

Research Paper

The Role of Heterogeneous Catalyst Transesterification in Single Droplet Combustion of Soybean Oil Based Biodiesel

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Abstract

The consumption of petroleum fuel in Indonesia is increasing, makes the globe climate change a lot. Thus, requiring a renewable energy alternative source such as biodiesel. This study analyzed the single droplet combustion characteristics of soybean oil-based biodiesel produced via transesterification using two heterogeneous catalysts: papaya leaf (PL) and papaya leaf combined with animal bone (PLAB). For comparison, petroleum diesel fuel also tested. Results show that catalyst origin significantly influences combustion behavior. PL exhibited the longest droplet lifetime 7,135 s/mm² and the highest peak temperature (546 °C), while PLAB showed shorter droplet lifetime 5,001 s/mm² and a lower peak temperature (467 °C), closer to petroleum diesel (4,081 s/mm² and 254 °C), respectively). In terms of ignition delay, petroleum diesel ignited fastest (3,528 s/mm²), followed by PLAB (4,837 s/mm²) and PL (0,612 s/mm²). The combustion behavior of PLAB is correlated with its higher FAME purity (98%) and methyl linoleate content (43.69%), as reflected by the reduced droplet lifetime. This suggests that the catalyst primarily improves biodiesel quality via enhanced transesterification efficiency, which in turn affects combustion characteristics.

Keywords: Biodiesel, Droplet combustion, Heterogenous catalyst, Synergistic catalytic effect

1. Introduction

Energy demand for transportation has increased over the past few decades, leading to global warming, pollution problems, and the depletion of fossil fuels [1]. Some researchers have tried to produced biodiesel as an environmentally friendly alternative energy resource [2], [3], [4]. In the conventional way, biodiesel is produced through the transesterification method using homogeneous catalysts [5], [6], [7]. Soybean oil is one of the common raw materials used for the transesterification reaction [8], [9]. Vegetable oils have limited suitability as diesel engine fuels due to their high viscosity, density, and volatility, which negatively impact atomization,

vaporization, and overall engine performance [10]. Their chemical structure is dominated by triglycerides with varying degrees of fatty acid saturation, which also affects ignition quality and oxidation stability [11]. Therefore, pretreatment or modification, such as the use of chemical additives, hydrotreating, or transesterification, is often necessary to improve combustion performance [12].

Among various heterogeneous catalysts employed in the transesterification, calcium oxide (CaO) is one of the most widely used due to its favorable physicochemical properties, including high catalytic activity, thermal stability, and ease of separation from the reaction mixture. These



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advantages make CaO an attractive option for large-scale and economically viable biodiesel production [13]. For preparing the base catalyst, combining two or more waste materials in smaller particle sizes prior to heat treatment can improve the catalyst's activity during the transesterification process. This improvement occurs because a catalyst produced from a blend of different precursor materials tends to exhibit more active sites, higher basic site density, and a larger BET surface area [14]. Study from Adepoju et al. [15] produced three activated CaO-based catalysts derived from chicken foot bone, catfish bone, and a combination of both materials, which were utilized to synthesize biodiesel from a blend of three vegetable oils (two non-edible and one edible). The catalysts were subjected to calcination at 1000 °C for 3 hours and subsequently characterized using scanning electron microscopy (SEM) and X-ray diffraction (XRD). Catalysts' characterization showed the amount of CaO-based found through XRD analysis in the catalysts was 93.52%, 91.24%, and 99.84%, respectively. The highest biodiesel yields obtained experimentally were 93.60, 92.47, and 97.12 wt%. In comparison, statistical optimization using the Box Behnken Experimental Design (BBED) model predicted yields of 93.86, 92.7685, and 97.2566 wt%. These predicted values were subsequently validated through confirmatory experiments, resulting in yields of 93.5400, 91.87, and 96.88 wt%, respectively. However, despite providing comprehensive insights into synergistic catalyst performance and biodiesel yield optimization, this study did not extend its analysis to the combustion behavior of the produced biodiesel. In particular, fundamental droplet combustion characteristics such as droplet evolution profile, ignition delay, droplet lifetime, or micro-explosion tendencies were not evaluated, leaving an important gap regarding how catalyst combination used for transesterification influence the thermo-physical and combustion characteristic of the resulting fuel.

