

COMBUSTION CHARACTERISTICS OF BIOSOLAR B20 FUEL ENHANCED WITH CLOVE OIL (SYZYGIUM AROMATICUM) BIOADDITIVES

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Abstract

This study focuses on improving the combustion characteristics of Biodiesel B20 fuel by adding clove oil (*Syzygium aromaticum*) as a bioadditive. The main issues addressed are improving combustion efficiency and reducing emissions, which are crucial for advancing sustainable biodiesel solutions. This study investigated the effects of varying concentrations of clove oil (1–5 ml) on key combustion parameters such as ignition delay, combustion duration, peak temperature, and emissions.

The experimental results showed that adding clove oil to Biodiesel B20 significantly reduced the ignition delay and combustion duration, indicating improved combustion efficiency. In addition, the peak temperature was higher for the fuel blend with clove oil, indicating improved thermal performance. Emission analysis revealed a decrease in harmful emissions, supporting the environmental benefits of clove oil bioadditive.

These findings are explained by the high eugenol content in clove oil, which facilitates better combustion due to its oxygenated compounds. The reduction in ignition delay and combustion duration, along with the increase in peak temperature, indicates more efficient and complete combustion.

The results showed that clove oil bioadditive can improve the performance of Biodiesel B20 by increasing combustion efficiency and reducing emissions. These features make clove oil a viable bioadditive for developing more efficient and environmentally friendly biodiesel blends. The practical use of these findings is relevant for biodiesel producers and environmental policy makers aiming to promote sustainable energy solutions. The results contribute to the optimization of biodiesel formulations, supporting the global transition to renewable energy sources.

Keywords: Biosolar B20, clove oil, bioadditives, combustion efficiency, emissions.

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1. Introduction

The global push towards sustainable energy solutions has prompted significant advancements in the development of biodiesel as an alternative to fossil fuels. Biodiesel, particularly biosolar,

offers a renewable, biodegradable, and environmentally friendly option [1–3]. The utilization of biodiesel can substantially reduce greenhouse gas emissions and reliance on depleting fossil fuel reserves. Biosolar B20, a blend of 20 % biodiesel with 80 % petroleum diesel, has emerged as a popular choice due to its balance between performance and environmental benefits [4–7].

Recent studies have focused on enhancing the properties of biodiesel through various additives. Clove oil (*Syzygium aromaticum*) has gained attention for its potential as a bioadditive due to its oxygenated compounds, which can improve combustion efficiency and reduce emissions [8, 9]. Previous research has demonstrated the efficacy of natural additives in enhancing fuel properties and performance, yet the specific impact of clove oil on Biosolar B20 combustion characteristics remains underexplored.

The primary challenge in biodiesel utilization lies in optimizing its combustion characteristics to achieve maximum efficiency and minimum emissions. This study addresses this issue by investigating the effects of clove oil bioadditives on the combustion behavior of Biosolar B20 fuel [10]. By conducting a detailed analysis of combustion parameters, this research seeks to provide a comprehensive understanding of how clove oil can enhance the performance of biodiesel blends.

A review of existing literature reveals that bioadditives can significantly influence the combustion properties of biodiesel. Clove oil, rich in eugenol, has been identified as a promising candidate due to its high oxygen content, which can facilitate better combustion. For instance, a study by [11] demonstrated that eugenol, a primary component of clove oil, can enhance the oxidative stability and combustion efficiency of biodiesel. Another investigation by [12] showed that bioadditives could reduce the ignition delay and combustion duration, leading to more complete combustion and lower emissions.

Despite these findings, there is a lack of comprehensive studies specifically focusing on the integration of clove oil with Biosolar B20. This research aims to fill this gap by conducting an experimental investigation into the combustion characteristics of Biosolar B20 blended with varying concentrations of clove oil.

The use of bioadditives in biodiesel has been extensively studied, with promising results reported for various natural additives. However, the majority of these studies have focused on additives such as ethanol, methanol, and other plant-derived oils [13]. Clove oil, despite its potential, has not been widely explored in the context of biodiesel combustion. Existing research primarily addresses the physicochemical properties of clove oil but lacks detailed combustion analysis, particularly in combination with biosolar fuels [14].

