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The Effect of Alcohol Compounds on Droplet Combustion Characteristics of Unsaturated Fatty Acid of Linoleic Acid

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Abstract

Alcohol compounds have become a popular choice as additives for improving the performance of biodiesel. However, given the complexity of biodiesel, which is composed of various components of vegetable oil, it requires intensive research to fully understand its behavior. This study aims to investigate the impact of alcohol compounds on the droplet combustion characteristics of linoleic acid, an unsaturated fatty acid. Four alcohol compounds, namely methanol, ethanol, propanol, and butanol, were utilized to evaluate their effects on the combustion properties of the fuel mixtures. The droplet combustion characteristics were observed under normal atmospheric pressure and temperature conditions, with the fuel mixture consisting of 80 % linoleic acid and 20 % alcohol compounds. Our findings indicate that the addition of alcohol compounds to linoleic acid significantly reduced the ignition delay time, although the droplet lifetime was slightly increased. Moreover, it was observed that alcohols with shorter carbon chains had a greater impact on reducing the ignition delay time. Additionally, the results demonstrated that the alcohol compounds could accelerate the rate of increasing combustion temperature, reduce soot formation, and shorten the duration of soot formation. Furthermore, it was found that alcohol with a short carbon chain had a more pronounced effect on the overall combustion characteristics of linoleic acid. Overall, our study sheds light on the effects of alcohol compounds on the droplet combustion characteristics of linoleic acid, providing valuable insights for the optimization of biodiesel performance.

Keywords: Linoleic acid, Unsaturated fatty acid, Droplet combustion, Alcohol compounds, Methanol, ethanol, Propanol, Buthanol

Nomenclature

FA: Fatty Acid	LiA-M: Linoleic Acid + Methanol
FAME: fatty acid methyl ester	LiA-P: Linoleic Acid + Propanol
LiA: Linoleic Acid	D: final droplet diameter (mm)
LiA-B: Linoleic Acid + Buthanol	D_0: initial droplet diameter (mm)
LiA-E: Linoleic Acid + Ethanol	t: burning duration (s)

Introduction

The limited availability of traditional energy resources highlights the urgent need for the development of sustainable and eco-friendly alternatives [1]. One promising candidate is biodiesel produced from vegetable oil. Many plant species can yield seeds for vegetable oil production, and biodiesel offers several advantages over fossil oil, including being renewable, non-toxic, and environmentally friendly, with a high cetane number and low sulfur content [2,3].

Despite its many benefits, biodiesel still has some drawbacks that make it inferior to diesel fuel. Its high viscosity and flame temperature, low heating value, low burning rate, and long ignition delay are among its main weaknesses. High fuel viscosity can reduce engine power due to a lack of atomization [4], while it can also negatively affect the engine injection pump and injector, preventing the proper atomization of fuel in the combustion chamber and leading to the production of difficult-to-burn fuel droplets [5]. Low

burning rates and long ignition delays can also negatively impact engine performance. Therefore, it is crucial to improve the quality of biodiesel to ensure its use in diesel engines without any necessary modifications.

Several attempts have been made to address the quality issues of biodiesel by incorporating additives such as essential oils [6], and alcohol compounds [7,8]. It was reported that the addition of ethanol to oil biodiesel can increase the evaporation rate, thus shortening the physical delay [8]. The addition of ethanol in single fatty acid also increases the burning rate of the fuel mixture with a higher peak temperature in fuel mixture compared to the base fuel [7]. Literature also reports that alcohol compounds' addition to biodiesel can enhance its performance, calorific value, and flash point while reducing its viscosity and improving engine performance [9]. The combustion and emission characteristics in CI engines fueled with biodiesel-methanol [10], and diesel-biodiesel-ethanol [11], also have been studied. Mixing biodiesel with methanol reduces the ignition delay time and CO emissions but promotes HC and NO_X emissions [10]. While adding ethanol in diesel-biodiesel blends reduces emissions of NO_X and smoke, also prevents emissions of CO and HC at higher loads. These studies give much information on the effect of adding alcohol compounds on biodiesel. However, of the numerous available alcoholic compounds, only methanol and ethanol are typically used in biodiesel blends. There is a lack of information on other types of alcohol that can serve the aforementioned purposes. Although methanol and ethanol can enhance some of the combustion properties of biodiesel, their low heating value leads to a decrease in the heating value of the biodiesel mixture due to the limited number of carbon atoms in their chemical structure. Therefore, exploring the use of alcohols with a higher calorific value (containing more carbon atoms), such as butanol, propanol, and others, to enhance the properties of biodiesel is an interesting avenue to explore.

