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Dynamic Thermofluid Study of Petrodiesel Droplet Combustion with Variations of Kesambi Biodiesel Composition Accompanied with TiO_2 Catalyst

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Abstract

The increasing global energy demand encourages the use of sustainable alternative fuels with combustion performance equivalent to petrodiesel. This study focuses on the droplet combustion characteristics of petrodiesel and biodiesel kesambi blends (B0, B10, B20, B30 B40 and B100), both without and with the addition of 100 ppm TiO_2 nanoparticle catalyst. Analysis was carried out on ignition delay, combustion duration, flame height, peak temperature, and flame visualization patterns. The results show that increasing the biodiesel fraction tends to prolong the combustion time and decrease the peak temperature, while the addition of TiO_2 provides significant improvements in the form of shorter ignition delay, higher peak temperature, and more stable flame. The novelty of this study lies in the use of a droplet approach to explore the role of TiO_2 catalyst in kesambi biodiesel, which is still limited in the literature. Thus, nanoparticle catalysts are proven to have great potential in increasing the efficiency and sustainability of the use of biodiesel–petrodiesel blends.

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1. Introduction

The increasing global human population continues to drive energy demand, raising concerns about the sustainability of fossil-based energy reserves, particularly petrodiesel, which remains the

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primaryy source of transportation, electricity generation, and the industrial sector (Winarko et al., 2022). The extensive use of fossil fuels has been shown to increase greenhouse gas emissions, which impact climate change (El-Adawy, 2023; Ooi et al., 2023; Ramalingam et al., 2023). However, biodiesel has limitations such as high viscosity, low volatility, and a lower calorific value than petrodiesel. This can significantly reduce the atomization quality, combustion efficiency, and exhaust emission characteristics (Abdullah et al., 2017; M. Jain et al., 2018; Pujirahayu et al., 2022).

One potential non-food biodiesel source that has rarely been optimized in Indonesia is kesambi oil (Schleichera oleosa). This is due to its high oil yield and abundance (Asri et al., 2022; Latumakulita et al., 2023). Several studies report that kesambi biodiesel meets basic diesel engine fuel specifications, but its use in high concentrations faces technical challenges such as ignition delay, incomplete combustion, and increased hydrocarbon emissions (Holil & Griana, 2020; Mahgoub, 2023; Muniyappan & Krishnaiah, 2024; Razzaq et al., 2023; Ren et al., 2021). This clearly requires clarification of optimization strategies for the wider application of kesambi biodiesel.

One promising approach to optimizing the characteristics of kesambi biodiesel is the addition of nanocatalysts. Nanocatalysts have been shown to improve atomization, accelerate oxidation reactions, and minimize combustion delays (Burkert & Paa, 2016; Ooi et al., 2019; Adu et al., 2020; Fan et al., 2020; Verdier et al., 2017). Among the various types of nanocatalysts, titanium dioxide (TiO_2) has high thermal stability and strong catalytic properties, making it effective for improving biodiesel combustion performance (Baruaha et al., 2020; Vigneswaran et al., 2021). However, studies on the thermofluid characteristics of kesambi biodiesel droplet combustion with the addition of TiO_2 are still very limited, while most previous studies have focused on dominant raw materials such as palm oil, jatropha curcas, and soybeans (Baruaha et al., 2020; Marsh et al., 2019; Verwey & Birouk, 2017). The novelty of this research lies in the application of the droplet combustion method to study the thermofluid behavior of kesambi biodiesel using a TiO_2 catalyst, thus providing new insights that are not widely reported in the kesambi biodiesel literature.

Building on previous research, this study employed the droplet combustion method to evaluate the ignition delay, combustion duration, flame height, peak temperature, and flame visualization in a blend of petrodiesel and kesambi biodiesel with a TiO_2 catalyst. This approach is expected to provide a scientific understanding of the interaction between fuel composition and combustion phenomena at the microscale level. Furthermore, the research findings are expected to provide practical contributions to the formulation of a more efficient and environmentally friendly kesambi biodiesel. This study aimed to examine the effect of TiO_2 nanoparticle catalysts on the dynamic thermofluid behavior of kesambi biodiesel, with the hypothesis that their presence can overcome the thermal limitations of biodiesel and improve combustion efficiency compared to conventional blends.

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2. Material and Methods

The biodiesel used in this study was synthesized from kesambi (Schleichera oleosa) seeds collected from Bukit Bentar, Probolinggo, Indonesia. Initial processing included drying to reduce the moisture content, dehulling, and grinding the seeds into a fine powder for easy extraction. The oil was extracted using a mechanical pressing process and refined before use. A schematic representation of the extraction process is shown in Figure 1.

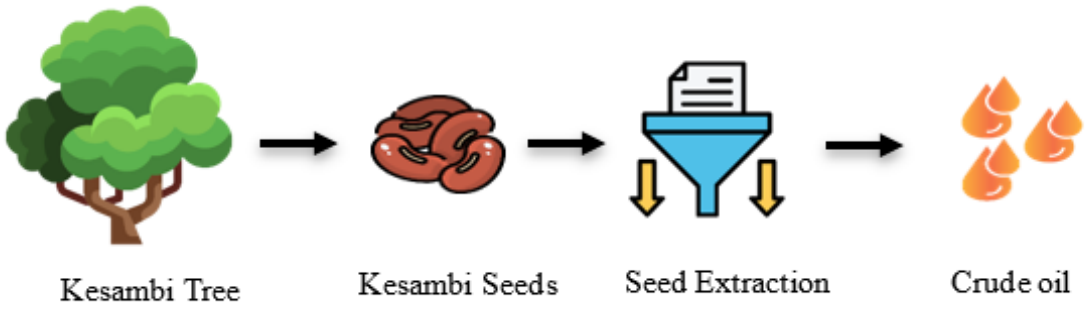

Figure 1. Kesambi Seed Extraction Process.