Furthermore, the impact of clove oil bioadditives on specific combustion parameters such as ignition delay, peak temperature, and emission characteristics remains under-investigated [14]. This research aims to bridge this gap by providing a thorough examination of these parameters, thereby contributing to a deeper understanding of the potential benefits and limitations of using clove oil in biodiesel blends.

The objective of this study is to investigate how the addition of clove oil to Biosolar B20 fuel affects combustion characteristics, including the reduction of ignition delay, combustion duration, and an increase in peak temperature. It aims to determine whether clove oil as a bioadditive can enhance combustion efficiency and reduce harmful gas emissions, with a focus on energy sustainability. An experimental approach and statistical analysis are employed to compare combustion parameters between pure Biosolar B20 and blends with varying concentrations of clove oil (1–5 ml). The findings are expected to provide new insights for the development of more efficient and environmentally friendly biodiesel formulations, leveraging the oxygenation content of clove oil.

2. Materials and Methods

Biosolar B20 fuel was prepared by blending 20 % biodiesel with 80 % petroleum diesel. Clove oil was extracted from *Syzygium aromaticum* and added to the Biosolar B20 in varying concentrations: 1, 2, 3, 4, and 5 ml. The combustion characteristics of the fuel mixtures were analyzed using a droplet combustion setup, which included a high-temperature furnace, a precision syringe for droplet formation, and high-speed cameras for capturing combustion events.

Data collection procedures: install and set up research equipment according to the research scheme has been made in **Fig. 1**.

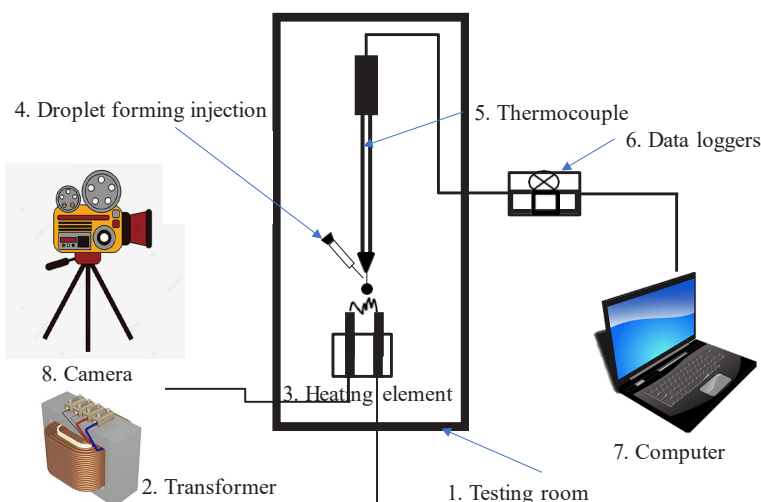


Fig. 1. Experimental setup

Install the camera on the front to see the droplets of the mixture burn. Adjust the distance, position and focus to image the tip of the thermocouple clearly depicted on the camera screen. Connect the thermocouple with the data logger. Connect the data logger to the computer. Connect the transformer with the heating element. Turn on the computer and open the data logger application used this is to see the temperature that will be read later through thermocouple that has been connected.

Take the syringe containing the fuel mixture, and press the head the injection forms droplets at the tip of the injection needle. Place the fuel mixture droplet on top of the thermocouple. Click start on the data logger application program at the same time as Turn on the heating element and press the record button on the camera. The droplet combustion process takes place in the combustion test chamber inside there is a heating element, thermocouple, and droplets from fuel mixture. Record the entire process using the camera and data logger from before a flame appears in the droplet until the flame goes out. Turn off the heating element immediately after the flame goes out. Click stop on the data logger application program and turn off recording on the camera. Save the data that has been taken from the data logger and camera. Return to step 7 to retrieve data for each variant 3 times and do the same steps for the other variations.

Data obtained from the experiments were analyzed using statistical methods to determine the significance of the observed differences between fuel mixtures. The combustion efficiency and emission reduction potential of clove oil bioadditives were evaluated by comparing the results with those of pure Biosolar B20.