Biodiesel, which is derived from vegetable oils from different plants, has varying compositions of fatty acids (FA) with unique physical and chemical properties that can affect its combustion characteristics. Before considering the use of alcohol as an additive in biodiesel, it is essential to comprehend the properties of vegetable oil, the primary ingredient in biodiesel, since alcohol can have distinct effects on each component of vegetable oil. The impact of ethanol, an alcohol, on saturated FAME is distinct from its effect on unsaturated FAME [12].

Fatty acids (FAs) are organic compounds made of hydrocarbon chains linked by carboxyl groups (COOH). The structure of a fuel molecule is determined by the length and degree of saturation of its carbon chain [13]. Fatty acids can be classified as saturated or unsaturated based on their hydrocarbon content. Saturated FAs contain a carbon chain with single bonds (C-C), while unsaturated FAs have one or more double bonds (C=C) [14]. All FAs and esters contain a carbonyl group as a C=O double bond. The alkyl ester has 2 C-O single bonds, while the FA has 1 C-O single bond and 1 O-H bond [15]. The physical and chemical properties of FAs, such as the presence of double bonds, chain length, position, the geometry of trans configurations of double bonds, and branching of alkyl groups in the FA chain, affect the properties of biodiesel. It has been observed that biodiesel's density increases when composed of FAs with long hydrocarbon chains and double bonds. The high density of biodiesel can affect the atomization process, evaporation, and combustion process [16]. Studies have shown that the geometric structure, boiling point, total number of carbon atoms and double bonds in FAs significantly affect the combustion characteristics of biodiesel or vegetable oils [12,17,18]. Highly saturated FAs generally have higher droplet combustion temperature, flame dimension, constant burning rate, and specific power output, but lower ignition delay and burning duration. Unsaturated FAs tend to form soot particles above the flame and lead to a larger flame dimension [12].

The physical and chemical properties of biodiesel fuel are influenced by the constituent fatty acid (FA). Among the parameters that affect the combustion characteristics of biodiesel, the total distribution and degree of unsaturation in the FA structure have the greatest influence. However, because biodiesel is composed of various components with different properties, it is difficult to attribute the properties of the fuel to a single dominant component [17]. The properties of each FA compound interact with each other, making it necessary to conduct further research on individual FAs in biodiesel to compare their effects on droplet combustion characteristics. Understanding the combustion characteristics of biofuels is crucial for their use in existing engines. Therefore, it is essential to study the combustion characteristics of individual or mixed FAs as constituents of biodiesel. A comprehensive understanding of the effects of FA molecular structure and composition in biodiesel fuel will lead to the production of higher-quality biodiesel products in the future [20].

Diesel engines use a diffusive combustion process for droplets sprayed through the nozzle. To better understand this combustion process, researchers have conducted numerous studies on single droplet combustion, including [12,13,21]. However, previous studies did not typically investigate the impact of alcohol additives on the combustion of individual compounds that make up biodiesel. While some studies

have explored the topic, they typically focused on the effects of ethanol or methanol as additives on biodiesel, which is a complex mixture of fatty acid methyl esters (FAME). This study aims to fill this gap by examining the combustion characteristics of saturated and unsaturated single fatty acids (FA) with the addition of different alcohol compounds. Specifically, the study focuses on the droplet combustion characteristics of linoleic acid, an unsaturated essential FA, with the addition of 4 alcohol compounds: methanol, ethanol, propanol, and butanol. Linoleic acid was chosen as it is the dominant FA in several oils for biodiesel such as rubber seed oil (39.6 wt%), soy oil (56 wt%), and jatropha oil (39.9 wt%) [22]. The study measures various parameters, including droplet lifetime, burning rate, ignition delay time, flame size, droplet diameter, and droplet temperature history. The results provide new insights into the effects of alcohol additives on the combustion of unsaturated linoleic acid.

Materials and methods

Materials

The study used Linoleic FA (Li) as the base fuel. It is an unsaturated fatty acid with 18 carbon chains, as shown in **Figure 1**. The molecule has a bent structure due to the presence of a cis double bond on the ninth carbon chain. For the experiment, Li was mixed with 4 different alcohol compounds (methanol, ethanol, butanol, and propanol) at a mass ratio of 80:20 (Li: Alcohol). A magnetic stirrer was used to blend the fuel mixtures, resulting in 5 different fuel blends: Linoleic FA (LiA), Linoleic + Methanol (LiA-M), Linoleic + Ethanol (LiA-E), Linoleic + Butanol (LiA-B), and Linoleic + Propanol (LiA-P).