After obtaining crude oil, biodiesel synthesis begins in the degumming stage. The degumming stage was carried out by adding 1% phosphoric acid (H_3PO_4) to the oil mass (m/m), followed by stirring using a magnetic stirrer at 60°C for 30 minutes to remove phospholipids and impurities. A schematic representation of the degumming process is shown in Figure 2.

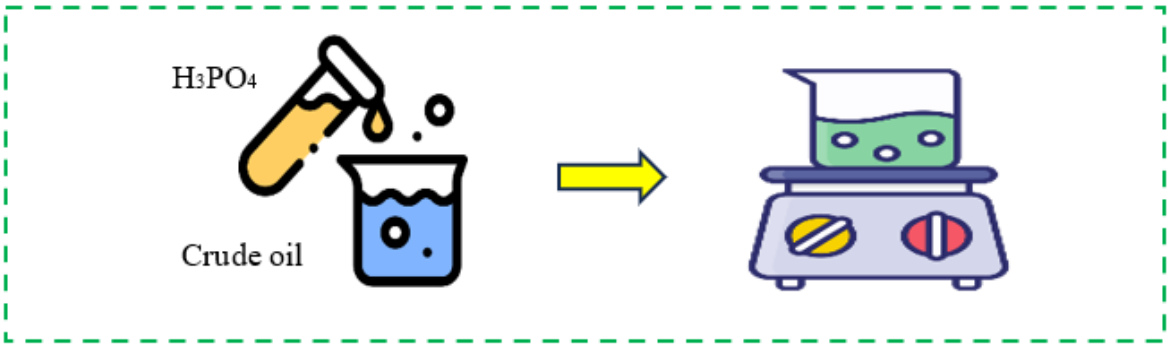

Figure 2. Degumming Process Scheme.

After the degumming process, the esterification stage is continued. The degummed oil was esterified using methanol with a molar ratio of 1:16 (mol/mol) and sulfuric acid (H_2SO_4) catalyst at 1% of the total oil mass. The stirring temperature is 60°C for 90 minutes to reduce the free fatty acid (FFA) content. A diagram of the esterification process is shown in Figure 3.

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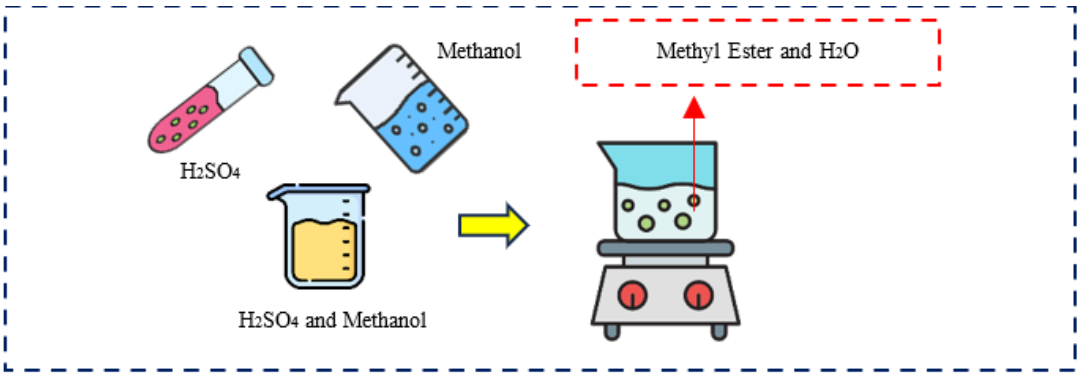

Figure 3. Esterification Process Scheme.

After the esterification stage, the transesterification stage was continued using a base catalyst, methanol with a molar ratio of 1:6 (mol/mol) and NaOH as much as 1% of the total oil mass at a temperature of 60°C for 60 minutes. The resulting transesterification products are methyl ester (biodiesel) and glycerol. The methyl ester is continued in the washing stage. The resulting biodiesel was washed three times with distilled water at a temperature of 98°C to remove residual catalyst and glycerol, and then dried before being mixed with petrodiesel. The transesterification process scheme is shown in Figure 4.

