Experimental investigation on the effect of carbon chain length to the droplet combustion characteristic of fatty acid methyl ester

Ibrahim Ahmad Ibadurrohman*, Nurkholis Hamidi, Lilis Yuliati, Benedict Amadeus Valentino

Mechanical Engineering Department, Brawijaya University
MT Haryono 167, Lowokwaru, Malang 65145, Indonesia
*Email: ibad_ahmad@student.ub.ac.id

Abstract. Biodiesel which produces from vegetable oil consists of various fatty acids as fatty acid methyl ester constituent. Each fatty acid has a specific combustion characteristic due to the difference in physicochemical characteristics. This study was done with a single fatty acid methyl ester from various saturated fatty acids to analyze the effects of carbon chain length on the droplet combustion during the evaporation and combustion stages in ambient temperature and atmospheric pressure. Results show that the ignition delay time increase with the longer carbon chain due to the higher viscosity and boiling point. The higher oxygen content in the fatty acid methyl ester molecule promotes the faster combustion, gives a higher burning rate, and cause the flame dimension shorter. Furthermore, oxygen content results in higher radiation caused a brighter flame. The high droplet temperature occurs in the long carbon chain due to the higher of combustible matter gives an increase to the heating value. Low radiation heat loss in a long carbon chain which indicates by the flameless bright also causes the droplet temperature higher. The higher droplet temperature gives the lower gas density which causes the flame dimension higher due to the natural convection.

Keywords: combustion characteristic, physicochemical properties, saturated fatty acid, carbon chain length

1. Introduction
The increase of the world population has an impact on various sectors that are closely related to the fulfilment of the demand for fossil fuel which causes in depleting of fossil fuel resources [1]. The massive use of fossil fuels into combustion systems have a big role in the carbon footprint. If the use of conventional combustion technology continues to produce greenhouse gas emissions, it is necessary to find an alternative fuel that has an advantage of efficient and eco-friendly [2]. Besides, there are limitations to the availability of non-renewable energy resources to meet future energy needs, so it is very important to find and develop renewable energy that is efficient, effective, sustainable, and eco-friendly [3]. One of the alternative fuels is biodiesel as a diesel engine fuel which made from methyl ester that contains various fatty acids. Biodiesel is considered as a sustainable alternative fuel and can replace diesel fuel from petroleum. This is because biodiesel is renewable, biodegradable, non-toxic, does not contribute to increasing levels of
carbon dioxide in the atmosphere, and no sulfur content so it can reduce the effect of greenhouse gases compared to diesel fuel [4]. Biodiesel can reduce carbon dioxide emissions by up to 78% compared to fossil fuels [5]. Biodiesel has several advantages, including environmentally friendly, renewable, low sulfur content, has a high cetane number, and biodegradable [6]. Some differences in biodiesel property compared to diesel fuel such as large molecular mass, low volatility, and high viscosity will deteriorate the engine performance. These problems need to be solved by implementing several methods such as esterification and transesterification, pyrolysis, micro-emulsification, and blending with diesel fuel [7]. Esterification and transesterification reaction to produce fatty acid methyl ester by using methanol and catalysts will break the bonds and result alkyl esters which have lower viscosity and better atomization properties [1]. Fatty acid methyl ester (FAME) is one of the compounds contained in biodiesel which is promising to be used as an alternative fuel [8].

The polarity and geometric structure of the composition of fatty acids in vegetable oils influence the process of evaporation and ignition. Vegetable oils which are predominant fatty acids with a straight geometry produce high temperatures during the ignition process but require a longer evaporation time. This is influenced by the intermolecular force of strong fatty acids so that during evaporation only a few bubbles appear [9]. The physicochemical properties of biodiesel vary depending on the chemical composition of fatty acids contained in raw material [10]. If accurate knowledge on the influence of the molecular structure of fatty acids on plants is known, various production parameters such as concentration and type of catalyst, type of alcohol, temperature, and duration of reaction can be selected accordingly for optimal transesterification processes and the production of good quality biodiesel [11]. Ignition delay from vegetable oils combustion depends on the physical and chemical properties of the fuel [12]. Ignition delay increase as the carbon chain length increases due to the lower volatility and diffusivity which causes the heat-up and vapor diffusion needs longer times [13]. The high viscosity of fatty acids with large molar mass causes the atomization process to form a large droplet, thus increasing the rate of fuel evaporation [9]. The preheating process is needed to make vegetable oil reach its melting point [14]. Kinematic viscosity increases as the carbon chain length increase [15] and fatty acid methyl ester with straight-chain relatively have a higher viscosity than bent chain [16]. The characteristics of droplet combustion are strongly influenced by the properties of the constituent fuels, such as volatility, reactivity, and molecular structure [13].