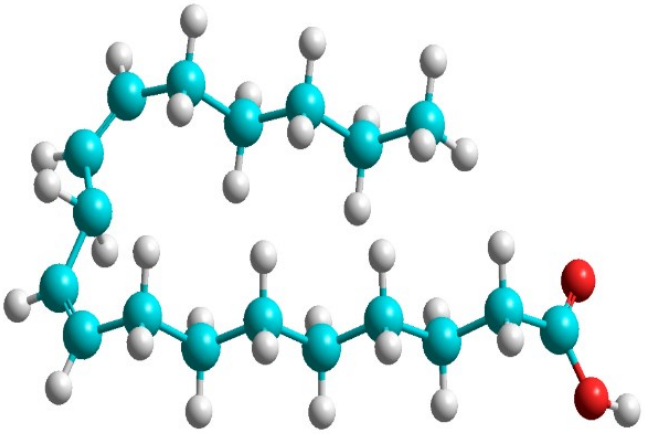

Figure 1 Molecular structure of linoleic acid.

Experimental setup and method

The experimental setup depicted in **Figure 2** was utilized to conduct the observation at room temperature (approximately 30 °C) and atmospheric pressure. A single isolated droplet combustion method was employed for the droplet combustion test. A micro syringe with a 10 µL volume was used to form fuel droplets of 1.8 ± 0.05 mm diameter at the tip of a thermocouple. An R-type thermocouple (Pt-Rh 13 %, f = 0.2 mm) was used to hold the droplets during observation and measure their temperature history. An electric heater placed 3 mm beneath the droplet was used to ignite the fuel droplet at a heating temperature of around 720 °C. The 50W power supply was immediately turned off after the droplets had ignited to avoid any impact of the heater heat on the temperature data. The temperature history of the droplets was acquired by connecting the thermocouple to the data acquisition module and storing the data on a PC. The droplet combustion observations were carried out in a chamber to eliminate any impact from the surrounding airflow during the test.

To further analyze the results (droplet evolution, flame evolution, and soot formation), 2 digital cameras were used to record the droplet combustion phenomena and droplet diameter evolution. The cameras were set to a frame rate of 60 fps and a resolution of 1,920×1,080 pixels. The same video capture technique used in prior studies [23], was employed for the droplet combustion test. Five samples of each fuel mixture were tested, and the standard deviations of the averaged data were used to calculate error bars on the ignition delay and droplet lifetime curve. All the droplet and flame phenomena were analyzed using Image-J software.

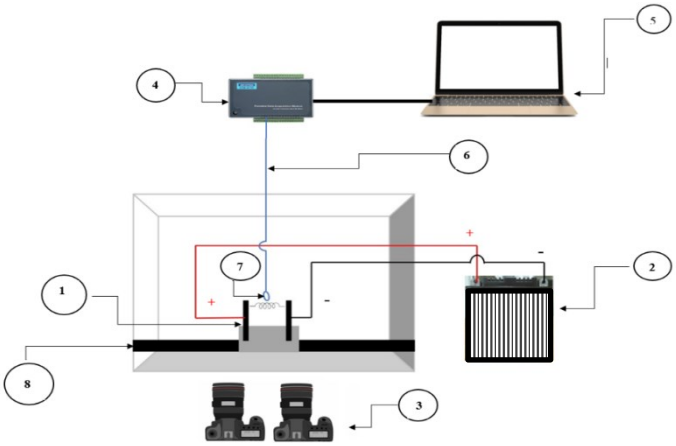

Figure 2 Experimental setup.

Results and discussion

Influence of alcohols on ignition delay time and droplet lifetime

The ignition delay time is a critical parameter in diesel engines, representing the duration between the initial exposure of a droplet to high-temperature surroundings and the occurrence of the initial flame [24]. This delay can be subdivided into physical and chemical delays. The physical delay encompasses the time required for fuel evaporation, molecular diffusion, and air-fuel mixing. During this phase, the fuel is atomized, vaporized, mixed with air, and heated to ignition temperature. Fuel viscosity plays a significant role in this stage, with lower-viscosity fuels having shorter ignition delays. On the other hand, chemical delay relates to the chemical reactions that happen before the air-fuel combustion process, leading to the formation of the reactive radical population necessary for a local homogeneous mixture's thermal explosion. During this period, the fuel's chemical composition, particularly the ratio of species with low volatility, is crucial [25]. While mixtures with high evaporation rates reduce physical ignition delay, those with limited chemical stability reduce chemical ignition delay [26]. High surface tension and boiling point of the fuel are additional contributing factors to prolonged ignition delay times [23].