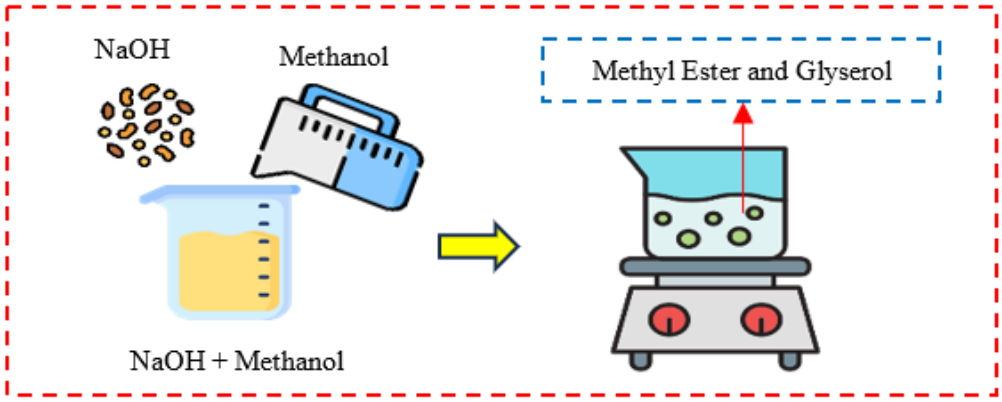

Figure 4. Transesterification Process Scheme

The processed biodiesel samples were mixed with petrodiesel (Dexlite). The samples consisted of two parts: the first part was a sample with a biodiesel mixture, and the second part was a biodiesel mixture sample with the addition of a nano titanium dioxide (TiO_2) catalyst. Titanium dioxide (TiO_2) nanoparticles were added to each mixture, including B0 and B100, at a concentration of 100 ppm, with the amount calculated using Equation (1). The process of mixing the catalyst was mixed with the fuel sample using ultrasonication to obtain an even dispersion of nanoparticles in the fuel mixture. Each formulation was coded according to its composition. The fuel sample codes can be seen in Table 1.

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$$\text{mass}TiO_2 = \frac{\text{PPM x Volume (ml)}}{1000} \quad (1)$$

Table 1. Composition of the Test Samples.

Sample	Petrodiesel / Dexlite (%)	Biodiesel (%)	Code
Sample 1	100	0	B0
Sample 2	90	10	B10
Sample 3	80	20	B20
Sample 4	70	30	B30
Sample 5	60	40	B40
Sample 6	0	100	B100

Droplet combustion experiments were conducted using a test apparatus with a heater connected to a data logger. The fuel volume used was half a milliliter. The fuel sample was dropped using a micropipette onto a nickel-in wire heated by a DC power supply as an ignition source. The flame was recorded using a camera positioned perpendicular to the flame axis, and a K-type thermocouple connected to a data logger was placed at the flame core to monitor the temperature profile during combustion. Measurements were initiated from the moment the droplet touched the wire until the flame was completely extinguished. A schematic of the test combustion chamber is shown in Figure 5.

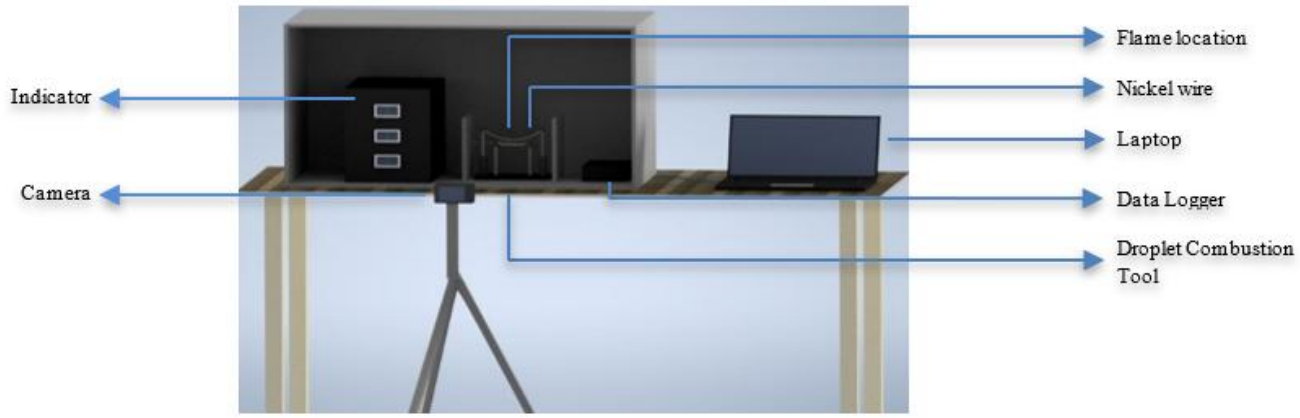

Figure 5. Droplet Test Combustion Chamber.

The evaluation was conducted based on five main parameters consisting of ignition delay, combustion duration, flame height, flame visualization, and maximum temperature. The ignition delay was measured as the time interval between the initial contact of the droplet with the hot wire and the first visible flame, synchronized with a digital stopwatch. The combustion duration was

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calculated from the start of ignition to flame extinguishment using a frame-by-frame analysis. The flame height was measured using ImageJ with calibration based on the heater length, and qualitative visual observations included the shape, symmetry, and color of the flame. The peak flame temperature was recorded in real time using a K-type thermocouple, with the highest value interpreted as the maximum thermal output of the fuel. Each test was repeated three times to ensure reproducibility, and the average values were calculated for all parameters to ensure data consistency. The reported values are the average standard deviation (SD) values of the replicate results to assess the effect of the biodiesel fraction and TiO_2 additive on the combustion behavior. The standard deviation equation used can be seen in equation (2). The interpretation of the visual characteristics of the flame is also linked to quantitative parameters such as ignition delay and combustion duration, which provide a comprehensive understanding of the thermofluid dynamics of the fuel.

