Captivating Combustion Traits of Bio-Oil Droplets Enriched with Bio-Additives from the Areca Shell Waste

Muhammad Alif Raehan*, Helen Riupassa, Hendry Y. Nanlohy

Department of Mechanical Engineering, Jayapura University of Science and Technology,
Jayapura, 99351, Indonesia
**Corresponding author: alifraehan123@gmail.com*

Article history:
Received: 30 September 2024 / Received in revised form: 20 October 2024 / Accepted: 29 October 2024
Available online 1 November 2024

ABSTRACT

Fuel derived from crude vegetable oil, such as coconut oil, holds promise as an alternative energy source to mitigate the increasing reliance on fossil fuels driven by population growth and industrial activities. The experiment involved suspending a single droplet of crude coconut oil mixed with activated carbon from areca shell waste and placed at the junction on R-type thermocouple (Pt/Pt-Rh13%). The droplets were ignited using a hot wire and subjected to atmospheric pressure and room temperature. Coconut oil comprises a saturated triglyceride carbon chain compound of approximately 91%, and areca shell waste possesses a porous structure that fosters favorable interactions between fuel molecules. The droplet combustion method was selected to streamline the process and enhance the contact area between air and fuel, thereby boosting the reactivity of fuel molecules. The research found that adding activated carbon shortens the carbon chain, making it more reactive and easier for the fuel to ignite. Specifically, activated carbon significantly enhances fuel performance at a concentration of two parts per million (ppm). At this level, the fuel absorbs heat more effectively and ignites faster compared to one ppm and three ppm levels. Moreover, the results show that heat absorption occurs slowly at one ppm, while at three ppm, the increased molecular mass of the fuel can strengthen carbon-bonding forces. These factors contribute to a longer ignition time for the fuel. The findings suggest that the activated carbon from areca shell waste can play a good role as a combustion catalyst, where overall, fuel performance increases.

Keywords: *Activated carbon, areca shell waste, crude coconut oil, droplet combustion characteristics*

I. Introduction

Increasing crude vegetable oil fuel is one solution to overcome the fossil fuel crisis due to rising energy consumption [1], [2]. Crude vegetable oil processed into fuel is one of the alternative energy sources or as a fuel that can be relied on as a solution to overcome the fuel energy crisis [3]. Previous researchers have used various types of vegetable oil in internal combustion engines, including coconut oil [4]-[6], castor oil [7], [8], sunflower [9], [10], corn oil [11], [12], palm oil [13], soybean oil [14], and glycerol [15]. Although many studies have successfully applied vegetable oil, they also state that pure vegetable oil has a long ignition delay, which results in slower combustion [16]. Therefore, additional materials are needed in the coconut oil combustion process to overcome this weakness, such as activated carbon catalysts, which are expected to improve fuel performance.

Furthermore, crude coconut oil is the same as other vegetable oils because it consists of triglyceride compounds and various fatty acids, with a saturated fatty acid content of 90% [17], [18]. Numerous studies have demonstrated the viability of utilizing vegetable oil as an alternative fuel source. However, there exists a significant amount of intricate scientific data

DOI: 10.17977/um016v8i22024p384

pertaining to vegetable oil, which may be challenging to comprehend. This complexity is attributed to the presence of multi-component compounds in crude vegetable oil, each fulfilling distinct roles. For instance, the high oxygen content and poor stability of surface-active chemicals present in vegetable oil can exert a notable influence during the combustion process. Moreover, vegetable oil is different from diesel oil due to its high viscosity, so under normal conditions, it isn't easy to burn [19]. However, by adding a catalyst in the form of activated carbon, this can be overcome because adding an activated carbon catalyst functions to reduce the activation energy of the reaction or by decreasing the activation energy such as changing the course of the response or the reaction method, so that the reaction occurs faster, in addition, activated carbon has a structure with a vast surface area and is porous [20], [21] so that it provides a large area for chemical reactions to take place. The reactant molecules can bind to activated carbon's surface, bringing them closer to each other and increasing the possibility of molecular interaction. Furthermore, activated carbon can act as a catalyst that provides a surface for the reaction, reducing the activation energy required. Moreover, activated carbon has good chemical stability, high surface area and thermal conductivity, attractive pore distribution, and a unique morphological structure. Its preparation process is straightforward and can be used as an electrode for supercapacitors [22]. Based on the advantages of active carbon catalysts, this study developed a new catalyst using areca shell waste (biomaterial). This renewable natural resource is environmentally friendly and readily available. Therefore, the aim is to maximize the use of areca shell waste as a valuable commodity while incorporating the local wisdom of the Papuan people. The study specifically investigates the combustion characteristics of CCO droplets with varying concentrations of activated carbon made from areca shell waste.

On the other side, previous studies comparing the relationship between activated carbon and the polarity of vegetable oil, which affects the characteristics of premixed combustion, show that adding activated carbon can make vegetable oil fuel easy to evaporate, increasing the burning rate [23]. They stated that volatility comes from the polarity of the oil used. The more polar an oil is, the easier it is to evaporate, so the flame speed can increase during combustion. In addition, this study also proved an increase in flame speed along with the addition of activated carbon. Therefore, adding activated carbon to the coconut oil combustion process is expected to have the same function: increasing the flame speed. Selecting vegetable oil such as pure coconut oil without a transesterification process depends on the material that is easy to obtain. Although there are weaknesses because it has a rigid saturated fatty acid carbon chain content, these characteristics can affect the oil flash point and increase viscosity [24]. Furthermore, high viscosity can hinder fuel performance by increasing flow resistance, resulting in slower flow rates. A viable solution to this issue is to add a catalyst in the form of activated carbon derived from the pyrolysis of areca shell waste. This addition can enhance the performance of pure coconut oil, optimizing its use as a sustainable and environmentally friendly alternative energy source through the utilization of biofuels.