3. Result and discussion

The provided **Fig. 2** illustrates a comparison of flame heights between pure B20 and a mixture of B20 with clove oil (ranging from 1 ml to 5 ml). The graph reveals that pure B20 consistently maintains a flame height of 50 mm across all tested volumes. In contrast, the mixture of B20 with clove oil shows a reduction in flame height as the volume of clove oil increases. Specifically, the flame height decreases from 46 mm at 1 ml of clove oil to 33 mm at 5 ml. This trend indicates that adding clove oil to B20 reduces the flame height, suggesting a possible inhibitory effect of clove oil on the combustion characteristics of B20.

The graph presented in **Fig. 3** illustrates the ignition delay times of pure B20 biodiesel and a mixture of B20 with varying volumes (1–5 ml) of clove oil. The results show a consistent ignition delay of 6.74 seconds for pure B20 across all measurements. In contrast, the mixture of B20 with clove oil demonstrates significantly reduced ignition delay times, which decrease progressively as the volume of clove oil increases. For a 1 ml mixture of B20 and clove oil, the ignition delay is observed at 2.5 seconds. As the volume of clove oil is increased to 2 ml, the ignition delay slightly decreases to 2.15 seconds. This trend continues with a further decrease to 2 seconds at 3 ml, 1.8 seconds at 4 ml, and the shortest delay of 1.38 seconds at 5 ml.

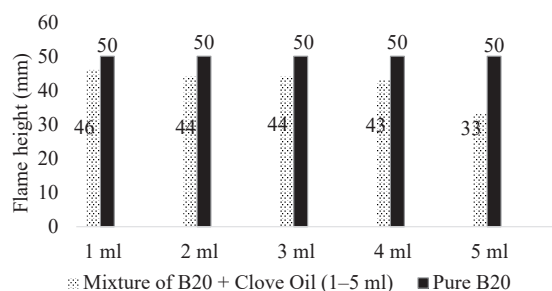


Fig. 2. Flame height comparison graph between pure B20 and a mixture of B20 with clove oil (1–5 ml)

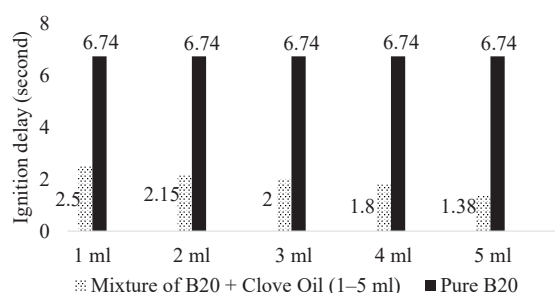


Fig. 3. Ignition delay comparison graph between pure B20 and a mixture of B20 with clove oil (1–5 ml)

These results suggest that the addition of clove oil to B20 biodiesel enhances the fuel's ignition properties, potentially due to the chemical characteristics of clove oil that facilitate quicker combustion initiation [15–19]. The reduction in ignition delay with increasing clove oil volume indicates a potential for optimized fuel formulations that can improve engine performance and efficiency.

The graph in **Fig. 4** illustrates the comparison of burning rates between pure B20 and a mixture of B20 with clove oil (in volumes ranging from 1 to 5 ml). The y-axis represents the burning rate in mm^2/s , while the x-axis shows the different volumes of clove oil added to B20.

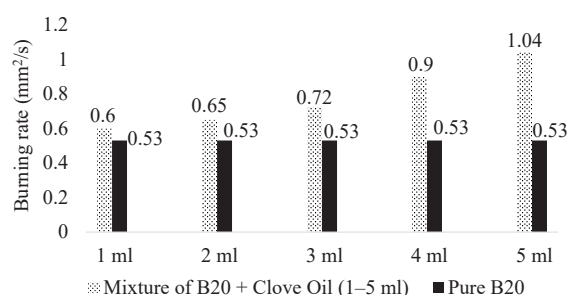


Fig. 4. Burning rate comparison graph between pure B20 and a mixture of B20 with clove oil (1–5 ml)

From the graph, it is evident that the mixture of B20 with clove oil consistently exhibits higher burning rates compared to pure B20 across all tested volumes. Specifically, at 1 ml of clove oil, the burning rate for the mixture is $0.6 \text{ mm}^2/\text{s}$, whereas pure B20 has a burning rate of $0.53 \text{ mm}^2/\text{s}$. This trend continues as the volume of clove oil increases, with the mixture reaching a burning rate of $1.04 \text{ mm}^2/\text{s}$ at 5 ml, while pure B20 maintains a constant burning rate of $0.53 \text{ mm}^2/\text{s}$.