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x)^2}{n-1}} \quad (2)$$

3. Results and Discussion

The results of the discussion present the results of the droplet combustion experiment with samples according to Table 1. The parameters observed include ignition delay, flame height, combustion duration, maximum flame temperature, and flame visualization. The analysis was carried out to identify the effect of the biodiesel ratio and the role of the TiO_2 catalyst as a combustion catalyst. The fuel characteristics are presented in Table 2. The discussion is organized in subsections 3.1 to 3.5, each of which reviews the parameters separately to provide a comprehensive understanding of the thermofluid behavior of the kesambi biodiesel mixture and the contribution of TiO_2 in influencing the combustion efficiency and stability.

Table 2. Fuel Characteristics.

Composition	Density (g/cm³)	Viscosity (cSt)	Flashpoint (°C)
B0	0,849	2,03	108,53
B100 + TiO_2	0,880	4,65	147,10
SNI Biodiesel 7182:2015	0,850 – 0,890	2,3 – 6,0	Min 100

3.1 Ignition Delay

The ignition delay is the time interval between a drop of fuel touching the hot filament and the appearance of the first flame. This parameter reflects the sensitivity of the fuel to heat and is an early

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indicatorr of combustion efficiency. The ignition delay test results for each fuel sample are shown in Figure 6.

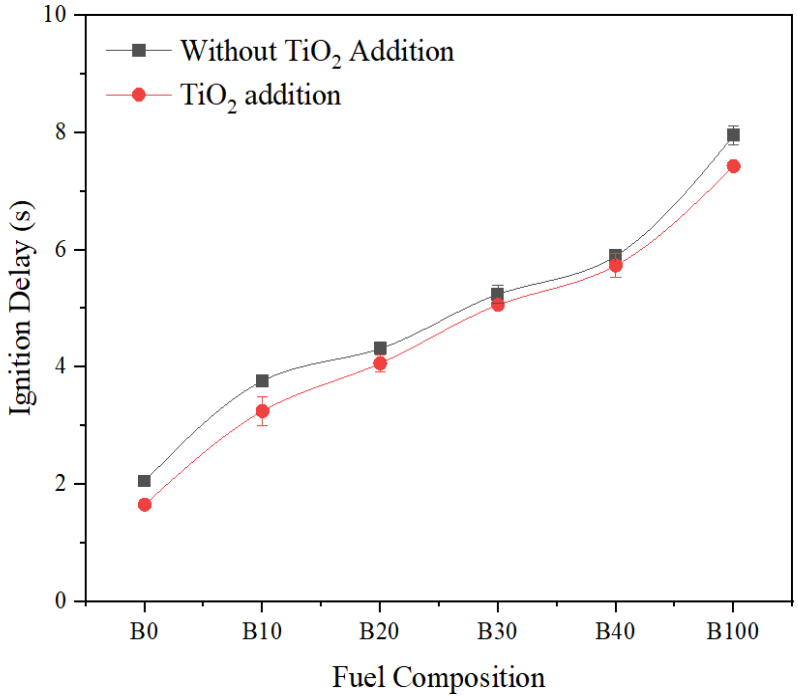

Figure 6. Ignition Delay Values for Each Fuel Sample.

Based on the results shown in Figure 6, the ignition delay value increased with increasing kesambi biodiesel fraction. Composition B0 showed the shortest delay time, at 2.05 seconds, while B100 reached the highest value at 7.95 seconds. This trend can be explained by the physical properties of biodiesel, which has a higher viscosity and flash point than petrodiesel, thereby lowering the vapor pressure and slowing the evaporation process and fuel-air mixing (Belkadi et al., 2016; Nurmukan et al., 2021). This pattern aligns with the report by Verwey and Birouk (2017) who tested palm oil and jatropha biodiesel, both of which showed longer ignition delays than pure diesel. However, the ignition delay of kesambi biodiesel in this study was relatively higher than that of soybean biodiesel reported by Bidir et al. (2021), which only ranged from 6.2–6.8 seconds under similar conditions. This suggests that the fatty acid composition of kesambi oil provides different evaporation characteristics compared to other vegetable oils.

The addition of TiO_2 nanoparticle catalysts consistently accelerated the ignition process. At B0, the delay time was drastically reduced to 0.39 seconds, while at B100, it dropped to 0.52 seconds. This effect is related to TiO_2's ability to lower the activation energy of oxidation reactions, accelerate free radical formation, and improve heat distribution around the droplet (A. Jain et al., 2023; Zhang et al., 2019). These advantages are due to the very small particle size (20–30 nm) with a high specific surface

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areaa, which provides numerous active reaction sites. However, if the dispersion is not homogeneous and the particles agglomerate, the catalyst's effectiveness can be significantly reduced due to the reduction in active surface area (Khujamberdiev & Cho, 2024; Zarko & Glazunov, 2020).

From an engine application perspective, a long ignition delay, such as that found in B100, can cause difficulties during cold starts and increase the combustion instability. Conversely, an ignition delay that is too short, as in B0 with TiO_2, can potentially trigger a sharp increase in the peak pressure, increasing the risk of knocking. Therefore, adding TiO_2 to the kesambi biodiesel blend can be a strategy to balance the ignition speed, resulting in more efficient combustion while maintaining safety for engine performance and reliability.

3.2 Burning Duration

The burning duration is defined as the total time from the ignition of a droplet to flame extinction. The burning duration reflects the fuel evaporation rate, oxidation reaction rate, and overall flame stability. Longer durations typically indicate gradual and slow combustion, whereas shorter durations indicate faster and more efficient combustion. The average burning durations for each fuel composition are shown in Figure 7.