II. Material and Methods

Prior to evaluating the characteristics of droplet combustion, it is crucial to ascertain the fatty acid compounds contained in coconut oil. To facilitate this, we conducted a GCMS analysis, with the findings presented in Table 1. Additionally, an EDX mapping test was conducted to analyze the chemical properties of activated carbon made from areca shell waste, and the results are displayed in Table 2. Additionally, we carried out droplet combustion and diffusion flame tests on coconut oil, both with and without incorporating activated carbon bio-additives sourced from areca shell waste. The experimental setup is illustrated in Figure 1.

Table 1. Fatty acid compounds of coconut oil [25]

Fatty acids	Formula	Composition (%)
Caproik	$C_6H_{12}O_2$	0.6
Caprylic	$C_8H_{16}O_2$	8.45
Capric	$C_{10}H_{20}O_2$	6.1
Lauric	$C_{12}H_{24}O_2$	31.43
Myristic	$C_{14}H_{28}O_2$	18.45
Palmitic	$C_{16}H_{32}O_2$	8.4
Stearic	$C_{18}H_{36}O_2$	1.65
Linoleic	$C_{18}H_{32}O_2$	1.4
Linolenic	$C_{18}H_{30}O_2$	0.05
Oleic	$C_{18}H_{34}O_2$	5.7

Table 2. The chemical properties of activated carbon

Element (K)	Weight (%)
C	75.8
O	19.2
Mg	0.3
Si	1.5
K	2.9
Ca	0.4

The setup in Figure 1 is designed to suspend the oil droplet precisely at the thermocouple intersection. Furthermore, to measure droplet size using ImageJ, follow these steps. Start the ImageJ program on computer → Open and select the image containing the droplets to measure → Set the droplet scale → Click on the line tool (straight line) and draw a line along the scale in the droplet image → Enter the known distance and units (mm) in the dialog box → Click OK. Meanwhile, this study's raw materials consist of crude coconut oil (CCO) and activated carbon from areca shell waste (see Figure 2).

High-speed photography was used to visually analyze the ignition process of coconut oil droplets and their combustion characteristics. The flame video was extracted using GOM Player, resulting in 900 images, each spaced 0.01 seconds apart. The experiment was conducted at standard gravity and room temperature, with humidity levels ranging from 57% to 62%. Meanwhile, the heater used is a Ni-Cr wire with a diameter of 0.9 mm and a voltage of 12 Volts. In the process of mixing coconut oil with activated carbon catalyst, a mixture ratio of 1 ppm to 3 ppm is used. Furthermore, a camera recorded the ignition and burnout times, while a thermocouple connected to a laptop monitored the droplet's temperature for reliability [26], [27].

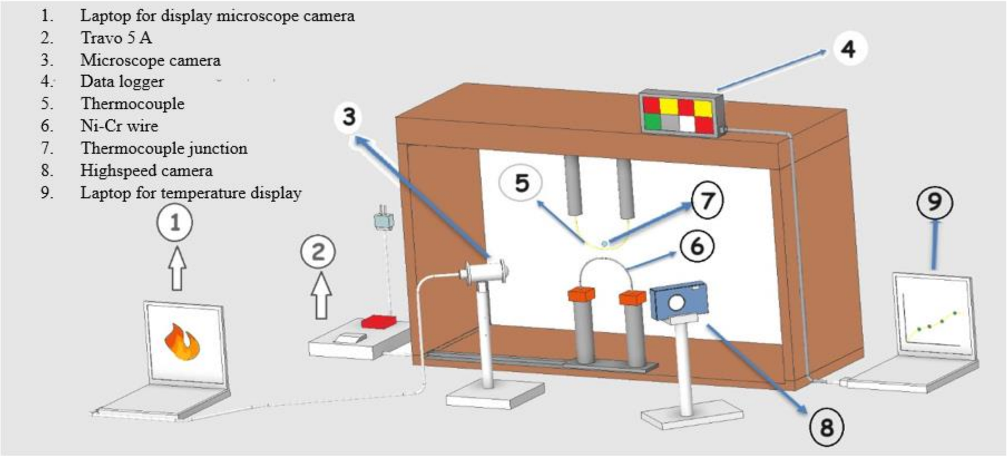

Fig. 1. Experimental apparatus

Fig. 2. Crude coconut oil (left) and activated carbon of areca shell waste (right)

III. Result and Discussion

Figures 3 to 7 and Table 3 are a complete presentation of the results obtained from the research conducted. The first stage in heating is the transfer of heat energy from the Ni-Cr wire to the droplet's surface. The heat generated by the Ni-Cr wire during the heating process until the ignition process to the initial combustion stage of the droplet causes an increase in the droplet temperature.