Recent studies have shown that organic, inorganic, and nanoparticle-based additives can improve fuel properties, ignition behavior, and heat transfer [16], [17], [18], [19]. Metal oxide nanoparticles, such as Al_2O_3 and CeO_2 , have shown significant improvements in thermal efficiency and emission reductions when blended

with diesel or biodiesel [20], [21]. Fundamental droplet studies have also shown that nanoparticles can accelerate ignition, enhance vaporization, or alter combustion characteristics depending on fuel type, boiling point, concentration, and ambient temperature [17], [18], [19]. Single droplet combustion has been recognized as an effective method to evaluate the fundamental burning behavior of biodiesel fuels. A burning droplet undergoes several phases, including transient heating, evaporation, burning and also potential secondary atomization such as micro-explosion, which are strongly influenced by the fuel's physical and chemical properties. These combustion characteristics offer a sensitive means to detect the influence of catalyst derived variations in fuel composition. However, previous research on biomass derived heterogeneous catalysts used for transesterification has rarely extended its analysis to the combustion scale

Despite the demonstrated improvements in catalyst activity, biodiesel yield, and process optimization achieved through synergistic CaO-based catalyst systems, prior studies have not examined how such catalytic interactions influence the subsequent combustion behavior of the resulting fuel. At the same time, although single-droplet combustion has been widely used to probe ignition, vaporization, and microexplosion phenomena, research employing biomass derived heterogeneous catalysts for transesterification has seldom extended its evaluation to this combustion scale. This leaves a critical knowledge gap regarding whether catalysts used during biodiesel synthesis particularly when combined to induce synergistic effects alter the thermophysical properties and fundamental droplet burning characteristics of the produced fuel. To address this gap, the present study utilizes two catalyst configurations for soybean-oil transesterification: (i) a CaO-based catalyst derived solely from papaya leaves, and (ii) a synergistic CaO-based catalyst produced from a mixture of papaya leaves and animal bone, followed by a detailed single-droplet combustion analysis. This approach aims to elucidate how catalytic pathways shape droplet evolution, ignition behavior, and microexplosion tendencies, thereby providing new insights into the combustion-relevant implications of catalyst synergy.

2. Methods

2.1. Material

The biodiesel whose combustion characteristics were tested using the single droplet test was produced through the transesterification process of soybean oil with the addition of papaya leaf catalyst and a combination papaya leaf and animal bone catalyst. Soybean oil has strong potential as a biodiesel feedstock because its carbon-chain structure is similar to that of conventional diesel fuel [22]. Unlike diesel, which is composed mainly of hydrocarbons, soybean oil contains bound oxygen. This higher oxygen content enhances combustion completeness and contributes to lower exhaust emissions [23].

Soybean oil has a relatively low free fatty acid (FFA) content. The FFA content is only slightly higher than the standard for vegetable oils suitable for biodiesel production [24]. Therefore, a purification process called esterification is required to reduce the FFA content. Transesterification can then be continued with the addition of heterogeneous catalysts (papaya leaves and animal bones). These heterogeneous catalysts are rich sourced of calcium, which can be utilized as a cheap raw material for CaO production through calcination process. Calcium oxide (CaO) is among the most commonly utilized catalysts because of its advantageous physicochemical characteristics, such as strong catalytic performance, good thermal stability, and

straightforward recovery from the reaction mixture [13]. For comparison purposes, commercial petroleum diesel fuel (Pertamina Dex) was selected as a reference fuel.

2.2. Synthesis of Biodiesel

The synthesis of catalyst based on calcium oxide (CaO) obtained from calcium (Ca) of papaya leaf and animal bone. From Table 1 and Table 2, the most dominant content from both material is calcium. The calcination process used 800 °C for 3 hours leaves catalyst based CaO.

Soybean oil with high free fatty acid (FFA) content need to be treated through esterification process to reduce the FFA level by converting it into fatty acid methyl ester (FAME). Soybean oil was first heated to 60 °C and reacted with methanol and sulfuric acid for 90 minutes, followed by a 2-hour settling period to obtain a mixture of methyl esters and triglycerides. The heterogeneous catalyst was prepared by oven-drying, grinding, and calcining cleaned animal bones and papaya leaves at 800 °C for 3 hours, after which it was stored in an airtight container. In the subsequent transesterification process, purified soybean oil was heated to 65 °C, mixed with 6 wt% of the catalysts, and allowed to react for 120 minutes before the product was separated; the resulting methyl ester layer was washed three times and then heated to remove any remaining methanol and water.

Table 1. Papaya leaf content [25]

Mineral	Green Leaf (Mg/kg)	Yellow Leaf (Mg/kg)	Brown Leaf (Mg/kg)
Ca	8612.5	3762.5	4362.5
Mg	67.75	28.55	35.35
Na	1782	567	324
K	2889	819	468
Fe	90.5	147.5	79.5

Table 2. Animal bone content [26]

Atom	Value (%)	Atom Oxide	Value (%)
Al	1.60	Al ₂ O ₃	3.00
Ca	40.90	CaO	57.30
Fe	0.20	Fe ₂ O ₃	0.20
Mg	1.30	MgO	2.10
Na	0.80	Na ₂ O	1.00
P	14.40	P ₂ O ₅	33.00
Sc	0.40	Sc ₂ O ₃	0.50
Si	1.00	SiO ₂	2.20
S	0.10	SO ₃	0.20
Sr	0.10	SrO	0.10

2.3. Characteristic Biodiesel

Table 3 present several properties, including FAME content from the GC-MS test, Specific Gravity, Density, Lower Heating Value (LHV), and Cetane Number. The FAME content PL is lower at 95,08% of the total biodiesel oil compared to PLAB with an almost complete conversion of 98%. The relatively lower FAME content in PL can be attributed to incomplete triglyceride conversion during the transesterification process. **Table 4** also lists the five major FAME components detected with their boiling point. PL was dominated by methyl linoleate with a concentration of 28.40%, whereas PLAB was dominated by methyl linoleate at 43.69%.