Droplet combustion in previous studies still consisted of various compositions of fatty acid compounds, so the effect of each fatty acid compound could not be defined certainly. The use of pure fatty acid compounds will make it easier to understand the influence of the geometry and structure of fatty acids on the droplet combustion to obtain the characteristics of each fatty acid more clearly. This study will further reveal insights about the effect of fatty acid composition on the droplet combustion and provide additional information to choosing suitable vegetable oil which is proper according to the engine requirements.

2. Method and material

2.1 Raw materials

Samples of fatty acid were collected in the form of pure fatty acid. This study uses 4 kinds of fatty acids consists of lauric acid, myristic acid, palmitic acid, and stearic acid. These fatty acids vary in carbon chain lengths with 12 to 18 carbon atoms, also contain oxygen and hydrogen atoms with the general molecular formula of \( \text{CH}_n(\text{CH}_2)_m\text{COOH} \). All of these materials were in the solid phase at room temperature because it included saturated fatty acid which has straight geometry. These saturated fatty acids have a high melting point in which the value increases with the increase in
the number of carbon chains. To represent these fatty acids as vegetable oils contain in biodiesel, an esterification reaction is required as an initial procedure before the droplet combustion experiment.

### 2.2 Fatty acid methyl ester extraction

The esterification process is carried out using a hot plate magnetic stirrer, utilizing the rotation of the stir bar and the heat from the plate to mix the reactants to form a homogeneous fatty acid methyl ester product. The reactants for this esterification process consist of fatty acids, sulfuric acid (H₂SO₄) as a catalyst, and methanol (CH₃OH) as alcohol which is selected to carry out the reaction. The fatty acids in this study consisted of lauric acid, myristic acid, palmitic acid, and stearic acid. In this study, a sulfuric acid catalyst was used as much as 0.5% of the mass of fatty acids and 500% excess methanol (the mole ratio of fatty acids to methanol is 1:6).

| Table 1. Properties of fatty acid methyl ester |
|-----------------------------------------------|
| Properties | LME | MME | PME | SME | Ref. |
| Molecular formula | C₁₃H₂₆O₂ | C₁₅H₃₀O₂ | C₁₇H₃₄O₂ | C₁₉H₃₈O₂ | [17] |
| Composition (in wt% of C, H, O) | 72.9; 12.2; 14.9 | 74.3; 12.5; 13.2 | 75.5; 12.7; 11.8 | 76.4; 12.9; 10.7 | [17] |
| Molecular weight (g mol⁻¹) | 214.3 | 242.4 | 270.4 | 298.5 | [11] |
| Higher heating value (MJ kg⁻¹) | 37.82 | 38.79 | 39.56 | 40.18 | [18] |
| Vaporization enthalpy at 25°C (kJ mol⁻¹) | 75.45 | 85.25 | 93.55 | 103.71 | [19] |
| Boiling point (°C) | 262 | 295 | 338 | 352 | [6] |
| Melting point (°C) | 5 | 18.5 | 30.5 | 39 | [11] |
| Cetane number | 61.25 | 68.05 | 77.33 | 84.95 | [20] |
| Density at 20°C (g/cm³) | 0.8692 | 0.8665 | 0.8644 | 0.8627 | [18] |
| Kinematic viscosity at 40°C (mm²/s) | 2.45 | 3.33 | 4.37 | 5.59 | [18] |