This comparison highlights the impact of clove oil addition on enhancing the burning efficiency of B20, suggesting that the presence of clove oil significantly boosts the burning rate. This could have implications for optimizing fuel performance by incorporating natural additives such as clove oil.

The provided **Fig. 5** illustrates the burning time comparison between pure B20 and a mixture of B20 with clove oil (in volumes ranging from 1 ml to 5 ml). The graph presents the burning time (in seconds) on the y-axis and the volume of the mixture (in ml) on the x-axis. For each volume increment, the burning time for pure B20 and the mixture of B20 with clove oil are compared. The results indicate that pure B20 consistently shows a longer burning time of 1.87 seconds across all measured volumes. In contrast, the burning time for the mixture of B20 with clove oil decreases as the volume of the mixture increases, with burning times of 1.67, 1.57, 1.38, 1.1, and 0.96 seconds for 1 ml, 2 ml, 3 ml, 4 ml, and 5 ml of the mixture, respectively. This comparison highlights the impact of adding clove oil to B20, suggesting that the inclusion of clove oil reduces the burning time of the fuel mixture.

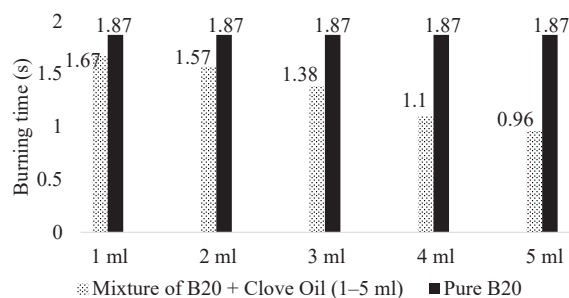


Fig. 5. Burning time comparison graph between pure B20 and a mixture of B20 with clove oil (1–5 ml)

The **Fig. 6** presented illustrates a comparison of flash points between pure B20 biodiesel and a mixture of B20 with varying concentrations of clove oil (ranging from 1 ml to 5 ml). The flash points are measured in degrees Celsius (°C) and are depicted on the y-axis, while the different volumes of clove oil are shown on the x-axis. The data reveals that pure B20 consistently has a flash point of 62.2 °C across all measurements. In contrast, the mixtures of B20 and clove oil exhibit decreasing flash points as the volume of clove oil increases. Specifically, the flash point drops from 59.8 °C at 1 ml of clove oil to 51.7 °C at 5 ml of clove oil. This trend indicates that the addition of clove oil to B20 biodiesel lowers the flash point, which suggests a potential alteration in the fuel's combustion properties [16, 20, 21]. Such changes might affect the safety and performance characteristics of the biodiesel blend, necessitating further investigation to understand the implications fully.

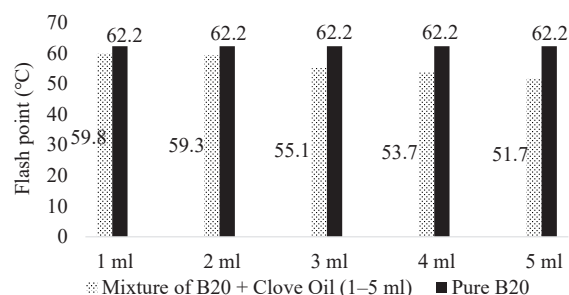


Fig. 6. Flash point comparison graph between pure B20 and a mixture of B20 with clove oil (1–5 ml)

The graph in **Fig. 7** illustrates the highest temperature comparison between pure B20 biodiesel and a mixture of B20 with varying volumes of clove oil (1–5 ml). The y-axis represents the highest temperature in degrees Celsius (°C), while the x-axis denotes the different test samples: pure B20 and B20 mixed with 1 ml, 2 ml, 3 ml, 4 ml, and 5 ml of clove oil.