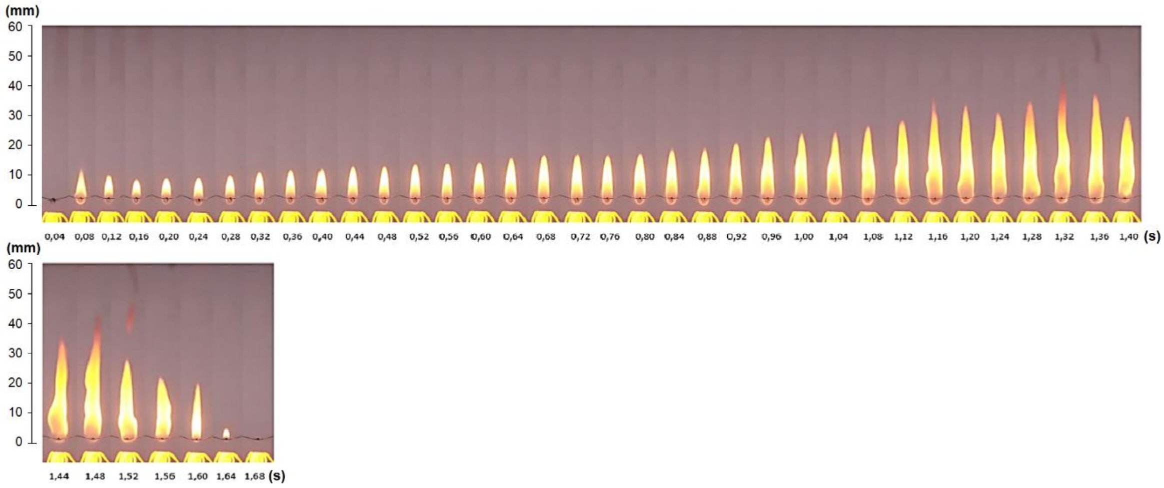

Fig. 3. Flame evolution of CCO droplets with activated carbon 1 ppm

In Figure 3, the flame development process in coconut oil is very clearly visible when one ppm of activated carbon catalyst from the areca shell is added. The duration of the flame in this period is 1.68 seconds, with the first flame igniting at 0.08 seconds. An exciting event is related to the flame, flame color and height, and variations in flame width. The occurrence of this phenomenon is based on temperature, materials used, and combustion rate. In the initial ignition stage, the flame height reaches 13.4 mm, the flame width is 4.2 mm, and the burning flame has a relatively bright orange color. At 1.32 seconds, the flame peaks, where its width is 6 mm and height is 41.9 mm. At this stage, the flame produces a striking orange color made from the combustion oxidation process with a low energy level and flame temperature. In addition, before the flame stage shrinks again and goes out at 1.68 seconds, the shape of the flame is slightly wavy, which is caused by a micro explosion that causes the width of the flame to change and sometimes is not aligned at each stage, which is also influenced by oxygen or air. Furthermore, micro-explosions in coconut oil fuel droplets occur when there is a significant temperature difference between the volatile and non-volatile components within the droplet. The phenomenon is primarily driven by the difference in pressure caused by the rapid vaporization of the more volatile components, such as water or lighter oil fractions, compared to the less volatile components. This is because when a coconut oil droplet is exposed to high temperatures (such as during combustion), the outer layer of the droplet heats up quickly. Coconut oil typically contains water and lighter fractions (e.g., free fatty acids) that vaporize at lower temperatures compared to the heavier triglycerides. After that, when the temperature rises, these volatile components vaporize rapidly inside the droplet. This vaporization creates high pressure within the droplet, while the less volatile components remain in liquid form and maintain a relatively lower pressure. This causes the high-pressure vapor inside the droplet to become trapped by the still-liquid outer layer of the droplet, leading to a significant pressure differential between the interior and exterior of the droplet. Furthermore, when the pressure inside the droplet exceeds the surface tension of the liquid shell, the droplet can rupture violently. This rupture releases the vapor, causing a micro-explosion. The droplet breaks into smaller fragments, which then evaporate and combust more rapidly.

The added activated carbon catalyst makes the molecular bonds in coconut oil more reactive, making it easier to decompose, and the evaporation process can react faster [22]. This happens because certain carbon atoms in coconut oil are drawn to activated carbon, filling the pores in the activated carbon.

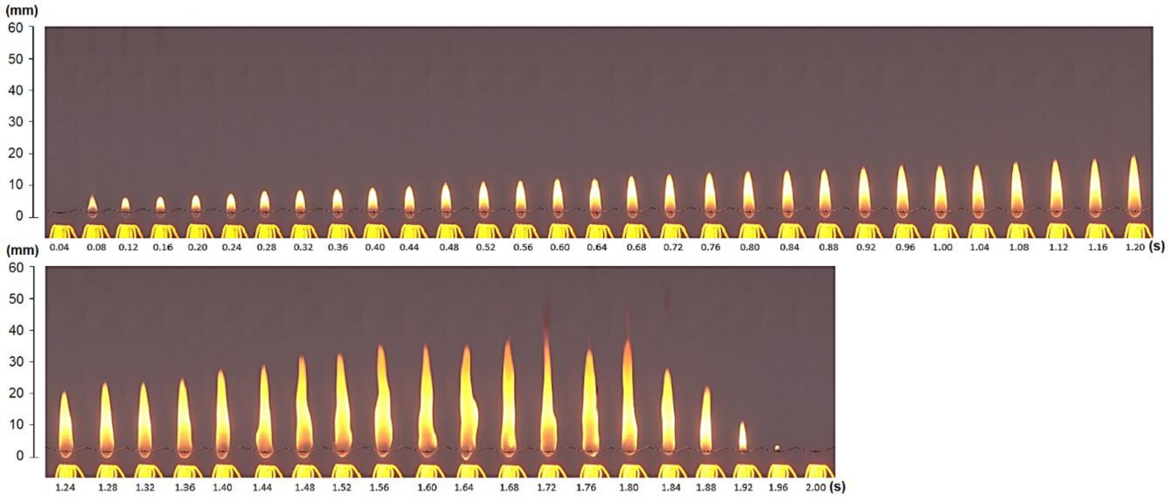

Fig. 4. Flame evolution of CCO droplets with activated carbon 2 ppm

In Figure 4, the flame development process in coconut oil is illustrated by adding a two ppm activated carbon catalyst. During this period, the flame lasts for 2.00 seconds because activated carbon has a large pore structure and a high internal surface area. This allows fuel or combustible vapors to be adsorbed effectively. As a result, the fuel remains on the surface longer, which slows the burning rate and extends the duration of the flame. Additionally, activated carbon can store some heat energy during combustion. This heat accumulation can potentially maintain the flame longer because the heat is released gradually. Initially, the flame ignites at 0.08 seconds and undergoes width, height, and color variations. Upon ignition, the flame reaches a height of 7.70 mm, a width of 3.30 mm, and exhibits a relatively bright orange color. The flame peaks at 1.72 seconds, reaching a height of 46.20 mm and a width of 5.80 mm, still displaying a striking orange color, as shown in Figure 3. Subsequently, the flame slightly curves before shrinking and extinguishing at 2.00 seconds. These findings indicate that adding a two ppm activated carbon catalyst can influence the combustion speed and visual characteristics of the coconut oil, leading to changes in shape, height, width, and color during combustion.