The initial stage of the esterification reaction is to mix a predetermined amount of sulfuric acid catalyst and methanol from the calculation of the chemical reaction into an Erlenmeyer flask, then stirred using a magnetic stirrer for 3 minutes with intermediate agitation speed to obtain a homogeneous mixture. Then the fatty acids are put into a homogeneous mixture, heated with the temperature at 60°C and the agitation speed at 500 rpm using a hot plate magnetic stirrer for 1 hour. After that, deposit the product into the separating funnel for 24 hours to form 2 layers in which the top layer is FAME (fatty acid methyl ester) mixed with methanol while the bottom layer is water, catalyst, and impurities. Separate the top and bottom layers by turning the tap into the separating funnel until the bottom layers are completely separated. Next, wash the top layer with distilled water for 2 times to separate the FAME from the excess methanol that is still left in the separating funnel. Then 2 more layers were formed in the separating funnel. Turn the tap to remove water and excess methanol at the bottom of the separating funnel. Next, heat the FAME product in a tub filled with boiling water for 10 minutes to evaporate the water content that may still be present in FAME. The FAME product for each fatty acid is obtained by carrying out this series of esterification reactions. Each FAME has specific properties as shown in Table 1.

### 2.3 Experimental apparatus and method

This study purposes to investigate the effect of carbon chain length on the droplet combustion of fatty acid methyl ester which experimental apparatus is shown in Figure 1. The method for testing the single FAME compound by using suspended droplet which diameter set in 1.8 mm which
placed on thermocouple junction. The droplet which made by using micro syringe and the testing took at atmospheric pressure and room temperature. Each FAME was given a preheating treatment by heating and maintaining the temperature at 40 °C (the maximum melting point of FAME used is 39 °C) to get the FAME in its liquid phase. The K type Thermocouple with a diameter of 0.1 mm is connected to the input of the Advantech data logger while the output of the data logger is connected to a computer. The DAQNavi-USB4718 software use to record the droplet temperature during the test with the sampling rate was determined at 10 Hz. Then the data stored in the computer in the form of comma-separated values (CSV) format files were read by using Microsoft Excel. Put the thermocouple junction with a distance of 3 mm above the coil heater. Nikon D3400 was used to capture and visualize the flame during the test and the camera set at frame rate about 60 fps. ImageJ software was used to process flame visualization data.

The accumulator supplies power to heat the coil heater until lights up brightly and reaches a temperature of ± 720 °C. The coil heater then heating the droplet until it start igniting. The camera and the data logger simultaneously started record when the coil heater was placed below the droplet. Then the coil heater was slide away as the droplet starts igniting to avoid the effect of heat transfer from coil heater during the droplet combustion. This method was repeated 5 times for each of FAME to improve the accuracy of the data and then tests are carried out for all the FAME that have been prepared including single droplet combustion in lauric methyl ester, myristic methyl ester, palmitic methyl ester, and stearic methyl ester.

![Experimental apparatus](image)

Figure 1. Experimental apparatus

3. Result and discussion
Saturated fatty acids are classified as non-polar fatty acids that have strong intermolecular bonds with high viscosity and melting points. Viscosity increases as the carbon chain length increase due to a higher number of van der Waals interactions with the adjacent molecules [21]. Consequently, for the utilization of saturated fatty acids into the combustion engine, these properties are improved by carrying out the esterification procedure to produce fatty acid methyl esters that have better properties. The carbon chain length in the saturated fatty acids as the constituent of fatty acid methyl ester (FAME) results in some specific characteristics. This is influenced by the varying physicochemical properties in the different carbon chain lengths. In this study, the effect of variations in carbon chain length was observed during the droplet evaporation and combustion stages. Single droplet combustion on methyl esters of lauric, myristic, palmitic, and stearic fatty
acids with molecular structures of 12:0, 14:0, 16:0, and 18:0, respectively resulted in a certain tendency in the observed combustion characteristics. This results in respect to the physicochemical properties of fatty acid constituents of FAME.

3.1 Ignition delay time and burning duration
In droplet combustion testing, the evaporation and combustion stages produce a specific duration known as ignition delay time and burning duration. The ignition delay time is defined as the time interval from when the droplet is first exposed to a high-temperature environment until the flame can be observed while the burning duration is the time interval from when the flame can be observed until the flame extinguishes [22]. Figure 2 illustrates the ignition delay time and the burning duration of each FAME. During the ignition delay time period, the fuel is atomized, evaporates, mixes to form a homogeneous mixture with air, then heated to ignition temperature [23]. The maximum ignition delay time occurs in stearic methyl ester with a value of 1.95 s. The value of ignition delay time increases at FAME with a high carbon chain length. FAME with a long carbon chain has a strong inter-atomic bonding force resulting in high viscosity. This high viscosity is closely related to the greater molar mass of the FAME compound [9]. The large internal friction force on the FAME with the greatest kinematic viscosity is possessed by the stearic methyl ester with a value of 5.59 mm² s⁻¹ (Table 1). The high internal friction force in the FAME with a long carbon chain requires a large bond dissociation energy, causing a low evaporation rate, resulting in a long ignition delay time. Long ignition delay times are possessed by combustible components with high surface tension [24]. Fatty acid compounds with long carbon chains have low volatility and a higher flash point results in a slower rate of evaporation [25]. In FAME, the faster evaporation rate causes the ignition to occur at lower temperatures because a large amount of heat energy is converted into latent heat during the evaporation phase [9]. This causes the lower ignition delay time occurs at FAME with a low boiling point. The shortest ignition delay time occurs on lauric methyl ester which the lowest boiling point with a value of 262 °C (Table 1).