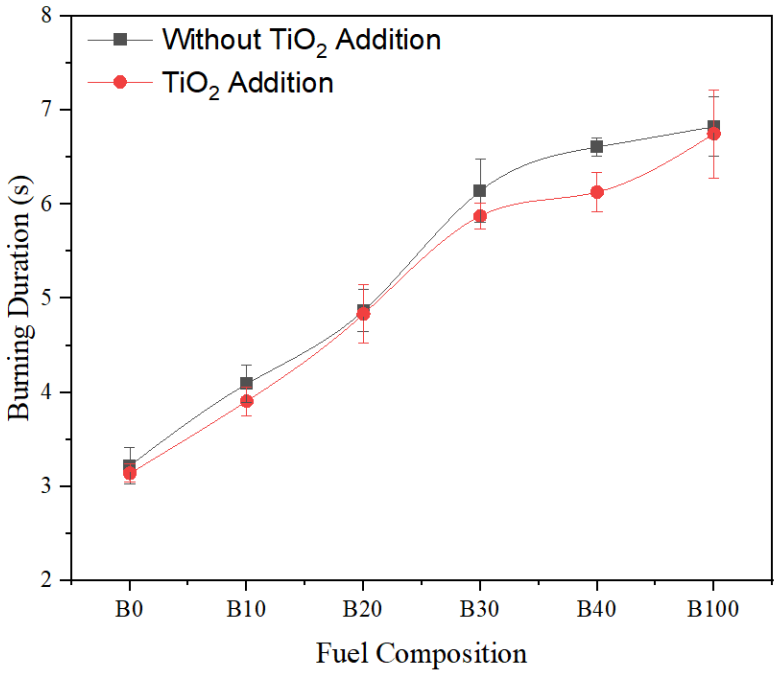

Figure 7. Burning Duration Value for Each Fuel Sample

The test results showed that increasing the kesambi biodiesel fraction resulted in longer combustion times. The B0 composition recorded 3.22 s, while the B100 composition reached 6.83 s. This longer duration is influenced by the high viscosity, high flash point, and long-chain hydrocarbon

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contentt of biodiesel, which slows atomization and vaporization. This finding aligns with that of Lü et al. (2021), who asserted that the bound oxygen content in biodiesel accelerates the oxidation reaction but results in a more gradual energy release.

The addition of TiO_2 nanocatalysts consistently shortened combustion time. In B0, the time decreased to 3.14 s, whereas in B100, it decreased from 6.83 s to 6.75 s. This decrease demonstrates the role of TiO_2 in accelerating free radical formation, enhancing heat absorption, and distributing energy more homogeneously around droplets. This trend is consistent with the findings of Zheng and Haeng (2024), who reported that metal oxides can accelerate oxidation and produce cleaner flames. These results also align with the findings of Chow et al. (2021) on palm oil-ethanol biodiesel blends, where ethanol volatility accelerated evaporation and shortened the burning duration. Thus, combustion acceleration can occur through increased volatility (ethanol) or catalytic activity (TiO_2). A similar phenomenon was also observed in the study by Meng et al. (2022), where micro-explosions in biodiesel-ethanol blends accelerated droplet fragmentation, thereby shortening the burning duration. In the context of this study, the acceleration effect was primarily attributed to the catalytic properties of TiO_2, consistent with a study on hydroprocessed vegetable oils supplemented with aluminum nanoparticles (Inês et al., 2021). That study confirmed that metal nanoparticles increase the reaction surface area, lower the activation energy, and accelerate the oxidation rate. Therefore, these results strengthen the evidence that nanomaterials play a significant role in improving the combustion characteristics of biodiesel.

From a practical perspective, a longer burning duration in pure biodiesel can improve flame stability but risks reducing the engine's thermal efficiency owing to slower energy release. Conversely, accelerating with TiO_2 has the potential to increase the energy conversion efficiency and improve the engine response under transient conditions, although it can also trigger peak temperature increases that impact NOx emissions. Therefore, the use of TiO_2 needs to be optimized not only in terms of particle size and distribution, but also in terms of the balance between combustion efficiency and emissions control. Overall, these findings support the concept of green nanotechnology for developing more efficient and sustainable renewable fuels (Kumar et al., 2024; Ooi et al., 2019).

3.3 Flame Height

Flame height is an important indicator of droplet combustion because it indicates the extent of the reaction zone and the intensity of the heat release. The flame heights for each fuel sample are shown in Figure 8. The experimental results showed that B0 produced the highest flame height, at 52.64 mm. This high flame height indicates a rapid flame diffusion process with intense energy release, which is consistent with the high volatility and specific energy properties of petrodiesel (Meng et al., 2022; Zheng & Cho, 2024). As the kesambi biodiesel fraction increased, the flame height gradually decreased, reaching 40.87 mm at B100. This decrease is closely related to the physical properties of

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biodiesell, particularly its viscosity and higher boiling point, which inhibit droplet atomization and slow evaporation. A similar phenomenon has also been reported for soybean- and jatropha-based biodiesels, where evaporation limitations resulted in lower flame heights than pure diesel (Fan et al., 2020).