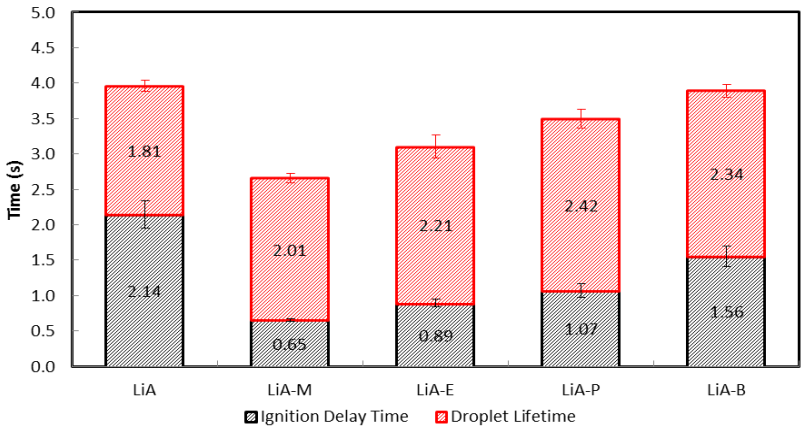

Figure 3 Ignition delay and droplet lifetime.

The ignition delay time is a critical stage in the droplet combustion process, where the fuel droplet undergoes a transient heating phase causing thermal expansion and bubble nucleation. **Figure 3** displays the ignition delay time for fuel mixtures containing linoleic acid and alcohol compounds (methanol, ethanol, butanol, and propanol). The results indicate that adding alcohol molecules to linoleic acid can decrease the ignition delay time of the combustion process. It can be observed that the addition of alcohols can reduce the ignition delay time of the fuel from 2.1 to 0.65 s (methanol), 0.89 s (ethanol), 1.07 s (propanol), and

1.56 s (buthanol). Alcohol compounds with low viscosity and high volatility tend to ignite sooner. Short carbon chain compounds break intermolecular bonds more easily, resulting in a quicker evaporation process that requires less heat energy. The fuel mixture's homogeneous nucleation further supports the evaporation process, reducing the ignition delay time by forming large bubbles that increase the internal pressure inside the droplet. This encourages the diffusion of fuel vapor to the droplet surface, where it mixes with the surrounding air to generate a flammable substance.

As an oxygenated additive, alcohol increases the air-to-fuel ratio, thereby improving combustion performance. This increase is evident in a decrease in ignition temperature, an increased probability of ignition, and a shorter ignition delay. **Figure 3** illustrates the effect of alcohol additives in reducing ignition delay time, with shorter carbon chain alcohols having a more significant impact. The fuel mixture containing linoleic acid and methanol (LiA-M) has the shortest ignition delay time among the tested mixtures. Low viscosity and surface tension of methanol improve the atomizing behavior of blended fuels and make the ignition earlier. Conversely, the sample with n-butanol has the longest ignition delay time due to its long carbon chain and lower volatility.

The ignition delay period in the combustion process ends when the ignition point temperature is reached, marking the start of the droplet lifecycle stage. The droplet lifetime also referred to as the burning lifetime, is the time taken for a droplet to burn out or the time interval between the beginning of the flame and when it begins to burn out [24]. Droplets with high evaporation rates form gas mixtures for the next combustion stage more readily, resulting in a shorter droplet lifetime. The presence of micro explosions during droplet combustion also reduces the droplet's lifetime [26]. Fuel mixtures with high alcohol concentrations experience micro explosions due to homogeneous nucleation, promoting secondary droplet ejection that significantly shortens the overall droplet lifetime.

During this stage, the fuel evaporation process continues, accompanied by the consumption of fuel vapor, resulting in a flame. However, observations show that the droplet combustion of the basic fuel (LiA) has a shorter droplet lifetime than that of droplets mixed with alcohol. This result is related to the longer ignition delay time in the Li droplet combustion process. When the ignition delay time is long, the more fuel burns in the partial premix mode, resulting in a shorter droplet lifetime in the diffusion mode [27]. In contrast, the use of alcohol additives leads to a relatively short ignition delay time, promoting a longer diffusion combustion mode in fuel mixtures. This result is evident when comparing the droplet lifetime between Li and all variations of fuel mixtures (LiA-M, LiA-E, LiA-P, and LiA-B) (**Figure 4**).