The burning duration value increases with the length of the carbon chain and the maximum burning duration occurs on stearic methyl ester with the value of 2.12 s. Short burning duration at
FAME with a fast evaporation rate due to an increase in the accumulation of the gas mixture during the combustion process [26]. FAME molecules with high heat capacity and heat of evaporation will produce a longer burning duration [24]. The concentration of oxygen molecules that act as oxidizing agents in the FAME compound decreases with the increasing length of the carbon chain with the lowest value in the stearic methyl ester compound about 10.7 wt% (Table 1). This matter makes the gas mixture more difficult to reach its flammability limit so that the combustion lasts longer. If the concentration of oxygen molecules increases, the concentration of carbon and hydrogen molecules as combustible matter decreases. The concentration of combustible matter in the lauric methyl ester is the lowest with a value of 85 wt%, resulting in the shortest burning duration about 1.78 s. This burning duration value is also related to the constant burning rate which is owned by each FAME where at the same initial diameter size, the constant burning rate has a greater value for a short burning duration, as explain in the next section.

3.2 Droplet temperature

Correlation between droplet temperature and combustion time is shown in Figure 3. The droplet combustion temperature is determined by the fuel heating value, burning rate, and heat loss through radiation from gas and soot caused by flames [27]. The droplet temperature increases linearly during the evaporation stages (Figure 4). During the evaporation stages, the relationship between droplet temperature and time results in a certain slope indicated by the coefficient in front of the x variable in each equation. The droplet evaporates when the boiling temperature is reached and the gasification process occurs in each component of the fuel [9]. The largest slope is owned by lauric methyl ester which has the fastest temperature rise rate. The longer the carbon chain gives a lower slope value, indicates a slower rate of temperature rise. This phenomenon is related to the greater latent heat of evaporation (Table 1) so that the ignition delay time period is longer due to the higher heat energy needed to reach the boiling point temperature.

![Figure 3. Correlation between droplet temperature and time during droplet lifetime](image_url)

The longer the carbon chain, the droplet temperature increases both the average value and the maximum value. The maximum droplet temperature values for lauric methyl ester, myristic methyl ester, palmitic methyl ester, and stearic methyl ester are 403 °C, 435.9 °C, 463.2 °C, and 477.8 °C,
respectively and the average droplet temperature are 272.9 °C, 280.6 °C, 295.1 °C, and 299.7 °C, respectively. FAME has a high flame temperature with a large heating value. The increase in heating value was due to the increasing amount of combustible matter in the FAME with the concentration on lauric methyl ester, myristic methyl ester, palmitic methyl ester, and stearic methyl ester are 85.1 wt%, 86.8 wt%, 88.2 wt%, and 89.3 wt%, respectively. Another factor that affects the droplet temperature is the presence of heat loss radiation to the surrounding environment which is indicated by the bright colored flame of the FAME combustion. Increasing the oxygen concentration in the FAME will result an increase in radiation heat loss which resulting in a brighter flame [26]. The high droplet temperature is also influenced by the constant burning rate of the FAME where the greater the value gives the greater the droplet temperature [27]. However, this factor has no effect in this study since the lauric methyl ester with the greatest constant burning rate has the lowest droplet temperature, as explain in the next section. Even though the burning rate is fast, the heating value is lower and the radiation heat loss is large in the lauric methyl ester. The maximum droplet temperature at each FAME occurs at the end of the combustion shortly before the flame extinguishes. This is because the droplet diameter is getting smaller caused the thermocouple junction has direct contact with the flame resulting in higher temperature measurement.