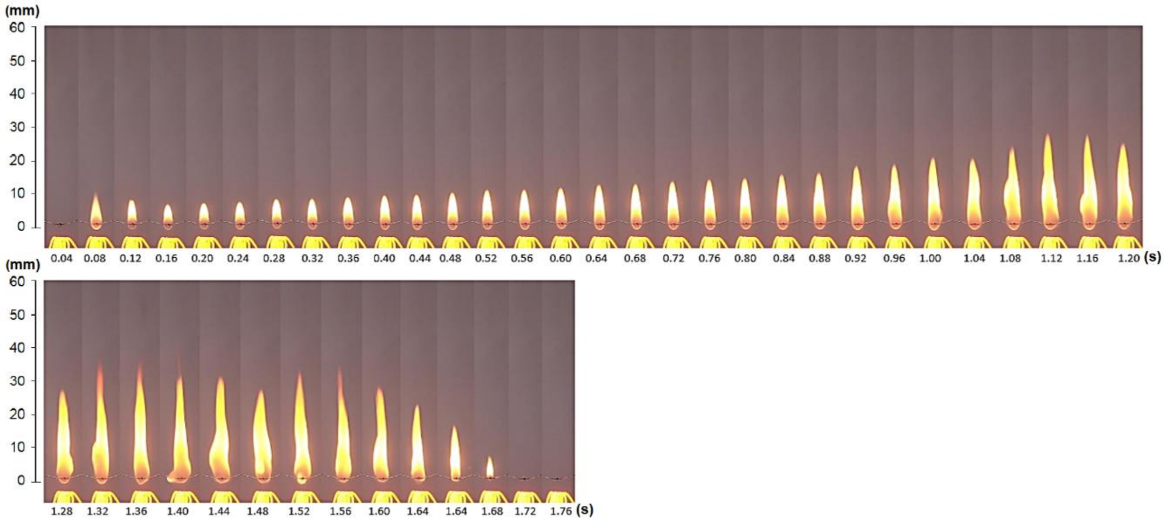

Fig. 5. Flame evolution of CCO droplets with activated carbon 3 ppm

In Figure 5, the flame development process in coconut oil is seen by adding three ppm of activated carbon catalyst. In this period, the duration of the flame in is 1.76 seconds, starting from the flame that ignites at 0.08 seconds, the flame varies in color, height and width. The first stage of the flame is ignited; the flame has a width of 3.80 mm and a height of 12.30 mm, and the flame is a relatively bright orange. The striking orange color of the flame from the combustion of coconut oil and activated carbon of areca shell waste is the result of a combination of the chemical composition of the fuel, the combustion temperature is not too high, and the combustion conditions may not be perfect, the cause of imperfect combustion is often due to a combination of lack of oxygen. It can be seen in Figures 3, 4, and 5 that the combustion process at two ppm is more efficient. This is confirmed by the flame, which is bright orange and reinforced with the temperature graph in Figure 11. While the amount of activated carbon that attracts oxygen makes the flame a relatively bright orange, the combustion process at three ppm experiences excess oxygen. The flame that reaches its peak occurs at 1.36 seconds, where the flame width is 7.20 mm, and the height is 41.00 mm.

Furthermore, the color of the resulting flame is the same as in Figures 3 and 4, namely orange, which is caused by the low energy and temperature of the flame used. Before the flame at the stage of shrinking and extinguishing at 1.72 seconds, the shape of the flame in Figure 5 is slightly curved but remains stable, which is caused by an unstable environment. In the last stage of the flame evolution process, increasing the concentration of 3-ppm activated carbon catalyst can improve the stability of the flame, making it more symmetrical and stable in the ignition process. This is because the amount of activated carbon is used at a concentration of 3 ppm to accelerate the decomposition reaction of triglyceride compounds in coconut oil. In addition, the study's results stated that the longer the carbon bond in oil (low polarity) could accelerate a reaction [28]. In coconut oil, there is a carbon bond Cıs, which causes coconut oil to evaporate quickly (high vapor flow mass); by adding activated carbon to coconut oil so that it can evaporate more quickly, the speed of the flame increases.