For the specific gravity and density tests using Pycnometer, the results showed that PL was heavier than PLAB. The properties of petroleum diesel were taken from the Pertamina specification sheet. The higher density of PL indicates that this biodiesel has a higher viscosity. The calculation of Lower Heating Value using the Dulong equation modified by Hosokai et al. [27], as follows:

$$LHV = 38.2m_c + 84.9 \left(m_H - \frac{m_O}{8} \right) - \Delta H \quad (1)$$

Where m_c , m_H , and m_O represent the mass fractions of carbon, hydrogen, and oxygen, respectively. The value of ΔH refers to the latent heat, which varies depending on the physical state: 0 kJ/g for gas, 0.5 kJ/g for liquid, and 0.62 kJ/g for solid. The cetane number (CN) in this study was calculated using the empirical equation

proposed by Ramírez-Verduzco [28], as presented in Equation (2). Where, CN is the cetane number, M_i molecular weight of i th FAME, and N is number of double bond $C=C$.

$$CN = -7.8 + 0.302 M_i - 20 N \quad (2)$$

2.4. Single Droplet Experimental Setup

The illustration of single droplet experimental set up can be seen in **Figure 1** Vegetable-oil droplets were produced using a 1 ml insulin syringe (100 strips, 10 μ l per strip). Combustion tests were conducted at atmospheric pressure and ambient initial temperature, which was gradually increased to observe evaporation behavior. Flame temperature was recorded using a K-type couple connected to a data logger (Advantech USB-4718) at 1 kHz, with five sampling runs. Droplet and flame images were captured using a Nikon D3300 (60 fps), while bubble-growth and micro-explosion events were recorded using a Canon EOS 700D (60 fps). An acrylic chamber minimized airflow disturbances. Before measure-

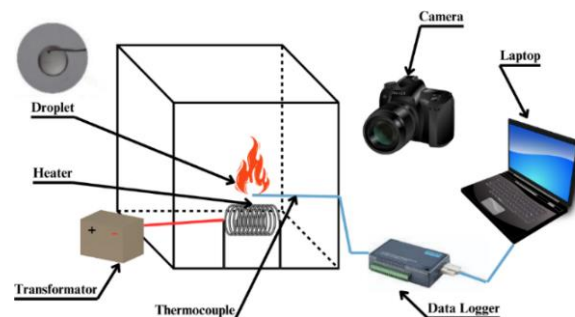


Figure 1. Single droplet experimental setup

Table 3. Properties of fuels

Properties	PL	PLAB	Petroleum Diesel
FAME Content (%)	95.08	98	-
Specific Gravity	0.918586	0.901285	0.809-0.849
Density (g/ml)	0.91956	0.90224	0.810-0.850
LHV (kJ/g)	38.054	37.921	-
Cetane Number	40.5	50.91	53

Table 4. FAME content

	FAME	Formula	Area (%)	Boiling point (°C)
PL	Methyl linoleate	C ₁₉ H ₃₄ O ₂	28.4	373 – 374
	Methyl elaidate	C ₁₉ H ₃₆ O ₂	24.83	382.1
	Methyl palmitate	C ₁₇ H ₃₄ O ₂	17.78	417
	Methyl stearate	C ₁₉ H ₃₈ O ₂	13.46	443
PLAB	Methyl linoleate	C ₁₉ H ₃₄ O ₂	43.69	373 – 374
	Methyl palmitate	C ₁₇ H ₃₄ O ₂	16.74	417
	Methyl eleostereate	C ₁₉ H ₃₂ O ₂	16.21	386
	Methyl stearate	C ₁₉ H ₃₈ O ₂	11.12	443

ments, the thermocouple was cleaned and the chamber set to room temperature. Recorded videos were converted into frames, and droplet evaporation analysis was performed using ImageJ software.