The diffusive combustion of fuel mixtures (linoleic acid + alcohol) typically results in a shorter overall combustion time (ignition delay time + droplet lifetime), as evidenced by the combustion of LiA-M, LiA-E, and LiA-B. Generally, the droplet lifetime of the fuel mixtures increases as the carbon chain length of the alcohol additive increases. However, the droplet lifetime decreases when n-butanol is added compared to 2-propanol. As explained earlier, the ignition delay time of the n-butanol additive is much longer than the other 3 alcohol additives, which encourages a partial premix combustion mode. Consequently, when the ignition delay period ends, there is less remaining fuel droplet liquid phase, leading to a shorter droplet lifetime. It is important to note that the burning rate of droplet combustion is affected by both the droplet lifetime and ignition delay time.

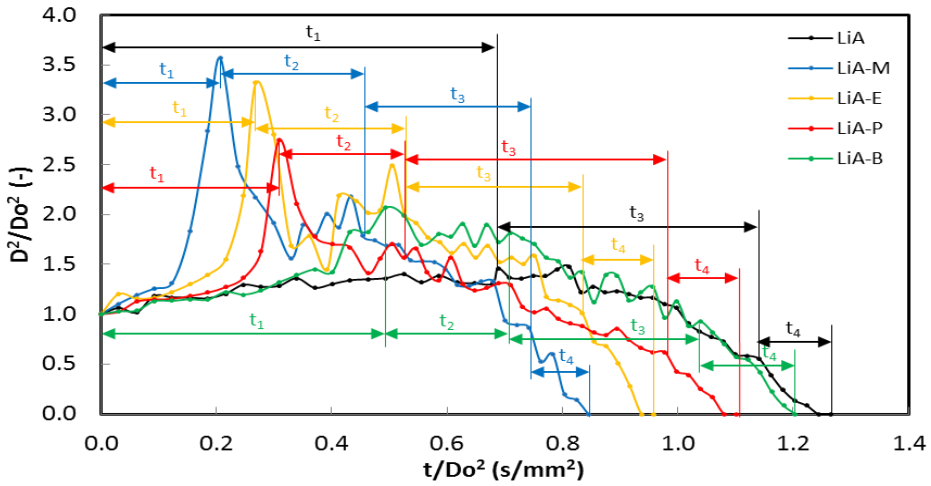

Figure 4 Correlation of normalized droplet diameter squared vs. normalized time.

Evolution of droplet diameter

Figure 4 illustrates the changes in droplet diameter that occur during linoleic acid combustion, with t1 representing the heating stage, t2 representing the micro explosive combustion stage, t3 representing the unstable combustion stage, and t4 representing the quasi-stable combustion stage. During the heating stage, the droplet's diameter slowly increases as heat is absorbed from the heater, leading to bubble nucleation and thermal expansion. This stage is characterized by the diffusion of fuel vapor to the droplet's surface and is not accompanied by fuel consumption. As a result, the droplet tends to increase in size, reaching its maximum diameter around the ignition point temperature.

Following the heating stage, the droplet's diameter decreases due to fuel consumption by the flame. The maximum thermal expansion (D^2/D_0^2) max on the base fuel, LiA, is lowest compared to the fuel mixture due to the slow bubble nucleation rate, with a value of 1.479. In contrast, the fuel mixture's high bubble population from earlier alcohol rise promotes high thermal expansion. Methanol's high volatility, among other factors, causes the highest value of thermal expansion in LiA-M, with a (D^2/D_0^2) max value of 3.570. When longer alcohol carbon chains are used as additives, the thermal expansion decreases due to the smaller boiling point difference between the base fuel and the alcohol. **Figure 4** compares the droplet evolution of LiA-B and LiA.

After reaching the ignition point temperature (t3), the base fuel enters the unsteady combustion phase, during which it burns. This stage is characterized by a slow reduction in droplet size due to the large droplet volume and small surface-to-volume ratio, which requires a longer diffusion time. The droplet diameter experiences fluctuations with less significant reductions because many bubbles are still trapped in the droplets.