![Figure 4](image.png)

**Figure 4.** Correlation between droplet temperature and time during evaporation phase

### 3.3 Constant burning rate

During the evaporation stage, the droplet diameter at FAME increases compared to the initial diameter. The droplet diameter increases due to the absorption of heat during high-temperature environmental conditions. Then the diameter will slowly decrease during the combustion period until the flame extinguishes in relation to d² law [26]. Heat absorption will increase the kinetic energy of the molecule, resulting in an expansion in the volume of the droplets which causes an enlargement of the droplet diameter during the heating time period [9]. This causes the normalized squared droplet diameter value to be greater than 1 at the first ignition period (Figure 5). The largest slope value is owned by the lauric methyl ester which indicates that the reduction rate of the diameter is high in fatty acids with short carbon chains. Figure 6 shows the
constant burning rate of FAME which is the slope of the droplet diameter quadratic evolution against time that calculated using the $d^2$ law equation (equation 1).

\[ D^2(t) = D_0^2 - K \cdot t \]  

where $D$ is the final droplet diameter (mm), $D_0$ is the initial droplet diameter (mm), and $K$ is the constant burning rate ($mm^2 s^{-1}$), and $t$ is time (s). The constant burning rate increases with the shorter carbon chain with the largest value being owned by the lauric methyl ester with a value of 1.482 mm$^2 s^{-1}$. The constant burning rate value will increase at the greater oxygen concentration found in FAME with short carbon chains [21]. Constant burning rate is one of the single droplet combustion properties related to the rate of droplet fuel evaporation where the greater the constant burning rate, the greater the power produced [28].

![Figure 5. Correlation between normalized squared droplet diameter and normalized time](image1)

![Figure 6. Constant burning rate of fatty acid methyl ester](image2)
A high rate of evaporation indicates that the constant burning rate is high [29]. At ambient temperature, constant burning rate increases with increasing combustion temperature and decreasing latent heat of evaporation, density, and fuel boiling point [22]. The high boiling point value of the FAME with long carbon chains causes a low constant burning rate due to the high latent heat of evaporation. At high latent heat of evaporation, liquid molecules of FAME have a strong intermolecular force, causing more heat energy is needed to break bonds into single molecules to form gas phase when it reaches the boiling point temperature. The effect of increasing temperature and decreasing density in this study not have a significant effect compared to the effect of boiling point and latent heat of evaporation because of the relatively small changes in value.

3.4 Flame visualization
The flame visualization was used to qualitatively analyze the combustion of each FAME. The flame dimension extends vertically with increasing of burning time. The flame dimension increases in the early stages of the droplet combustion due to droplet heating and the influence of fuel vapor accumulation around the droplet surface during the ignition delay time period. In contrast to the change in droplet diameter, the flame dimension changes non-linearly and does not depend on $d^2$ law. The changes in the value of the dimensions of flame height are shown in Figure 7 while flame visualization is shown in Figure 8. The longer the carbon chain gives an increase of flame height, both at maximum and average values. The flame dimensions of the lauric methyl ester, myristic methyl ester, stearic methyl ester, and myristic methyl ester have an average flame height of 16.9 mm, 18.4 mm, 19.4 mm, and 19.48 mm, respectively.

![Figure 7. Correlation between flame height and time](image)

The presence of higher oxygen bonds in the molecular structure of FAME will encourage combustion and suppress the formation of soot [27]. Therefore, lauric methyl ester has a shorter burning duration because of the rich oxygen content. The higher oxygen concentration results in greater radiation as indicated by a brighter flame on the lauric methyl ester compared to the stearic methyl ester. A higher flame is indicated by the higher of the ratio of combustible matter (C and H) to non-combustible matter (O). The decrease in oxygen concentration causes the flame
front to move away from the droplet surface to maintain stoichiometric combustion conditions [30]. This causes stearic methyl ester with the lowest concentration of oxygen molecules to have the highest flame dimension. The high dimension of the flame is also influenced by the combustion temperature. The higher flame height will result in a lower gas density. This causes the flame dimension to be higher due to the effect of natural convection. The droplet flame dimension is inversely proportional to the burning rate value. Fast combustion occurs when the flame is closer to the droplet at a higher oxygen concentration produces a shorter flame dimension both vertically and horizontally [26]. The increase in oxygen concentration causes the flames to get closer to the droplets resulting in the shorter flame height.