Figure 2 shown the procedure for droplet images processing refers to previous study [11], [16], [17], [19] using ImageJ software. The binarization process convert the digital image into a black and white format to separate the droplet from the background in image analysis. The thermocouple trimmed to get the droplet projection area, and the the droplet evolution measurement is obtained by determining the equivalent area. To calculate the diameter using Equation (3) and (4).

$$A = \frac{N}{a^2} \quad (3)$$

$$d = \sqrt{\frac{4a}{\pi}} \quad (4)$$

A represent the droplet projection area (mm²), N is the number of pixels, a is the area image pixel scale (pixels/mm), and d is the equivalent droplet diameter (mm). The method processing the droplet evolution graph as presented in Figure 3, was adapted from Rahman et al. [21]. The normalized diameter is expressed as Dt^2/Do^2 and the normalized evolution time is expressed as t/Do^2 . The uncertainty level of the droplet combustion measurements was evaluated based on five repeated experiments for each fuel sample (PL, PLAB, and petroleum diesel). The uncertainty levels of the droplet diameter and temperature (Table 5) were quantified solely based on statistical sampling. For each fuel sample, five repeated measurements were performed, from which the mean, standard deviation, and the 95% confidence interval were calculated using the T-statistic table value for small sample size. The detailed statistical parameters for all measured

variables are summarized in the corresponding table to ensure transparency and consistency between the uncertainty analysis and the presented results.

2.5. Mechanism of Droplet Evolution

The droplet evolution during single droplet combustion test divided into three phases as shown in Figure 3. These phases are important for understanding the evolution of droplet, which are transient heating, evaporation, and burning. Investigating each phase is important for understanding the effects of FAME content in biodiesel. According to Wang et al. [29], the duration of the transient heating phase begins when the normalized diameter size increases from 1 to a maximum. It is have same opinion with [30], where the initial heating process phase (transient heating) ends when there is a linear reduction in the surface area. Wang et al. [31] added that droplets in the transient heating phase, when no bubbles appear in them. It can be concluded that transient heating ends when which one of these two phenomena occur first. The first one, occurs when the droplet surface area decreases after thermal expansion. The second one, occurs when bubbles begin to form within the droplet. For example in PLAB (Figure 3) it happened when the first phenomena occur first, where the droplet reach maximum expansion with the normalized time (t/Do^2) in 2,457 s/mm² before it start to decrease. The evaporation phase occurs between the end of transient heating and the point of ignition in 4,837 s/mm². When droplet start at ignition point until the flame extinguished, it is called burning phase.