An additional phase called the micro explosive combustion stage (t2) occurs when alcohol additives are added, and the fuel mixture reaches the ignition point temperature. A bluish flame and the ejection of child droplets around the primary droplet mark this stage. The intensity of child droplets during this stage is an essential aspect to consider. The main droplet volume splits into smaller-sized droplets, which burn simultaneously in a relatively short time if the ejection intensity is high. Child droplet ejection effectively improves the combustion rate because small droplet sizes have a larger surface-to-volume ratio. The t2 period is shorter as the carbon chain length of the alcohol increases, with LiA-B having the shortest t2 period among other fuel mixtures due to its higher boiling point. As a result, when linoleic acid burns with n-butanol, the intensity and power of the micro explosions decrease.

After the micro explosive combustion phase at the beginning of combustion, the droplet combustion process enters the unsteady combustion stage (t3), which follows the t2 period. This stage is characterized by a rapid combustion rate due to droplet fragmentation, resulting in a shorter duration for the t3 period of the fuel mixture combustion. The transition from t3 to t4 occurs as the droplet size decreases. The rate of diameter decrease of the droplet is faster during the quasi-steady combustion stage (t4) due to the increase in the surface-to-volume ratio of the smaller droplet volume. This leads to an increase in fuel diffusion into the air, resulting in a considerable rise in droplet temperature until it reaches the peak temperature at the end of combustion, as shown in **Figure 5**. At smaller droplet volumes, fuel vapor transport from the droplet center to the droplet surface becomes easier, resulting in fewer bubble populations and a more linear droplet diameter evolution curve.

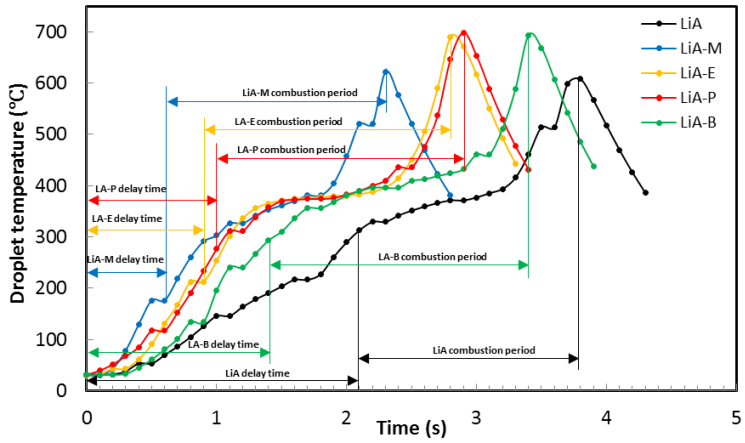

Figure 5 Droplet temperatures during the combustion of linoleic acid with the addition of alcohol compounds.

Temperature history of droplet

When exposed to a hot environment, a droplet absorbs a significant amount of heat from high-temperature gas molecules, which causes its surface temperature to rise sharply. At the boiling point, the droplet evaporates, and the gasification process begins in each fuel component [28]. The combustion process in a droplet starts with the droplet evaporating and occurs at the point where the diffusion of oxygen into the droplet and the diffusion of fuel vapor from the droplet surface reach equilibrium. The occurrence of a reaction on the outside of the flame at a specific distance from the droplet identifies this equilibrium stage [29]. **Figure 5** illustrates the temperature history of a burning linoleic acid droplet as a base fuel. The droplet temperature increases linearly during the ignition delay stage due to heat absorption from the heater. This process continues until the temperature exceeds the ignition point and the transient heating step finishes. During combustion, the droplet temperature is mainly affected by the flame, particularly in the non-luminous flame zone.

Heat absorption in the fuel mixture droplet drives the temperature of the alcohol as the mixture with higher volatility rises more rapidly. When the droplet of the fuel mixture's temperature curve reaches the ignition point, it exhibits a curve break with a faster temperature-increasing rate that takes place during the micro explosive combustion phase. As stated in the previous discussion, during this time, the combustion rate increases and encourages greater fuel consumption which, in turn, increases droplet temperature. When entering the unsteady combustion phase, there is no significant increase in droplet temperature because there is thermal equilibrium with the surrounding environment. When the base fuel reaches the temperature of the ignition point, there is no micro explosion period. Therefore, the droplet temperature does not significantly increase as it does at the beginning of the mixed fuels combustion process. The droplet temperature augments as the droplet volume decrease, and the combustion rate increases again under these conditions. The droplet's peak temperature is reached at the end of combustion when the fire goes out because the droplets are getting thinner, and the flame is in direct contact with the sensor at the thermocouple junction.