The results indicate that pure B20 achieves a maximum temperature of approximately 409.4 °C. When clove oil is added to B20, the highest temperatures recorded are 430.6 °C,

447.3 °C, 499 °C, 533.7 °C, and 553.3 °C for 1 ml, 2 ml, 3 ml, 4 ml, and 5 ml of clove oil, respectively. The data suggests a clear trend: as the volume of clove oil increases, the highest temperature reached by the mixture also increases. This implies that the addition of clove oil enhances the thermal performance of B20 biodiesel, potentially leading to improved combustion efficiency [22–25].

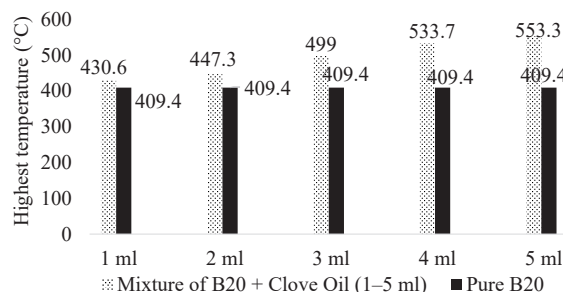


Fig. 7. Highest temperature comparison graph between pure B20 and a mixture of B20 with clove oil (1–5 ml)

Table 1 presents the results of GC-MS analysis on pure B20 and B20 mixed with 3 ml of clove oil. The analysis reveals various organic compounds detected in both samples. For pure B20, prominent compounds include hexadecanoic acid (8.535), 9-octadecenoic acid (7.174), and octadecanoic acid (5.871). Notably, Eicosane exhibits the highest presence among the hydrocarbons with a value of 12.141. Other significant hydrocarbons in pure B20 include heptadecane (5.093), hexadecane (7.684), and pentadecane (7.85).

When B20 is mixed with 3 ml of clove oil, several changes in the organic compounds are observed. The presence of 3-allyl-6-methoxyphenol (6.108) and trans-caryophyllene (0.835) indicates the influence of clove oil. Additionally, some compounds such as hexadecane and heptadecane see notable increases, with values of 12.143 and 4.774, respectively. Eicosane remains a significant component, although its concentration drops to 7.558. The variation in the composition and concentration of these organic compounds highlights the impact of clove oil on the B20 biodiesel blend [15–17, 26, 27].

Table 1

GCMS test results on pure B20 and a mixture of B20 with clove oil (3 ml)

Pure B20	Organic compounds	B20+clove oil 3 ml	Organic compounds
Hexadecanoic acid	8.535	Hexadecanoic acid	8.713
9-Octadecenoic	7.174	3-Allyl-6-methoxyphenol	6.108
Octadecanoic acid	5.871	9-Octadecenoic acid	5.99
9,12-Octadecadienoic acid	5.5	Octadecanoic acid	5.282
Heptadecane	5.093	Hexadecane	12.143
Hexadecane	7.684	Heptadecane	4.774
Nonadecane	4.701	9,12-Octadecadienoic acid	4.725
Pentadecane	7.85	Pentadecane	7.65
Tetradecane	4.309	Tetradecane	4.316
Eicosane	12.141	Eicosane	7.558
Docosane	3.666	Nonadecane	3.912
Tridecane	3.392	Tridecane	3.43
Pentacosane	6.272	Pentacosane	3.115
Dodecane	2.663	Naphthalene	7.875
Naphthalene	8.402	Hexacosane	5.06
Tetradecanoic acid	2.396	Dodecane	2.71
Undecane	2.073	Tetradecanoic acid	2.246

The provided GC-MS analysis **Table 2** showcases the chemical composition of B20 biodiesel blends with clove oil at two different concentrations (4 ml and 5 ml). For the B20 blend with 4 ml of clove oil, significant organic compounds identified include 3-Allyl-6-methoxyphenol (8.657 %), octadecanoic acid (5.884 %), Heptadecane (7.5 %), and 9,12-Octadecadienoic acid (5.192 %). Other notable compounds present are nonadecane (5.064 %), pentadecane (7.301 %), and naphthalene (8.874 %). The varied presence of these compounds suggests that the addition of clove oil introduces a range of organic acids, hydrocarbons, and aromatic compounds, which may influence the fuel properties and combustion characteristics of the biodiesel blend [15, 17, 28].