Table 5. Uncertainty level

Instruments	Uncertainty
Droplet Diameter	± 0.097
Thermocouple	± 0.995

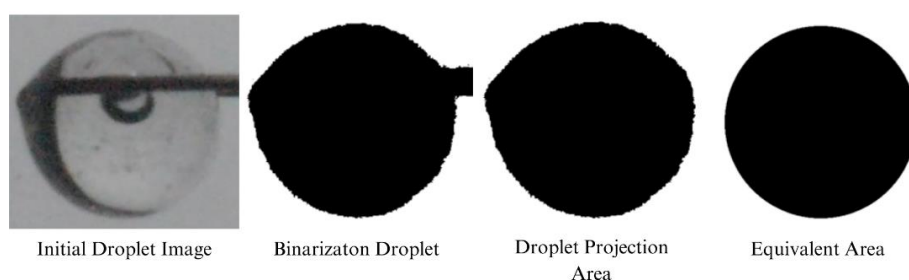


Figure 2. Image processing procedure

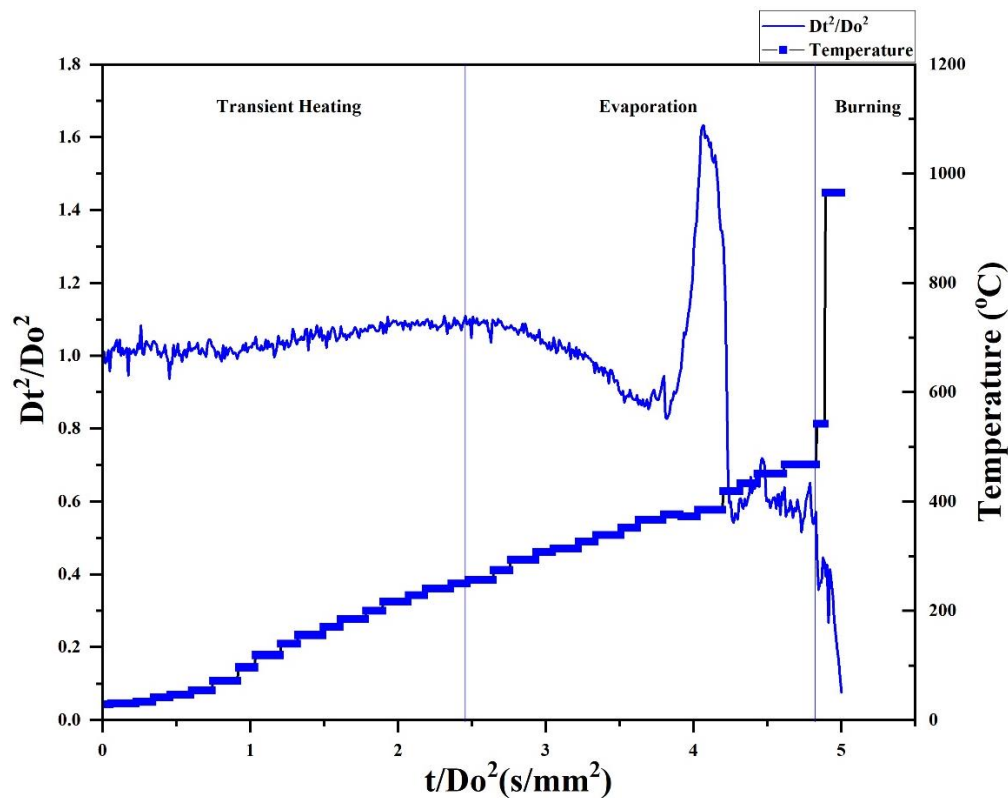


Figure 3. Droplet evolution of PLAB

3. Results and Discussion

3.1. Effect Catalyst on Droplet Evolution Behavior

Table 6 present the the time of every phase, including transient heating, evaporation, and burning. PL take the most longer time for transient heating, while PLAB and Petroleum Diesel are quite Similar. The addition of animal bones catalyst in transesterification reaction enhance the heat absorption of the biodiesel. The faster transient heating observed in PLAB compared to PL can be related to its higher proportion of unsaturated FAMES, particularly methyl linoleate. According to [32] methyl linoleate have good thermal conductivity, This indicates that methyl linoleate can effectively transfer absorbed heat throughout the droplet, thereby facilitating faster heating and evaporation. The higher content of methyl linoleate in PLAB (43.69%)

compared to PL (28.40%) thus explains its shorter transient heating phase and enhanced droplet volatility. Physically, density also influences the duration of the transient heating process leading affect the droplet lifetime. Table 3 showed the density of PLAB is lighter than PL, with a difference 0,017 g/ml. PL with higher density require higher energy to increase the droplet temperature, thus explain why it takes more duration to reach the evaporation phase. Based on the boiling-point distribution, PL exhibits a larger fraction of high-boiling compounds compared to PLAB. Specifically, PL contains 31.24% of components with boiling points above 400 °C, which is higher than the 27.86% observed in PLAB. In addition, PL has 53.23% of its components boiling in the 373–382 °C range, whereas PLAB shows 59.9% in the slightly higher range of 373–386 °C. The higher proportion of

Table 6. Comparative droplet evolution parameters

Parameter	PL	PLAB	Petroleum Diesel
Transient Heating duration (s/mm ²)	3.65	2.457	1.951
Evaporation duration (s/mm ²)	3.056	2.38	1.559
Burning duration (s/mm ²)	0.413	0.163	0.497
Evaporation Rate (mm ² /s)	0.1059	0.1833	0.1477
Droplet Lifetime (s/mm ²)	7.135	5.001	4.018

high boiling point in PL increases the temperature required for droplet to reach onset of active evaporation, thereby extending the heating period before evaporation phase occurs [33]. The shorter transient heating can lead to shorter droplet lifetime. As we can see in Figure 4, more faster transient heating in Petroleum Diesel and PLAB make the droplet lifetime much shorter than PL

In evaporation phase experience longer time for biodiesel, especially PL. Biodiesel consists of multiple FAME components with different boiling points, and this compositional variation leads to a delayed stabilization of the evaporation process, as the lighter components vaporize earlier while the heavier ones require longer heating [34], [35], [36]. Physically, density also influences the duration of the steady-state evaporation process leading affect the droplet lifetime. However, the difference in density between PL and PLAB is relatively small; therefore, density is not considered a major factor affecting the duration of the steady-state evaporation period. Nevertheless, the higher density of PL biodiesel makes it more difficult to atomize, which in turn hinders its evaporation compared to PLAB biodiesel.

3.2. Effect of Catalyst on Temperature

The results from Figure 5 indicate that the catalyst type significantly influences the ignition temperature of biodiesel droplets. Both PL and PLAB require higher temperatures to initiate combustion compared to petroleum diesel, reflecting the influence of FAME composition on fuel volatility based on their boiling point (Table 4). Among the biodiesel samples, PL exhibits the highest ignition temperature (546 °C), followed by PLAB (467 °C), while petroleum diesel ignites at the lowest temperature (254 °C). PL exhibits higher density (Table 3) leading to higher viscosity [37], which reduce internal heat and mass transport and hinder atomization factors that effectively raise the ignition temperature [38], [39]. PL have delaying vaporization and allowing more energy accumulation before complete combustion, thereby raising the peak temperature. Table 3 observed PL has higher LHV, which increased heat release leading to higher peak temperature [40]. This finding demonstrates that the incorporation of animal bone into the papaya leaf catalyst alters the FAME distribution in such a way that combustion initiation shifts to higher temperatures compared to PL alone.