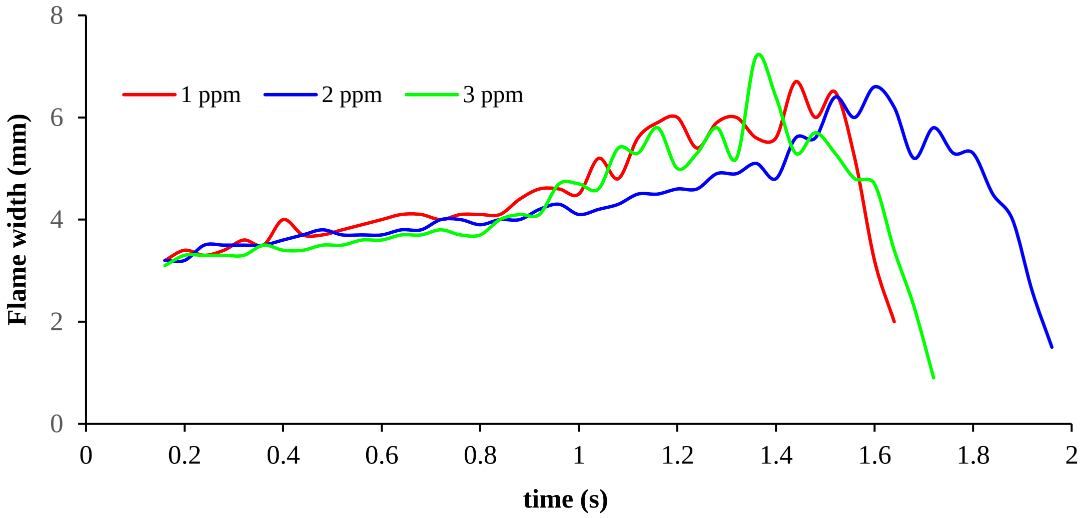

Fig. 6. The effect of activated carbon on droplet flame width

The graph in Figure 6 shows that the mixture, by adding activated carbon at concentrations of one ppm, two ppm, and three ppm, affects the flame width. The results obtained in the graph above are that the flame width at one ppm is 6 mm, 2 ppm is 5.80 mm, and three ppm is 7.20 mm. Activated carbon is frequently used as a catalyst and binder in fuel mixtures. Its addition can improve the mixture by increasing its density and accelerating the combustion process as it expands the surface area exposed to oxygen. Furthermore, the surface characteristics of activated carbon—such as its specific surface area and pore size distribution—significantly affect how the fuel burns, influencing the speed and size of the flame in various sections. The high flame width increase affects the activated carbon mixture's concentration. The higher the activated carbon mixture, the resulting flame width will also increase and accelerate the combustion rate reaction [29] because activated carbon has a large surface area and a porous structure. Having a large surface area makes it easier for oxygen to interact with carbon and trigger a combustion reaction [30]. More activated carbon particles are available at an activated carbon concentration of three ppm. This can cause more combustion points and reactions to coincide, thus expanding the flame width.

From Figure 7, it can be seen from the mixture that adding one ppm, two ppm, and three ppm of activated carbon can affect the flame height. The flame height results obtained in the graph above are at one ppm, 41.9 mm; two ppm, 46.20 mm; and three ppm, 41.00 mm high.

In general, increasing the addition of carbon causes the flame height to decrease. The decrease in flame height with the addition of three ppm activated carbon is due to the high concentration of the activated carbon mixture. It has an impact on the flame height becoming low and increasing the combustion reaction. There is an increase in the speed of the combustion reaction so that the resulting flame time is shorter, so the flame does not have time to get high and then extinction.

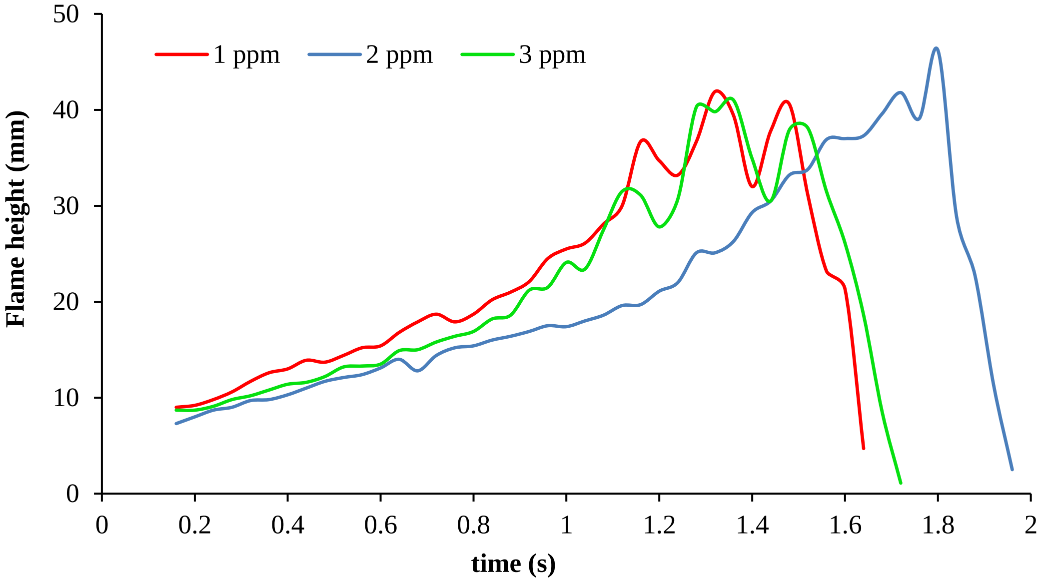

Fig. 7. The effect of activated carbon on droplet flame height

Table 3. Compare the properties of CCO with different masses of activated carbon

Properties	ASTM	1 ppm	2 ppm	3 ppm
Flash Point PM cc, °C	D97	251	251	244.5
Density 15 °C gr/ml	D1298	0.9181	0.9281	0.9283
Kinematic Viscosity 40 °C, cSt	D445	27.37	27.40	27.46
Caloric value Kcl/kg	D240	9.151	8.983	8.959

Table 3 illustrates the impact of increasing activated carbon levels from 1 ppm to 3 ppm on the combustion characteristics of coconut oil. It reveals that the flash point remains constant at 251 between 1 ppm and 2 ppm but decreases at 3 ppm. Additionally, there is a decrease in calorific value at each concentration, with values of 9.151 (1 ppm), 8.983 (2 ppm), and 8.959 (3 ppm); furthermore, both density and viscosity increase as the concentration of activated carbon increases. The density values are 0.9181 (1 ppm), 0.9281 (2 ppm), and 0.9283 (3 ppm). Moreover, the viscosity values for combustion also increase from 27.37 (1 ppm) to 27.40 (2 ppm) to 27.46 (3 ppm). The addition of activated carbon breaks the carbon chain shorter, making it more reactive and more accessible for the fuel to ignite quickly. At 1 and 3 ppm, it takes longer to absorb heat because, at one ppm, the heat absorption that occurs still takes quite a long time; this is confirmed by the temperature data, which shows that the addition of 2 ppm activated carbon is the most effective. This result is supported by low density and viscosity in addition the temperature data also indicates that at two ppm it reaches the highest temperature compared to the others, namely 722.10 °C. In comparison, the addition of 3 ppm activated carbon is also effective. Still, it has a high density and can potentially increase the molecular mass of the fuel so that the carbon bonding force increases. This is what makes the fuel take longer to ignite. The findings indicate that the lower flash point suggests the fuel can easily reach its combustion temperature, causing it to burn quickly. This conclusion is supported by the increase in density and slightly higher viscosity, which suggests that the molecular structure of the CCO droplets has expanded, leading to a larger contact area between molecules. This is due to the tighter density between the fuel molecules, creating the potential for stronger attractive forces [31]. These attractive forces occur due to the release and acceptance of electrons by atoms or the formation of radicals. The double bonds in the activated carbon are not concentrated, causing its position to shift, as shown in Figure 8. Adding a catalyst alters the structure of the triglyceride molecule and weakens the van der Waals bond; moreover, because of this phenomenon, activated carbon has a weak magnetic field, which disrupts the stability of the bonds in the chemical structure of coconut oil.