In comparison, the B20 blend with 5 ml of clove oil displays hexadecanoic acid (14.904 %) and 3-Allyl-6-methoxyphenol (8.228 %) as the dominant compounds. This blend also contains octadecanoic acid (4.902 %), heptadecane (6.257 %), and eicosane (11.488 %). The increase in clove oil concentration alters the chemical profile, with a noticeable increase in the concentration of certain acids and hydrocarbons. Notably, the presence of hexadecanoic acid and eicosane is significantly higher in the 5 ml blend compared to the 4 ml blend. These variations indicate that increasing clove oil concentration in B20 biodiesel blends enhances the presence of specific organic compounds, potentially impacting the overall performance and emission characteristics of the biodiesel [29–32].

Table 2

GCMS test results on a mixture of B20 with clove oil (4 ml) and (5 ml)

B20+clove oil 4 ml	Organic compounds	B20+clove oil 5 ml	Organic compounds
3-Allyl-6-methoxyphenol	8.657	Hexadecanoic acid	14.904
Octadecanoic acid	5.884	3-Allyl-6-methoxyphenol	8.228
Heptadecane	7.5	Octadecanoic acid	4.902
9,12-Octadecadienoic acid	5.192	Heptadecane	6.257
Nonadecane	5.064	9,12-Octadecadienoic acid	4.394
Pentadecane	7.301	Eicosane	11.488
Hexadecane	5.01	Pentadecane	7.163
Tetradecane	4.847	Hexadecane	4.164
Eicosane	8.467	Tetradecane	4.029
Nonadecane	4.322	Nonadecane	3.616
Tridecane	3.84	Tridecane	3.17
Docosane	3.477	Pentacosane	2.938
Naphthalene	8.874	Naphthalene	5.724
Hexacosane	3.056	Hexacosane	4.788
Dodecane	3.029	Dodecane	2.536
9-Octadecenoic acid	2.875	Tetradecanoic acid	2.107
Pentacosane	2.608	1,2-Benzenedicarboxylic acid	2.06
Tetradecanoic acid	2.471	9-Octadecenoic acid	2.029
Undecane	2.385	Undecane	2.004
Decane	1.562	Decane	1.287
Trans-caryophyllene	1.218	Trans-caryophyllene	1.205
Hexadecane	2.362		

The **Fig. 8** illustrates the percentage yields of four chemical compounds-3-allyl-6-methoxyphenol, trans-caryophyllene, and 1,2-benzenedicarboxylic acid-produced using varying amounts of clove oil catalyst. As the amount of clove oil catalyst increases from 1 ml to 5 ml, there is a notable trend in the yield percentages. Specifically, the yield of 3-allyl-6-methoxyphenol shows a gradual increase from 2.631 % at 1 ml to 8.228 % at 5 ml. The yield of trans-caryophyllene is observed starting from 3 ml of catalyst at 0.035 % and increases to 2.060 % at 5 ml. Similarly, 1,2-benzenedicarboxylic acid first appears at 4 ml of catalyst with a yield of 1.218 %, increasing slightly to 1.208 % at 5 ml.

This data indicates that the amount of clove oil catalyst has a significant effect on the production efficiency of these chemical compounds. The highest overall yield for 3-allyl-6-methoxyphenol is achieved at 4 ml of catalyst, while the production of trans-caryophyllene and 1,2-benzenedicarboxylic acid is maximized with 5 ml of catalyst. This suggests an optimal range of catalyst volume that enhances the synthesis process, contributing to a better understanding of the catalytic efficiency of clove oil in chemical reactions.

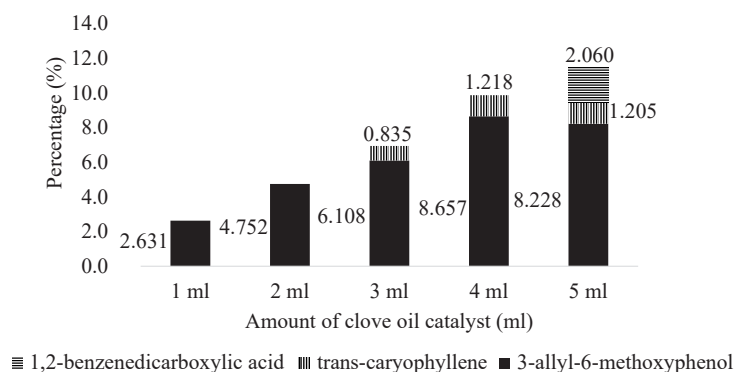


Fig. 8. Percentage of eugenol formed when mixing B20 with clove oil (1–5 ml)