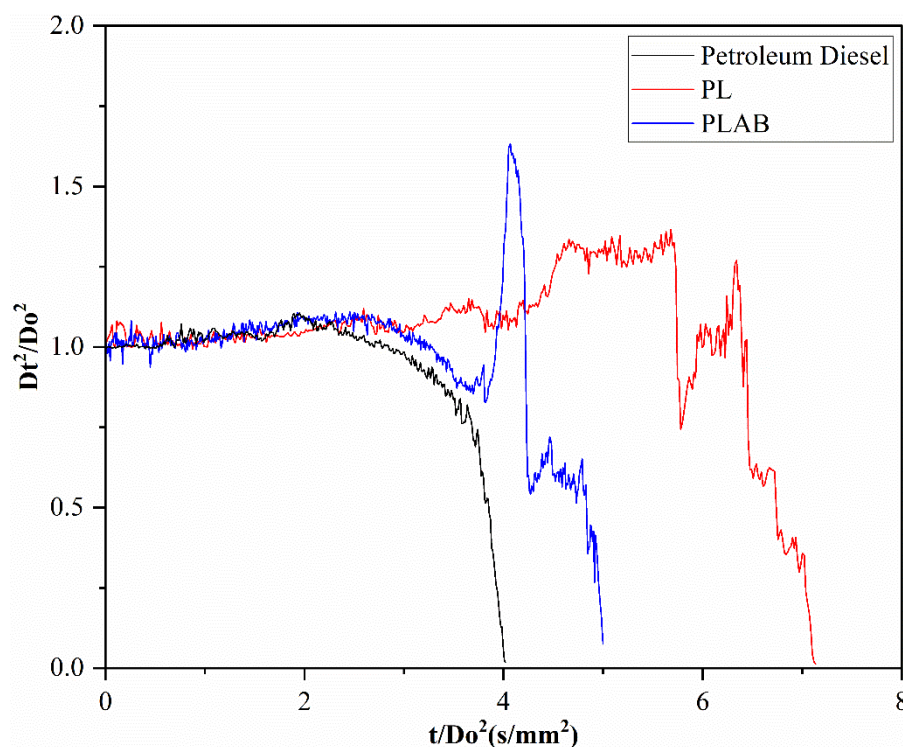


Figure 4. Droplet evolution of petroleum diesel, PL, PLAB

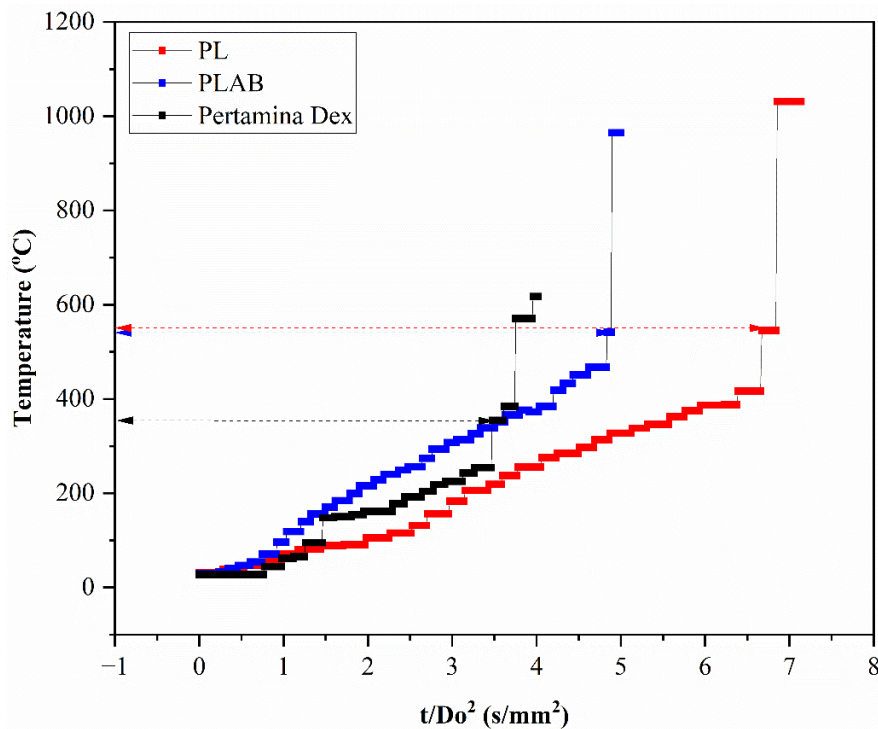


Figure 5. The evolution of droplet and flame temperature

3.3. Effect of Catalyst on Microexplosion

The evaporation phase include microexplosions (Figure 6) phenomenon that goes through three stages: nucleation, microexplosion, and shape recovery. In this study, the microexplosions phenomenon is divided into two categories: strong microexplosion and weak microexplosion. This is in line with the study of Wang et al. [31], where strong microexplosion is caused by the rupture of large bubbles due to homogeneous nucleation, where several small bubbles merge. The same surface tension and van der Waals forces in the composition between small bubbles cause homogeneous nucleation. A Strong microexplosion is triggered when the high volatile component has reached a superheated temperature but its evaporation is still resisted by the low volatile component. Strong microexplosion causes a significant reduction in droplet diameter. After a while, the high volatile component evaporates, leaving the low volatile component. The different compositions between small bubbles in the droplet cause different levels of surface tension and Van Der Waals forces that prevent several small bubbles from merging, which can be called heterogeneous nucleation.