According to Zhu *et al.* [30], the temperature of a fire is influenced by various factors, such as the heating value of the fuel, the rate at which it burns, and the amount of heat lost through radiation from gas and soot in the flame. One way to lower the heating value of the fuel is by adding alcohol component, which have a lower calorific value than the base fuel. However, the combustion rate can increase with alcohol as an additive, leading to higher heat generation and droplet temperature. It is observed that using alcohol as an additive can create an optimal balance between the contradictory effects of alcohol, where the burning rate increases, causing the temperature to rise rapidly. Thus, the peak temperatures of the fuel mixtures (LiA-M, LiA-E, LiA-P, and LiA-B) are higher than the base fuel (LiA). The measurement results of the combustion peak temperature of basic fuel (LiA) = 607.87 °C, while LiA-M = 622.43 °C, LiA-E = 690.13 °C, LiA-P = 698.42 °C, and LiA-B = 693.36 °C.

The addition of oxygenate compounds to biodiesel fuel has a disadvantage in that their heating value is lower than that of biodiesel alone. This means that a greater amount of fuel is required to generate the same output power when oxygenate molecules are present [31]. However, the addition of oxygenated substances, such as alcohol, can lower the ignition temperature and shorten the ignition delay time, which can increase the likelihood of ignition occurrence and accelerate the combustion of the fuel droplets [32]. Since alcohol is more volatile than biodiesel, it can be used in conjunction with biodiesel to enhance disintegration and promote faster fuel combustion. This, in turn, is expected to lead to earlier ignition in a compression ignition engine, allowing for a more consistent combustion process.

Influence of alcohols on flame evolution

Figure 7 plots the evolution of flame dimensions against the normalized droplet lifetime for a mixture of linoleic acid and alcohol droplet combustion. As the burning period increases, the flame dimensions elongate vertically. An increase in flame diameter caused by the heating of the droplets and the accumulation of fuel vapor around the droplet surface during the ignition delay period marks the initial stages of droplet combustion. The height of the flame is directly proportional to the amount of soot that forms during droplet combustion [33]. Therefore, the combustion of unsaturated molecules such as linoleic acid likely results in soot formation (as in **Figure 7**). Since soot generation occurs regularly and simultaneously during linoleic acid combustion, the soot accumulation leads to variations in the size of the flame.

The size of the droplet combustion flame is inversely related to the burning rate. The best circumstances for combustion occur when the flame is near the droplet and more oxygen is available [24]. Our study's findings are consistent with this tendency. We found that alcohols, which contain more oxygen than linoleic acid, shorten the flame. Specifically, methanol, ethanol, 2-propanol, and n-butanol contain

49.93 weight percent, 34.73 weight percent, 26.62 weight percent, and 21.58 weight percent oxygen, respectively. **Figures 6** and **7** show the effect of adding alcohol on flame characteristics. Soot forms later and over a shorter period when more oxygen is present in the fuel mixture due to the addition of alcohol. Soot formation can be observed visually through video recordings of the flames, as it appears as a dark color at the flame tip. During the droplet combustion of LiA, we observed soot formation earlier in 0.596 of the droplet's lifetime. In the droplet combustion of LiA-B, soot formation was further delayed with a formation time of 0.492 of the droplet's lifetime. Successively, the soot formation period was shorter in the burning of LiA-P, LiA-E, and LiA-M (**Figure 6**). LiA-M had the shortest soot generation duration, which was only 0.339 of the droplet's lifetime. This finding demonstrates that the higher the oxygen concentration in the fuel mixture, the later the development of soot and the shorter the formation period. Increasing the oxygen concentration in the fuel mixture also promotes the diffusion of fuel vapor with air at a lower area close to the droplets, resulting in shorter average flame dimensions than in the LiA combustion case.

Droplet combustion is a form of diffusion combustion that produces a yellow flame. Flame visualization techniques can provide a quantification of the intensity of soot production during combustion. **Figure 7** depicts the fundamental flame properties of a linoleic acid and alcohol mixture. Due to the buoyancy effect, the bright non-luminous flame zone in the LiA case shows the early production of soot precursors, which eventually float away and accumulate towards the flame tip. These precursors and soot aggregates form between the droplet surface and the flame front, rising upwards due to natural convection, resulting in significant soot concentrations at the top of the flame [31]. Under normal gravity, burning droplets produce soot particles at the flame's tip due to natural convection [34]. A bright yellow flame indicates the presence of soot development with increased radiation intensity. As alcohol does not produce soot under normal air conditions (stoichiometric or reach mixtures), the alcoholic component addition decreases the radiation intensity. Alcohol can limit particle emission by reducing the number and size of primary particle aggregates [35]. The addition of alcohol reduces the size of the fire, causing the combustion region to close around the droplets. Additionally, as demonstrated in **Figure 6**, alcohol helps reduce soot formation.