![Flame visualization](image)

**Figure 8.** Flame visualization of (a) lauric methyl ester (b) myristic methyl ester (c) palmitic methyl ester (d) stearic methyl ester during combustion period

4. **Conclusion**

The number of carbon lengths in saturated fatty acids and their physicochemical properties have an important role in the evaporation and combustion stages of its FAME in droplet combustion testing. The differences in the molecular structure of FAME given some tendency to droplet
combustion characteristics. FAME with a long carbon chain has longer in ignition delay time due to the strong inter-atomic bonding forces resulting in high viscosity and an increase in boiling point cause the molecule needs higher heat energy to reach its gas phase. The burning duration also increases proportionally to the increase in carbon chain length caused by less oxygen content in FAME molecules which plays a role to promote faster combustion. The droplet temperature increases linearly during the evaporation stages and the higher temperature during combustion occurs in FAME with long carbon chain due to the higher heating value and the lower of radiation heat loss. The burning rate increase with the shorter carbon chain length due to the greater oxygen content in the molecule and the lower of boiling point temperature and latent heat of evaporation. Long carbon chain result in a high flame dimension due to the lower oxygen content cause the flame front moves away to maintain the stoichiometric condition. Furthermore, the increase of temperature causes lower gas density which result in higher flame dimension due to the effect of natural convection.

5. Acknowledgement
The author is grateful for the financial support from Directorate General of Higher Education, Ministry of Research Technology and Higher Education of Republic of Indonesia.

6. References
[1] Maneechakr P and Karnjanakom S 2019 A combination of 2k factorial with Box-Behnken designs for FAME production via methanolysis of waste cooking palm oil over low-cost catalyst Journal of Environmental Chemical Engineering 7.
[2] Basu S and Miglani A 2016 Combustion and heat transfer characteristics of nanofluid fuel droplets: A short review International Journal of Heat and Mass Transfer 96 pp 482–503.
[3] Suprarukmi D D, Sudrajat B A and Widayat 2015 Kinetic Study on Esterification of Oleic Acid with Ultrasound Assisted Procedia Environ. Sci. 23 pp 78–85.
[4] Martínez A, Mijangos G E, Romero-Ibarra I C, Hernández-Altamirano R and Mena-Cervantes V Y 2019 In-situ transesterification of Jatropha curcas L. seeds using homogeneous and heterogeneous basic catalysts Fuel 235 pp 277–287.
[5] Coronado C R, de Carvalho J A and Silveira J L 2009 Biodiesel CO2 emissions: A comparison with the main fuels in the Brazilian market Fuel Processing Technology 90, pp 204–211.
[6] Ando S, Wu Y, Nakaya S and Tsue M 2020 Droplet combustion behavior of oxidatively degraded methyl laurate and methyl oleate in microgravity Combustion and Flame 214 pp 199–210.
[7] Zahan K A and Kano M 2018 Biodiesel production from palm oil, its by-products, and mill effluent: A review Energies 11 pp 1–25.
[8] Jamil M A R, Touchy A S, Poly S S, Rashed M N, Siddiki S M A H, Toyao T, Maeno Z and Shimizu K 2020 High-silica HB zeolite catalyzed methanolysis of triglycerides to form fatty acid methyl esters (FAMEs) Fuel Processing Technology 197.
[9] Marlina E, Wijayanti W, Yuliati L and Wardana I N G 2020 The role of pole and molecular geometry of fatty acids in vegetable oils droplet on ignition and boiling characteristics Renewable Energy 145 pp 596–603.
[10] Torres-Jimenez E, Jerman M S, Gregorc A, Liseć I, Dorado M P and Kegl B 2011 Physical and chemical properties of ethanol-diesel fuel blends Fuel 90 pp 795–802.
[11] Folayan A J, Anawe P A L, Aladejare A E and Ayeni A O 2019 Experimental investigation of the effect of fatty acids configuration, chain length, branching and degree of unsaturation on biodiesel fuel properties obtained from lauric oils, high-oleic and high-linoleic vegetable oil biomass Energy Reports 5 pp 793–806.
[12] Plank M, Wachtmeister G, Remmele E, Thuneke K and Emberger P 2017 Ignition characteristics of straight vegetable oils in relation to combustion and injection parameters, as well as their fatty acid composition Fuel Processing Technology 167 pp 271–280.
[13] Aggarwal S K 2014 Single droplet ignition: Theoretical analyses and experimental findings
Progress in Energy and Combustion Science 45 pp 79–107.