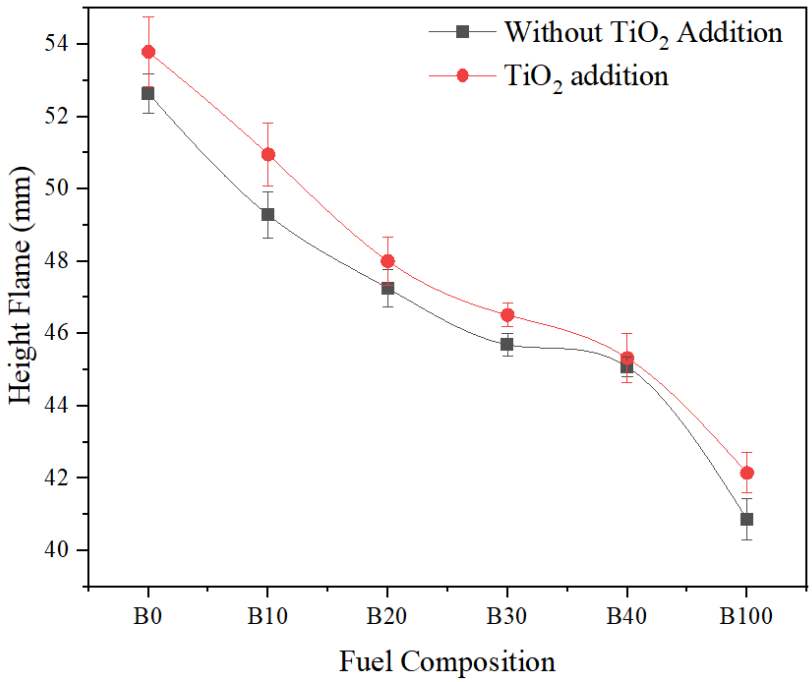

Figure 8. Flame Height.

The catalytic effect of TiO_2 was observed in most blends, although the magnitude of the effect varied significantly. At B0, the increase was only approximately 1 mm (from 52.64 mm to 53.79 mm), but at intermediate blends such as B20, the increase was more pronounced, from 47.25 mm to 48.01 mm. The mechanism of this increase is related to the ability of TiO_2 to provide active sites for oxidation reactions and accelerate radical formation, resulting in a more even heat distribution around the droplet. This finding is consistent with that of Zheng and Chao (2024), who showed that the addition of aluminum nanoparticles to hydroprocessed vegetable oil can enhance flame intensity by increasing the catalytic surface area. However, at B100, the effect of TiO_2 was insignificant, indicating that the physical limitations of pure biodiesel, such as slow diffusion and high viscosity, could not be completely overcome by the catalyst. The catalytic effectiveness of TiO_2 is strongly influenced by the particle size and dispersion level. Particles measuring 20–30 nm with a homogeneous distribution can increase combustion reactivity, whereas agglomeration decreases the active surface area and reduces its effect (Ooi et al., 2019). This explains why the increase in flame height was more pronounced in blends with medium biodiesel fractions but was limited in pure biodiesel.

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From an engine application perspective, these results have several implications. A lower flame height with pure biodiesel can suppress peak temperatures, potentially reducing NOx formation, but simultaneously reduces thermal efficiency. Conversely, a higher flame height with the TiO_2 catalyst supported more efficient combustion but could also increase radiant heat loss and the thermal load on the engine components. Therefore, medium blend compositions, such as B20 with TiO_2, could be a promising alternative, providing a balance between energy efficiency and emission control.

3.4 Peak Temperature

The peak temperature is a key parameter indicating the maximum combustion intensity and is directly related to the thermal efficiency and formation of pollutants such as NOx. This value is strongly influenced by the physicochemical properties of the fuel, energy distribution, and heat transfer dynamics during the oxidation of the droplet. The peak temperature measurements for each fuel composition are shown in Figure 9.

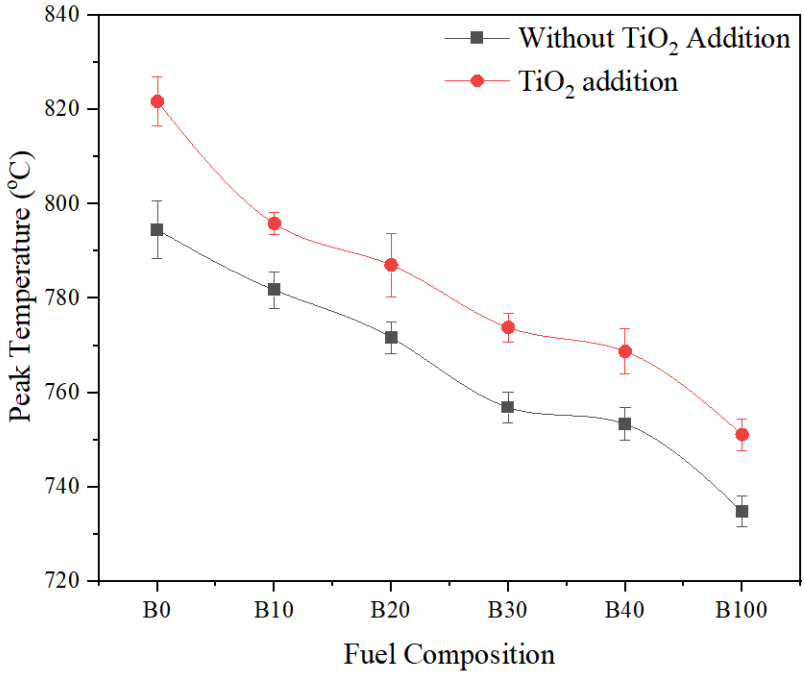

Figure 9. Peak Flame Temperature.