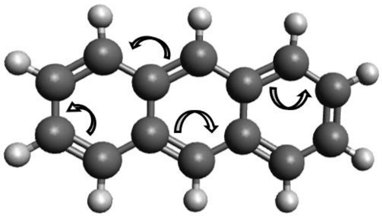

Fig. 8. Surface interaction in activated carbon

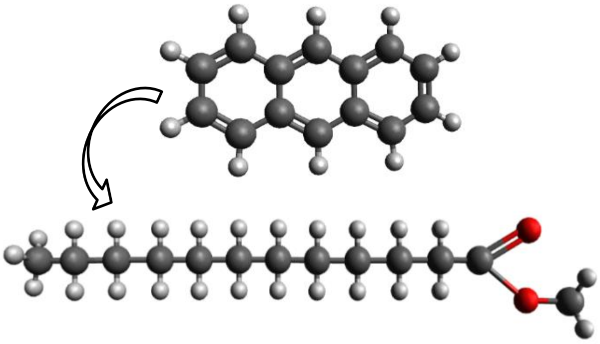

Fig. 9. Illustration of the attractive force between activated carbon and fatty acids

As seen in Figure 9, activated carbon's magnetic field disrupts the bonds' stability in coconut oil, stimulating electrons in fatty acids and glycerol to jump out of their orbits. With carbon as an element that makes up the same compound, activated carbon compounds can act like graphene, which can bind carbon atoms in triglyceride compounds; this causes carbon atoms in coconut oil to decompose [32]. The change in some hydrogen atoms into free radicals is because graphene bonds carbon atoms from triglycerides [33]. Additionally, hydrogen atoms that are loosely bonded and form magnetic graphene allotropes can influence the release of triglyceride electrons from their orbits, leading to weak triglyceride bonds. The fragility of these bonds can aid in the breakdown of molecules such as fatty acids and glycerol.

Following the breakdown of molecules in coconut oil, a process like oxidation between charged molecules or atoms with oxidants takes place. This occurs due to the interaction between oxygen from the surrounding air and the carbon elements in coconut oil. This process happens rapidly due to the difference in charge between the oxygen in the air and the carbon in the fuel, resulting in a robust and attractive force [34].

The diagram in Figure 10 illustrates the oxidation process of unbound coconut oil molecules. Unbound molecules, which are not bound to other molecules, allow them to move and interact freely. The illustration also depicts a potential difference between molecules and atoms, leading to electrostatic forces between adjacent molecules or atoms, resulting in different potential energies and electron jumps. This process facilitates the transfer of electrons between atoms or molecules, promoting interaction through strong attractive forces. Consequently, it can enhance the burning speed of droplets. This analysis is grounded in prior research findings [35].

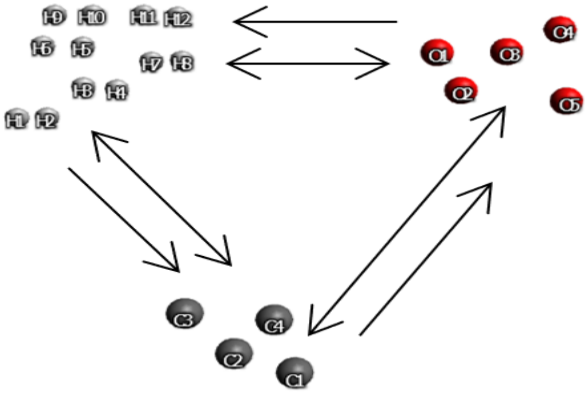

Fig. 10. The illustration depicts the process of free molecule oxidation of coconut oil

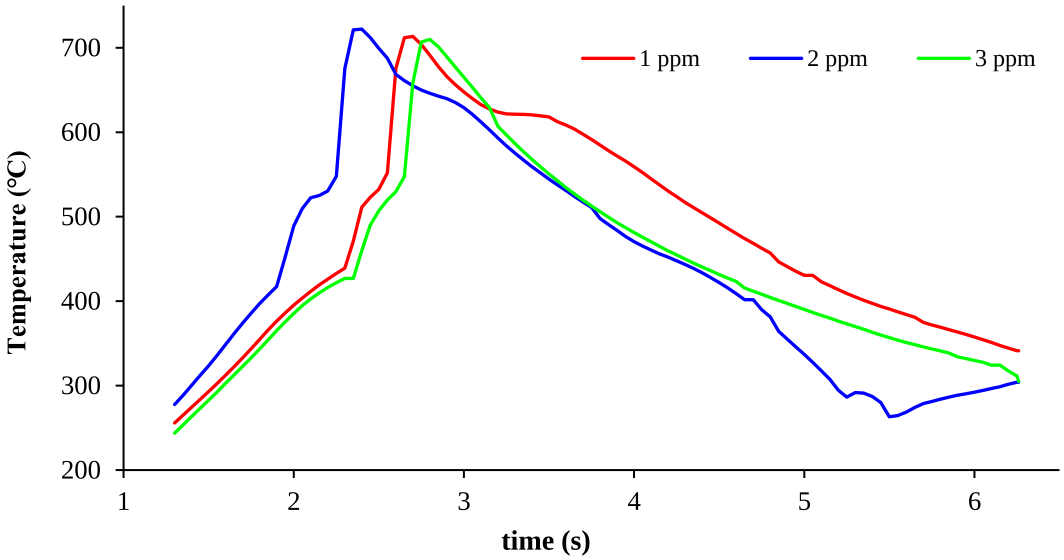

Fig. 11. Comparison of the evolution of the flame temperature

Figure 11 depicts a temperature and flame time graph for a sample of coconut oil with the addition of biocatalysts at concentrations ranging from 1 ppm to 3 ppm. The graph illustrates changes in temperature over time. When 1 ppm of biocatalyst was added to the coconut oil, it ignited at 0.08 seconds with an initial temperature of 33°C. At 2.69 seconds, it reached the highest temperature of 713.44°C before the flame was extinguished.