[14] Misra R D and Murthy M S 2010 Straight vegetable oils usage in a compression ignition engine-A review Renewable and Sustainable Energy Reviews 14 pp 3005–3013.

[15] Knothe G and Steidley K R 2005 Kinematic viscosity of biodiesel fuel components and related compound influence of compound structure and comparison to petrodiesel fuel components Fuel 84 pp 1059–1065.

[16] Hoekman S K, Broch A, Robbins C, Cenceros E and Natarajan M 2012 Review of biodiesel combustion, properties, and specifications Renewable and Sustainable Energy Reviews 16 pp 143–169.

[17] Sukjit E, Herreros J M, Dearn K D, Garcia-contreras R and Tsolakis A 2012 The effect of the addition of individual methyl esters on the combustion and emissions of ethanol and butanol-diesel blends Energy 42 pp 364–374.

[18] Ramírez-Verduzco L F, Rodríguez-Rodríguez J E and Jaramillo-Jacob A D R 2012 Predicting cetane number, kinematic viscosity, density and higher heating value of biodiesel from its fatty acid methyl ester composition Fuel 91 pp 102–111.

[19] Zaitsau D H, Pimerzin A A and Verevkin S P 2019 Fatty acids methyl esters: Complementary measurements and comprehensive analysis of vaporization thermodynamics J. Chem. Thermodynamics 132 pp 322–340.

[20] Xue S, Steinberger Y and Wang J S 2014 Biodiesel Potential of Nonfood Plant Resources from Tsinling and Zhongtiao Biodiesel Potential of Nonfood Plant Resources from Tsinling and Zhongtiao Mountains of China Bioenergy Resources 6 pp 1104-1117.

[21] Berman P, Meiri N, Colnago L A, Moraes T B, Linder C, Levi O, Parmet Y, Saunders M, Wiesman Z 2015 Study of liquid-phase molecular packing interactions and morphology of fatty acid methyl esters (biodiesel) Biotechnology for Biofuels 8 pp 1–16.

[22] Han K, Pang B, Ma X, Chen H, Song G and Ni Z 2017 An experimental study of the burning characteristics of acetone-butanol-ethanol and diesel blend droplets Energy 139 pp 853–861.

[23] Garzón N A N, Oliveira A A M and Bazzo E 2019 An ignition delay correlation for compression ignition engines fueled with straight soybean oil and diesel oil blends Fuel 257.

[24] Antonov D V, Kuznetsov G V, Strizhak P A and Fedorenko R M 2020 Micro-explosion of droplets containing liquids with different viscosity, interfacial and surface tension. Chemical Engineering Research and Design 158 pp 129-147.

[25] Carareto N D D, Kimura C Y C S, Oliveira E C, Costa M C and Meirelles A J A 2012 Flash points of mixtures containing ethyl esters or ethylic biodiesel and ethanol Fuel 96 pp 319–326.

[26] Han K, Chen H, Yang B, Ma X, Song G and Li Y 2017 Experimental investigation on droplet burning characteristics of diesel-benzyl azides blend Fuel 190 pp 32–40.

[27] Zhu M, Setyawann H Y, Zhang Z and Zhang D 2020 Effect of n-butanol addition on the burning rate and soot characteristics during combustion of single droplets of diesel-biodiesel blends Fuel 265.

[28] Waluyo B, Wardana I N G, Yuliati L, Sasonko M N and Setiyono M 2020 The role of polar ethanol induction in various iso-octane ethanol fuel blend during single droplet combustion Fuel Processing Technology 199.

[29] Li T X, Zhu D L, Akafuah N K, Saito K and Law C K 2011 Synthesis, droplet combustion, and sooting characteristics of biodiesel fuels produced from waste vegetable oils Proceedings of the Combustion Institute 33 pp 2039–2046.

[30] Li H, Rosebrock C D, Rie N, Wriedt T and Mädler L 2019 Experimental investigations on the effects of water vapor and oxygen concentrations in the ambience on the burning constant, lifetime and residuals of single isolated xylene, isobutanol and ethanol droplets Experimental Thermal and Fluid Science 109.