Figure 7a and Figure 7b contain capture frames of microexplosion phenomena, which shows greater homogeneous nucleation at PLAB

compared to PL. The normalized diameter size of droplet during homogenous nucleation in PLAB is 1.60386 at 4,213 s/mm², while PL are observed smaller with 1.31641 at 5.698 s/mm² and 1.01643 at 6.425 s/mm². The boiling-point distribution of the FAME components strongly supports the microexplosion behavior observed in PL and PLAB droplets. PLAB contains a significantly higher fraction of the most volatile component, methyl linoleate (43.69%), which has the lowest boiling point (373–374 °C). The larger volatile fraction allows PLAB droplets to reach superheated conditions more easily, promoting the formation of multiple small bubbles with similar composition and intermolecular forces, which enhances homogeneous nucleation and leads to stronger microexplosions.

In contrast, PL contains a lower amount of methyl linoleate (28.4%) and a higher proportion of high-boiling components such as methyl palmitate and methyl stearate (totaling 31.24%). These heavier FAME components resist evaporation and inhibit bubble growth, making bubble coalescence less favorable and resulting in weaker microexplosion phenomena. Therefore, the FAME composition and boiling-point distribution in Table 4 directly explain why PLAB exhibits stronger microexplosions compared to PL.

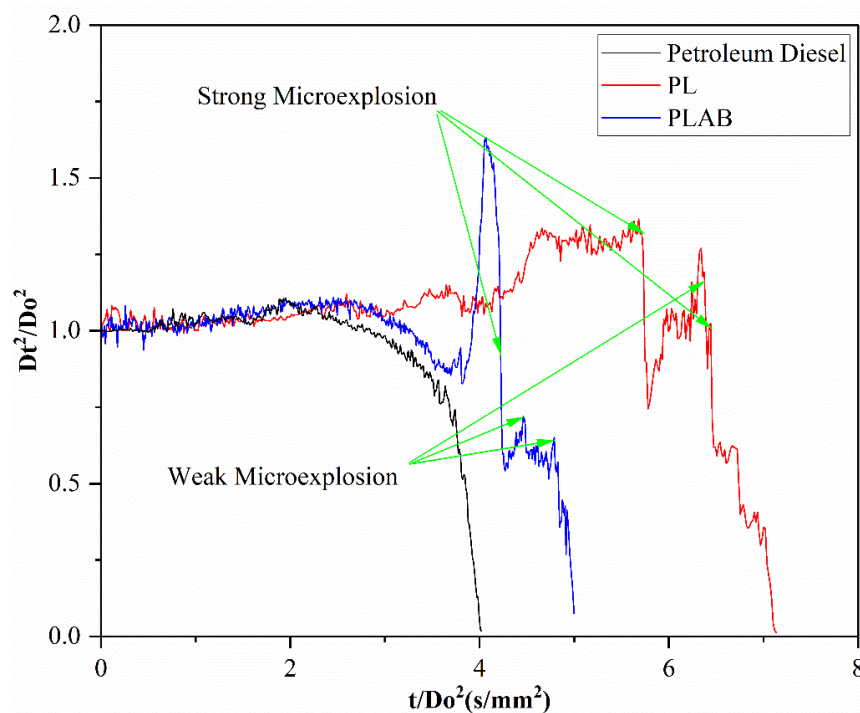


Figure 6. Microexplosion in Droplet Evolution

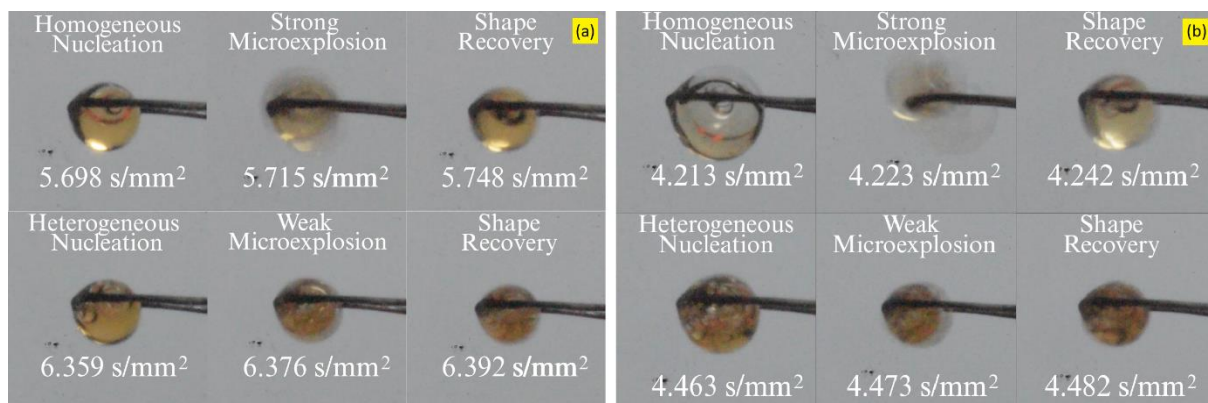


Figure 7. Microexplosion on PL (a), microexplosions on PLAB (b)