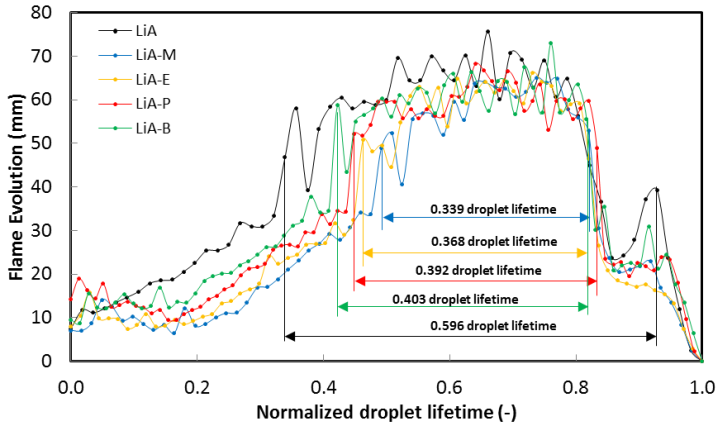

Figure 6 Evolution of flame dimension and soot formation zone.

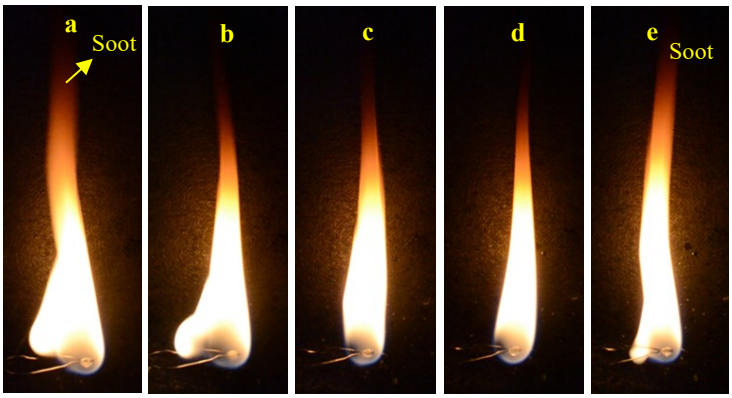

Figure 7 Flame visualization a) LiA, b) LiA-M, c) LiA-E, d) LiA-P, and e) LiA-B.

Conclusions

We conducted an experimental investigation on the effect of alcohol's addition on the droplet combustion of linoleic acid. We can draw the following conclusions from the findings of this study;

1) In general, adding alcohol as an additive can reduce the overall period of combustion processes in fuel mixtures, making them shorter than the base fuel. Methanol is the most relevant alcohol component in reducing ignition delay time. According to the findings, alcohol with a short carbon chain is more effective at ignition delay reduction. It can be identified that the addition of alcohols can reduce the ignition delay time from 2.1 to 0.65 s (methanol), 0.89 s (ethanol), 1.07 s (propanol), and 1.56 s (buthanol). However, adding alcohol molecules to linoleic acid somewhat enhances the droplet's lifetime. It is because of the extended ignition delay time.

2) The behavior of droplet diameter evolution is also affected by the existence of alcohol molecules. The methanol compound significantly impacts the evolution behavior of fuel droplets, while butanol plays a minor contribution.

3) The addition of alcohol molecules has a substantial effect on the temperature history of the combustion. The alcohol compounds can accelerate the rate of increase in temperature of the base fuel. Methanol compounds had the most significant effect in accelerate the temperature increase but resulted a lower maximum temperature. Meanwhile, ethanol, propanol, and buthanol can increase the temperature acceleration and also result a higher maximum temperature.

4) The addition of alcohol compounds reduces the dimensions of the fire so that the combustion area tends to be closed around the droplets. The addition of alcohol compounds is also able to reduce the formation of soot from combustion. The higher the oxygen concentration in the fuel mixture due to the addition of alcohol, the more it can delay the start of soot formation and shorten the time interval for soot formation. The duration of soot formation of base fuel is about 0.6 of the total droplet burning time (droplet lifetime), after adding alcohols it becomes less than 0.4 of the droplet lifetime.

Further research is necessary to investigate on the droplet combustion characteristics of saturated essential FA, with the addition of alcohol compounds. Thus, the effect of adding alcohols to the biodiesel component will be well understood and can be used as a reference in biodiesel production.

Acknowledgements

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