Similarly, when 2 ppm of biocatalyst was added to the coconut oil, it ignited at 0.08 seconds with the same initial temperature. The highest temperature of 722.10°C was reached at 2.37 seconds before the flame went out, and the temperature returned to normal. When 3 ppm of biocatalyst was added to the coconut oil, it also ignited at 0.08 seconds with an initial temperature of 33°C. The highest temperature of 709.90°C was reached before the flame was extinguished, and the temperature returned to normal. The graph indicates that the temperature and flame time changes have a positive impact, specifically in increasing the speed of fuel combustion.

Figure 12 is the result of the FTIR test. Activated carbon functions as a maker of oil molecules to be charged and facilitates their distribution with oxygen in the combustion reaction process, this is because the number of protons in activated carbon is less than oxygen, therefore activated carbon often releases its electrons to oxygen, because oxygen is a strong electron acceptor, and carbon has an electronic structure that allows it to easily release electrons. This happens because it is facilitated by a large surface area and the presence of oxygen functional groups so that an oxidation reaction occurs which results in the transfer of electrons from carbon to oxygen. Electrons from activated carbon are given to oxygen which can make oxygen negatively charged and activated carbon can be positively charged. The cathodic energy of a molecule is constant, but if the diameter of the atom increases due to the molecules receiving heat, so that the distance between the atom nuclei increases and the atomic catharsis decreases [36]. Thus, to break the atomic bonds the energy used becomes lower and in the energy absorption process can be better, so that the amount of %T infrared (IR) heat absorbed by CCO with the addition of activated carbon at a concentration of 1 ppm is 110%T, 2 ppm 109%T, and 3 ppm 108%T. These results indicate that the addition of activated carbon makes the molecular bonds of CCO weak causing the molecules to react more quickly when absorbing heat energy.

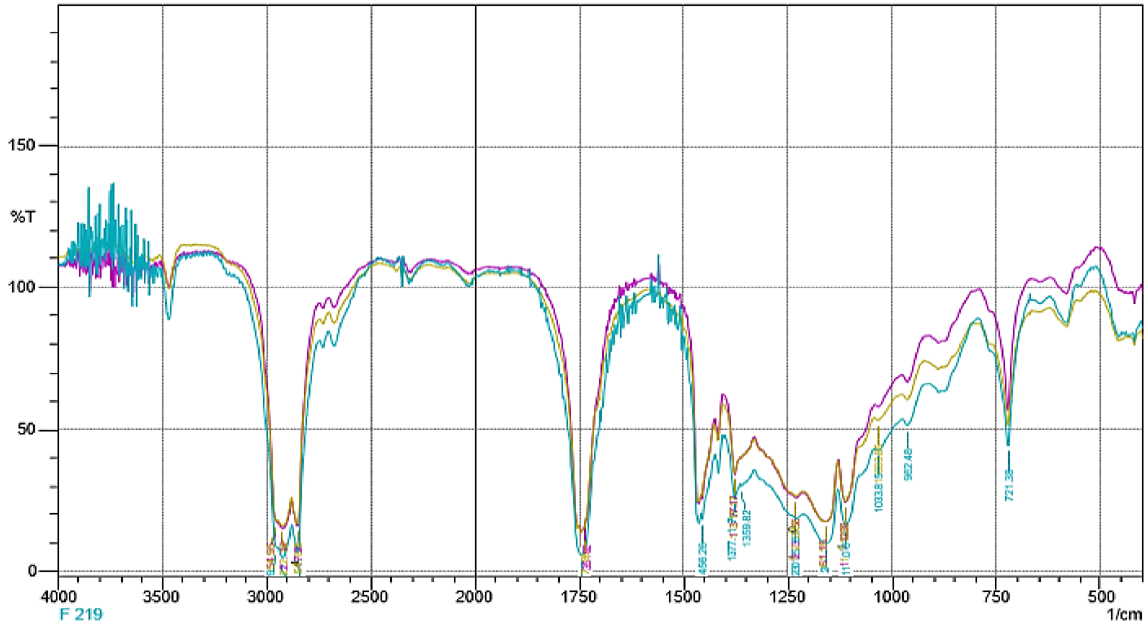

Fig. 12. FTIR graph of CCO with variations in activated carbon.
(Purple = CCO with 1 ppm; Yellow = CCO with 2 ppm; Blue = CCO with 3 ppm)

The addition of activated carbon causes the absorption of energy to increase, therefore at a concentration of 3 ppm it experiences turbulence because it absorbs quite a lot of energy in the form of heat compared to 1 ppm and 2 ppm which tend to be stable. Activated carbon with a positive charge will be mixed with coconut oil so that activated carbon often attracts electrons in the double bonds of coconut oil. In redox reactions, activated carbon can function as a reducing agent or oxidizer. In this case, activated carbon can accept or donate electrons, depending on the reaction conditions and the interacting molecules. This interaction is a weak force of attraction between molecules due to fluctuations in electron distribution. Although these interactions are not very strong, they are quite effective in attracting organic molecules to the surface of activated carbon.