3.4. Effect of Catalyst on Ignition

The addition of a catalyst to the transesterification process can affect the ignition delay that occurs in biodiesel. Figure 8 presents the ignition delay of PL, PLAB, and Petroleum Diesel. For Petroleum Diesel have the shortest ignition delay followed by PLAB. The ignition delay in combustion is influenced by the fuel's cetane number [41]. The order of estimated cetane numbers from highest to lowest is Petroleum Diesel, PLAB, and PL, the higher the cetane number, the faster the combustion process and the shorter the ignition delay time [42], [43]. The boiling-point distribution strongly supports the difference in ignition delay observed between PLAB and PL. PLAB contains a larger fraction of low-boiling,

highly volatile components, particularly methyl linoleate (43.69%), compared to PL (28.40%). In addition, PLAB has a smaller proportion of heavy FAME species with boiling points above 400 °C (27.86%) than PL (31.24%). The higher volatile fraction in PLAB promotes faster vapor formation and reduces the heating time required for the droplet to reach an ignitable condition, resulting in a shorter ignition delay. Conversely, the higher content of high-boiling components in PL suppresses evaporation and delays the accumulation of vapor near the droplet surface, leading to a longer ignition delay. Therefore, the boiling-point distribution provides a clear explanation for why PLAB ignites more rapidly than PL. Another factor that influences ignition

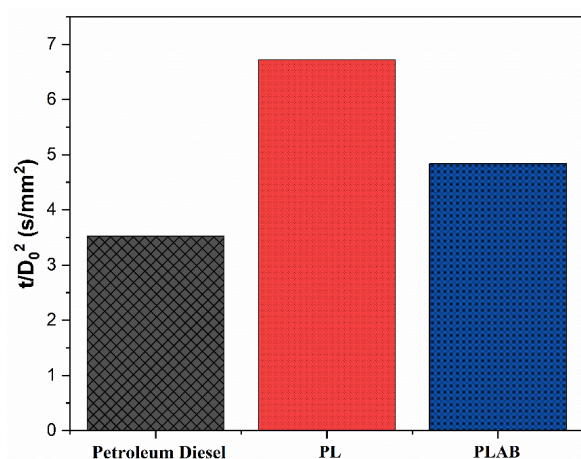


Figure 8. Ignition delay of petroleum diesel, PL, and PLAB

delay is its properties, such as density and viscosity. According studies from Esteban et al. [37], a good estimated viscosity can obtain from the measure of the density. From Table 3, we can conclude PLAB observed have lower viscosity than PL. The lower the density and viscosity of a biodiesel make it more volatile resulting in faster combustion [44].

4. Conclusion

This study identified the enhanced combustion characteristic of synergistic heterogenous catalyst from papaya leaf and animal bones catalyst in soybean oil based biodiesel, as confirmed by single droplet experimental setup. The unique contribution of this work lies in demonstrating how catalyst origin influences droplet combustion behavior, micro-explosion intensity, and ignition characteristics. Comparative fuel properties analysis between PL, PLAB, and Petroleum Diesel revealed lighter components, density, lower LHV, and higher cetane number in PLAB approaching Petroleum Diesel. These compositional and fuel-property differences correspond to the shorter ignition delay and droplet lifetime observed for PLAB relative to PL in the droplet combustion tests.

While the results indicate that catalyst modification using synergistic catalyst can improve the combustion quality of biodiesel, several limitations must be acknowledged. This study did not include direct measurements of key thermophysical properties such as viscosity and volatility are only estimated rather than experimental measured, and catalyst characterization techniques (e.g., XRD, FTIR,

SEM) were not performed. As a result, mechanistic interpretations based on viscosity, volatility, or catalyst structure should be considered indicative and not conclusive.

Future work should incorporate detailed catalyst characterization and direct measurement of thermophysical properties to validate the proposed interpretations and to further clarify how catalyst composition governs biodiesel combustion behavior.

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Author's Declaration

Authors' contributions and responsibilities

Haidar Hanief: Writing – review & editing, Writing – original draft, Formal analysis, Data curation.; Arya Radya: Original draft, Formal analysis; Mitsuhsa Ichianagi: Writing – review & editing, Investigation; Supervision; Willyanto Anggono: Writing – review & editing, Investigation; Cepi Yazirin: Validation, Formal analysis; Muhammad Akhlis Rizza: Review, Validation, Formal analysis; Ena Marlina: Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization, Investigation.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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