At B0, the peak temperature reached 794.54 °C with a relatively short flame duration (3.22 s), indicating rapid combustion owing to the high volatility of petrodiesel. Increasing the kesambi biodiesel fraction caused a gradual decrease in the peak temperature, from 781.76 °C at B10 to 734.76 °C at B100. This phenomenon is consistent with the report of Chow et al. (2021) on biodiesel blends with ethanol, where the high viscosity and high flash point slowed droplet evaporation, resulting in

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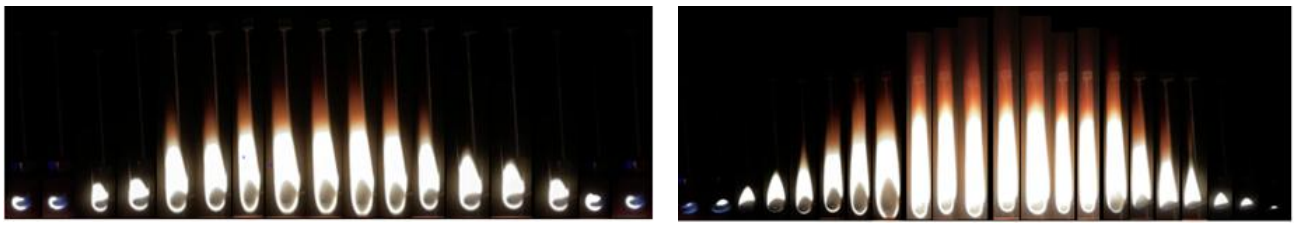
a slower energy release. Although the oxygen content in biodiesel supports more uniform combustion, the reaction rate remains lower than that of pure petrodiesel.

The addition of TiO_2 nanoparticles increased the peak temperature for all compositions. In B0 + TiO_2, the peak temperature reached 821.76 °C, whereas those of B10 with TiO_2 and B20 with TiO_2 were 795.87 °C and 787.06 °C, respectively. This increase is consistent with the results of Muniyappan et al. (2024), who showed that the TiO_2 catalyst accelerated the formation of free radicals and improved heat distribution in the flame zone. However, the effectiveness of the catalyst decreased at high biodiesel fractions; for example, B100 with TiO_2 only reached 751.09 °C. This is likely due to the heat diffusion barrier owing to the high viscosity and tendency for micro-soot formation, which hinders droplet surface oxidation (Zeleke & Tefera, 2024). This finding is consistent with that of Meng et al. (2022), who emphasized that droplet behavior greatly determines the stability of energy distribution in the flame phase.

From a practical perspective, increasing the peak temperature with the addition of TiO_2 implies increased engine thermal efficiency, but also potentially increases NOx emissions due to higher peak temperatures. Further strategies, such as the use of EGR or catalytic after-treatment systems, need to be considered to maintain a balance between efficiency and emissions. The B10 composition with TiO_2 emerged as the most optimal candidate, as it exhibited a high peak temperature with a moderate flame duration, thus potentially being applied in modern diesel engines with more efficient performance while maintaining controlled emissions.

3.5 Flame Visualization

to height to stability. In this study, cameras were used to capture the flame patterns of each fuel variation, allowing for detailed analysis of the morphological differences. The visual parameters observed included flame shape, light distribution, and color intensity. The results are shown in Figures 10–15.



(a) (b)

Figure 10. Flame Visualization with Compositions (a) B0 and (b) B0+TiO2.

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Figure 10 shows the B0 and B0+TiO_2 flames. B0 produced a flame height of 52.64 mm with a yellow-orange color that oscillated at the tip, indicating a fast reaction but accompanied by soot formation. After the addition of TiO_2, the flame became denser, brighter, and more stable, with a height of 53.79 mm and a shorter ignition delay. A similar phenomenon was reported by Ooi et al. (2019), who found that the color transition of the biodiesel flame was closely related to the increase in combustion homogeneity.

Figure 11. Flame Visualization with Compositions (a) B10 and (b) B10 + TiO_2.

Figure 11 shows the observation results for B10 and B10+TiO_2. The B10 mixture produced a pale orange flame with a height of 50.95 mm and a peak temperature of 781.76 °C, whereas the ignition delay was recorded at 3.77 s. The addition of TiO_2 resulted in a brighter flame, with a slightly reduced height of 49.28 mm but an increased temperature of 795.87 °C. Jain et al. (2023) also found that the TiO_2 catalyst could reduce unburned carbon emissions, resulting in a brighter flame.