The addition of clove oil bioadditives to Biosolar B20 resulted in significant improvements in combustion characteristics. The ignition delay decreased with increasing clove oil concentration, indicating a more rapid onset of combustion. The combustion duration was also reduced, leading to more complete combustion. Peak temperatures were higher for fuel mixtures containing clove oil, suggesting enhanced combustion efficiency.

The findings of this study are consistent with previous research on the use of oxygenated bioadditives in biodiesel. Studies by [33, 34] have reported similar improvements in combustion efficiency and emission reductions with the use of bioadditives. However, the specific impact of clove oil on Biosolar B20 combustion characteristics provides new insights into the potential of this bioadditive, highlighting its advantages over other additives studied in the literature.

The improved combustion characteristics and reduced emissions observed in this study suggest that clove oil bioadditives can significantly enhance the performance of Biosolar B20. These findings have important implications for the development of more efficient and environmentally friendly biodiesel blends [35–39]. The use of clove oil could contribute to the reduction of greenhouse gas emissions and the promotion of sustainable energy solutions.

The limitations of this study are that the findings are confined to laboratory testing using the droplet combustion method. The study has not evaluated the performance of clove oil bioadditives in actual engines or under real-world operating conditions. For reproducibility, testing parameters (such as clove oil volume, combustion chamber temperature, and measurement instruments) must be described in detail. Additionally, potential variations in fuel batches (e.g., biodiesel content) could influence the results. There is no evaluation of the impact of clove oil bioadditives on engine systems, such as fuel injection systems, metal components, or deposit formation. The decrease in flash point with increasing clove oil concentration may affect the safety of fuel storage and transportation, warranting further attention. The study does not address how changes in fuel composition (e.g., eugenol content) might impact broader chemical properties, such as corrosivity or storage stability.

Developments that could in future be undertaken include evaluating clove oil bioadditives in real engines by conducting performance and emission tests across various engine types and real-world operating conditions, such as in vehicles or generators. Further studies should determine the optimal concentration of clove oil, considering performance, efficiency, and emissions simultaneously. Investigations into the effects of clove oil bioadditives on engine components, fuel stability during storage, and deposit formation are necessary. Assessing the production costs and economic benefits of using clove oil bioadditives compared to other additives is crucial. Broader environmental

impacts, including greenhouse gas emissions during the lifecycle of clove oil production and usage as a bioadditive, should also be evaluated. Additionally, the safety risks associated with flash point reduction could be mitigated through the development of additive formulations or proper storage procedures. By addressing these limitations, future research could provide more comprehensive and practical insights into the application of clove oil bioadditives for biodiesel fuels.

4. Conclusions

This study highlights the potential of clove oil as a bio-additive to enhance the combustion characteristics of B20 biodiesel fuel:

- the addition of clove oil as a bio-additive to B20 biodiesel resulted in significant improvements in combustion properties. Ignition delay progressively decreased with increasing concentrations of clove oil, from 6.74 seconds for pure B20 biodiesel to 1.38 seconds at 5 ml of clove oil. Similarly, the combustion duration shortened from 1.87 seconds for pure B20 biodiesel to 0.96 seconds with 5 ml of clove oil;
- the peak combustion temperature rose from 409.4 °C for pure B20 biodiesel to 553.3 °C at 5 ml of clove oil. Moreover, the burning rate substantially increased, rising from 0.53 mm²/s for pure B20 biodiesel to 1.04 mm²/s at 5 ml of clove oil;
- these improvements are attributed to the high eugenol content in clove oil, which facilitates better combustion due to its oxygenated compounds. Additionally, emissions were reduced, as evidenced by the lower flame height observed, which decreased from 50 mm for pure B20 biodiesel to 33 mm with 5 ml of clove oil;
- these findings underscore the potential of clove oil as an effective bio-additive for enhancing combustion efficiency and the environmental sustainability of B20 biodiesel.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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