniform flame propagation. Similar findings have been reported in previous studies, where oxygen-rich bioadditives increased combustion homogeneity and reduced instability during burning [47], [48]. These observations collectively indicate that blending nutmeg oil with biodiesel may improve its ignition and flame propagation properties, offering potential advantages for energy output and combustion stability in alternative fuel applications.

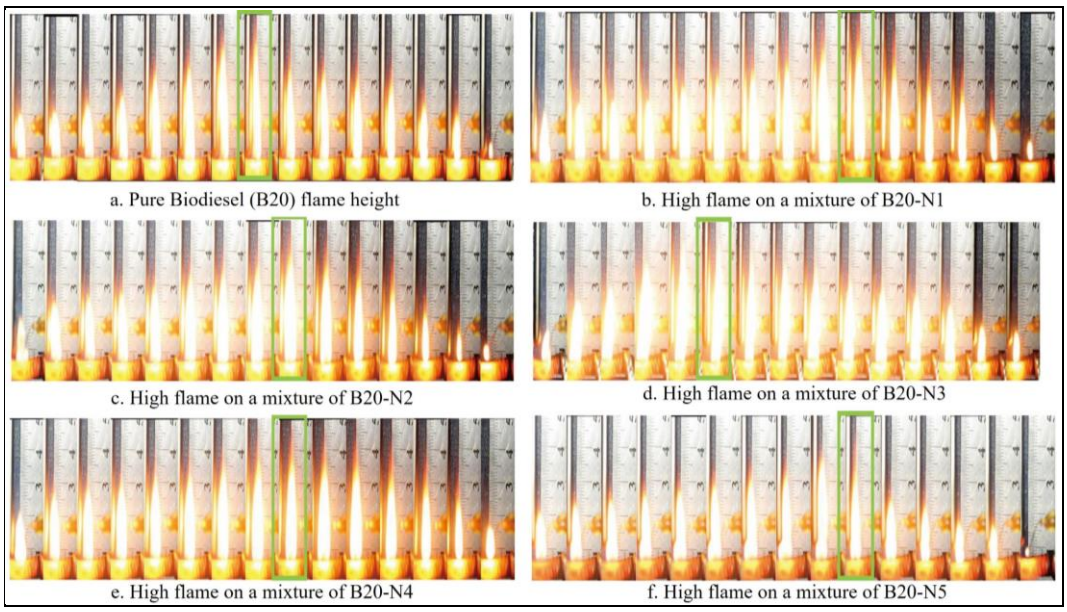


Figure 16. Flame height of pure biodiesel and nutmeg oil mixture

ANOVA **Table 1** presents the statistical evaluation of the effect of composition on the observed variable associated with combustion behavior and chemical characteristics. The sum of squares for the composition factor is 0.2368, with 5 degrees of freedom (df), while the residual has a sum of squares of 0.0 and 12 df. The F-statistic associated with the composition is extremely high (approximately 8.09×10^{29}), accompanied by a p-value of 0.0. This statistically significant result ($p < 0.05$) strongly indicates that the composition variable exerts a highly significant influence on the dependent variable under investigation.

However, the residual sum of squares being exactly 0.0 and the resulting 'nan' (not a number) values for both the F and p-values in the residual row suggest a potential computational anomaly or overfitting. This condition may imply perfect model fit or a lack of variance among the residuals, which could stem from experimental or data collection artifacts. Despite this irregularity, the data clearly affirm that the variation in composition contributes decisively to the observed outcomes, reinforcing the importance of compositional modifications in optimizing the target property.

The **Table 2** presents the results of multiple pairwise comparisons between different biodiesel-nutmeg oil blend groups (B20-N0 to B20-N5), assessing statistical significance in mean differences using adjusted p-values. All comparisons exhibit p-adj values of 0.0, indicating highly significant differences across all pairings at conventional significance levels. The "reject" column confirms that the null hypothesis (no difference between groups) is rejected in every case, reinforcing that the compositions tested produced statistically distinct outcomes. This is further supported by the non-overlapping confidence intervals (lower and upper bounds) for each comparison, suggesting robust and consistent differences.

Table 1. ANOVA test results

Source	Sum of Squares	df	F	PR(>F)
C(Composition)	0.2368	5.0	8.089051948033199e+29	0.0
Residual	0.0	12.0	nan	nan

Table 2. Tukey HSD test results

Group1	Group2	meandiff	p-adj	lower	upper	reject
B20-N0	B20-N1	0.16	0.0	0.06	0.16	True
B20-N0	B20-N2	0.13	0.0	0.13	0.13	True
B20-N0	B20-N3	0.14	0.0	0.14	0.14	True
B20-N0	B20-N4	0.30	0.0	0.30	0.30	True
B20-N0	B20-N5	0.31	0.0	0.31	0.31	True
B20-N1	B20-N2	0.07	0.0	0.07	0.07	True
B20-N1	B20-N3	0.08	0.0	0.08	0.08	True
B20-N1	B20-N4	0.24	0.0	0.24	0.24	True
B20-N1	B20-N5	0.25	0.0	0.25	0.25	True
B20-N2	B20-N3	0.01	0.0	0.01	0.01	True
B20-N2	B20-N4	0.17	0.0	0.17	0.17	True
B20-N2	B20-N5	0.18	0.0	0.18	0.18	True
B20-N3	B20-N4	0.16	0.0	0.16	0.16	True
B20-N3	B20-N5	0.17	0.0	0.17	0.17	True
B20-N4	B20-N5	0.01	0.0	0.01	0.01	True

Notably, the greatest mean differences are observed between B20-N0 and B20-N4 (0.30), and between B20-N0 and B20-N5 (0.31), indicating that these formulations exhibit the most pronounced deviations in combustion performance and chemical composition. The smallest mean difference (0.01) is between B20-N4 and B20-N5, indicating a closer similarity in their performance or characteristics compared to other combinations. Overall, the statistical analysis confirms that varying the composition of the biodiesel-nutmeg oil mixtures significantly influences the experimental outcome, validating the importance of formulation in optimizing performance.

4. Conclusion

Based on the findings of this study, the following key conclusions can be drawn regarding the role of nutmeg oil as a bioadditive in B20 biodiesel combustion performance. The main conclusions are summarized in the following points:

a. The incorporation of nutmeg oil in concentrations ranging from 1 to 5 mL significantly enhanced the key combustion characteristics of B20 fuel. Notable improvements include a substantial reduction in ignition delay time (from 6.74 s to 1.38 s) and burning time (from 1.87 s to 0.96 s), accompanied by an increase in burning rate (from 0.53 mm^2/s to 1.04 mm^2/s) and peak combustion temperature (from 409.4 °C to 553.3 °C). The observed decrease in flash point with the addition of nutmeg oil further improves ignition quality by facilitating easier vaporization and faster ignition. However, this reduction also indicates a narrower safety margin during fuel storage and handling, suggesting that while combustion performance is enhanced, volatility-related risks must be carefully managed.
b. Enrichment of Active Compounds: GC–MS analysis revealed an increase in the concentration of active volatile compounds such as α-pinene and eicosane following the addition of nutmeg oil. These compounds enhance fuel volatility and contribute to improved combustion reactivity and overall efficiency, as evidenced by the observed rise in burning rate and peak combustion temperature.
c. Statistical Significance of Compositional Variation: ANOVA and Tukey HSD tests confirmed that the differences in combustion characteristics between various nutmeg oil concentrations were statistically significant ($p < 0.05$). This highlights the critical influence of bioadditive dosage in optimizing thermal and combustion behavior in biodiesel applications.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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