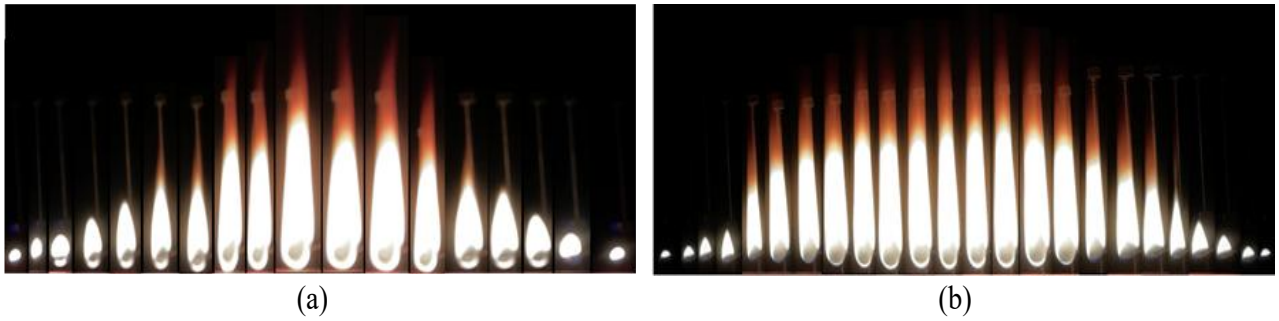

Figure 12. Visualization of Flame with composition (a) B20 and (b) B20+TiO_2.

Figure 12 shows the visualization of B20 and B20+TiO_2. In the B20 composition, the flame appeared diffuse with a golden color, the ignition delay reached 4.32 s, and the maximum temperature was 779.67 °C. After the addition of TiO_2, the flame became more focused, the peak temperature increased to 787.06 °C, and the ignition delay decreased to 4.07 s. These findings support the report of Vigneswaran et al. (2021), who stated that the presence of a catalyst accelerates radical formation and improves atomization.

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(a) (b)

Figure 13. Visualization of Flame with composition (a) B30 and (b) B30+TiO_2.

Figure 13 compares the B30 and B30+TiO_2 flames. The B30 flame tended to expand with a dim orange color, an ignition delay of 5.24 s, and a temperature of 756.87 °C. With TiO_2, the flame shape became more compact, the ignition delay was reduced to 5.06 s, and the temperature increased to 773.83 °C. These changes indicate that the catalyst accelerates the oxidation reaction, resulting in a more stable flame, even though the biodiesel fraction is larger.

(a) (b)

Figure 14. Flame Visualization with compositions (a) B40 and (b) B40+TiO_2.

Figure 14 shows the flames of B40 and B40+TiO_2. In B40, the flame appeared shorter and wider with a red-orange color, an ignition delay of 5.90 s, and a temperature of 753.32 °C. The addition of TiO_2 produced a more focused flame with a bright yellow core, decreased the ignition delay to 5.74 s, and increased the temperature to 768.74 °C. Ooi et al. (2019) stated that better heat distribution can suppress flame oscillations and improve combustion stability, while studies by Yuvarajan et al. (2018) and Vigneswaran et al. (2021) confirmed that the TiO_2 catalyst is able to accelerate oxidation and improve flame stability by improving fuel atomization.

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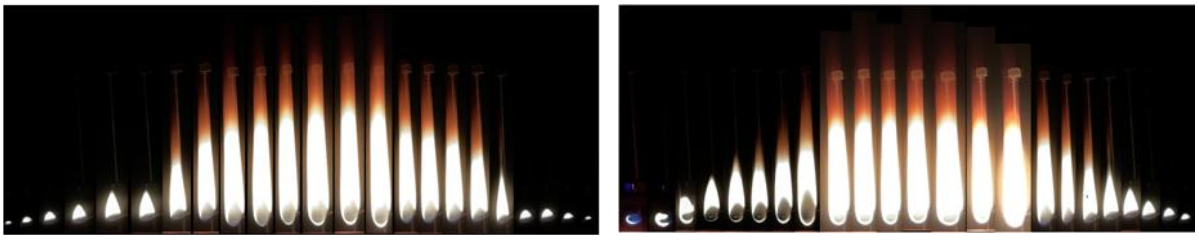

(a) (b)

Figure 15. Visualization of Flame with composition (a) B100 and (b) B100+TiO_2.

Figure 15 shows the difference between B100 and B100+TiO_2. B100 produced a low flame height of 40.87 mm with a dim red color, an ignition delay of 7.95 s, and a peak temperature of 734.76 °C, indicating slow combustion. With TiO_2, the flame became brighter at the core, the height increased to 42.15 mm, the ignition delay decreased to 7.43 s, and the temperature reached 751.09 °C. These effects indicate that although the viscosity limitation of biodiesel still exists, the catalyst can improve combustion homogeneity.

4. Conclusion

This study revealed the thermofluid dynamics of droplet combustion of petrodiesel–kesambi biodiesel blends with and without the addition of TiO_2 nano catalysts. Increasing the kesambi biodiesel fraction was proven to reduce the flame height and peak temperature owing to the relatively lower energy density, whereas the combustion duration and ignition delay time increased with the high viscosity and slow oxidation rate. The addition of 100 ppm TiO_2 consistently resulted in significant improvements, characterized by shorter ignition delay times, higher peak temperatures, and more stable and cleaner flame morphology. These results confirm the catalytic role of TiO_2 in enhancing the combustion performance of diesel blends with biodiesel. Although this study was conducted at the droplet scale, its implications are important for real diesel engine applications, particularly in improving thermal efficiency and reducing incomplete combustion products. Further research should be directed toward engine-scale trials with varying loads and analysis of the resulting exhaust emissions, especially those related to nitrogen oxides (NOx) and particulates. This approach is expected to provide a more comprehensive scientific basis for the utilization of kesambi biodiesel with TiO_2 catalyst in efficient, sustainable, and environmentally friendly diesel-engine systems.

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thiss study will make a tangible contribution to the development of science and technology, particularly in the field of renewable energy and non-food biodiesel-based combustion engineering.

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