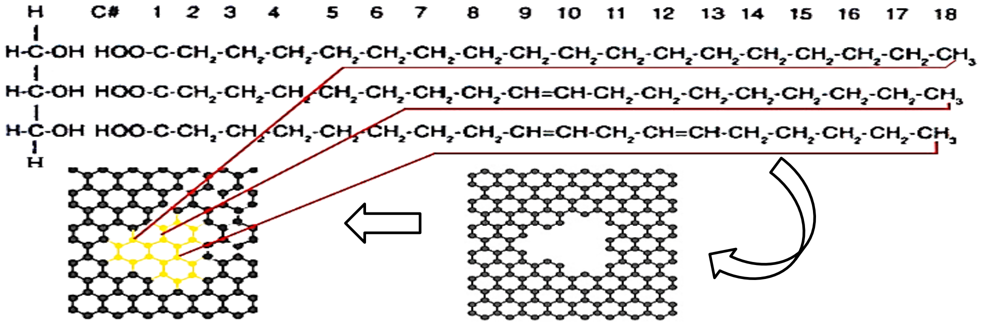

Fig.13. Illustration of the formation of bonds between the triglyceride carbon chain and the activated carbon chain of areca shell waste

Some carbon atoms in coconut oil are attracted by activated carbon to cover the defects that occur in activated carbon due to the lack of carbon atoms (this analysis is illustrated in Figure 13). Furthermore, a double bond breaking reaction or addition reaction occurs, causing the double bond in coconut oil to break into a single bond that is positively charged. With this condition, the oxygen around the droplet is negatively charged, causing an attractive force, making the diffusion process more accessible and accelerating combustion. In addition, the conjugation and delocalization of electrons between atoms reduce the energy of fuel molecules, making them easier to heat, vaporize, and ignite. Several studies that we have conducted before are per this analysis, namely by using CCO as fuel [37], morinda citrifolia oil [38], as well as crude castor oil [39] and crude sunflower oil [40], and this analysis is even clarified from the FTIR test result graph in Figure 12. With the addition of active CCO fuel molecules at concentrations of 1 ppm and two ppm, they begin to absorb the transmittance (T) of infrared (IR) energy of around 109% T, while at three ppm, it is around 110% T. This result proves our previous hypothesis, which states that adding activated carbon catalyst can reduce the reaction activation energy of fuel molecules. In addition, CCO molecules with the addition of activated carbon catalyst can absorb IR energy more strongly, indicated by more profound peaks around the waves of 1450, 1750, and 2400, and the waves of 2750 to 3000. These results suggest that adding an activated carbon catalyst to CCO will weaken the bond strength between carbon chains or the reaction activation energy of fuel molecules so that the fuel quickly absorbs heat and burns.

IV. Conclusions

The research on the combustion characteristics of coconut oil droplets mixed with areca shell-activated carbon has been completed. The findings indicate that the incorporation of areca shell-activated carbon alters the fuel's physicochemical properties, resulting in improved performance. This improvement is evidenced by a decrease in the flash point and calorific value, along with an increase in density.

An optimal addition of two ppm of activated carbon significantly enhances fuel performance; at this level, the fuel absorbs heat quickly and ignites quickly. In contrast, at one ppm and three ppm, ignition takes longer. At one ppm, the heat absorption is relatively slow, while adding three ppm may increase the fuel's molecular mass, leading to stronger carbon bonding and a longer ignition time. Areca shell-activated carbon acts as a biocatalyst, modifying the carbon chain structure in coconut oil. This alteration creates attractive forces between fuel molecules, facilitating combustion. The presence of activated carbon shortens the carbon chains, making them more reactive and allowing for easier ignition.

The complex molecular structure of areca shell-activated carbon and crude vegetable oil opens avenues for future research, particularly in exploring molecular dynamics, including bond characteristics, atomic interactions, and bond angles and their effects on fuel properties and combustion characteristics.

Acknowledgment

We sincerely thank the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia for their generous financial assistance towards this research, provided under the Fundamental scheme research, grant number 01/LPPM-USTJ/N/VI/2024. Thank you also for supporting all teams in the Fuel Engineering and Combustion Technology Laboratory of the Mechanical Engineering Department of Jayapura University of Science and Technology (USTJ) so that this research runs well and is completed within the specified time.

References

[1] O. Andreev, O. Lomakina, and A. Aleksandrova, “Diversification of structural and crisis risks in the energy sector of the ASEAN member countries,” *Energy Strategy Reviews*, vol. 35, no. April, p. 100655, 2021, doi: 10.1016/j.esr.2021.100655.

[2] A. Janzwood and K. Harrison, “The political economy of fossil fuel production in the Post-Paris Era: Critically evaluating Nationally Determined Contributions,” *Energy Research & Social Science*, vol. 102, p. 103095, Aug. 2023, doi: 10.1016/J.ERSS.2023.103095.

[3] X. Yu, N.S. Sandhu, Z. Yang, and M. Zheng, “Suitability of energy sources for automotive application – A review,” *Applied Energy*, vol. 271, p. 115169, Aug. 2020, doi: 10.1016/J.APENERGY.2020.115169.

[4] F. Jurić, M. Krajcar, N. Duić, and M. Vujanović, “Investigating the pollutant formation and combustion characteristics of biofuels in compression ignition engines: A numerical study,” *Thermal Science and Engineering Progress*, vol. 43, p. 101939, Aug. 2023, doi: 10.1016/J.TSEP.2023.101939.

[5] G. T. Hidegh, D. C. Semány, O. D. Ali, S. A. H. Rizvi, J. Han Ng, C. T. Chong *et al.*, “Comparison of thermophysical properties and combustion characteristics of various biodiesels in a non-MILD ultra-low emission swirl burner,” *Fuel*, vol. 334, p. 126583, Feb. 2023, doi: 10.1016/J.FUEL.2022.126583.

[6] S. Marianingsih, F. Mar’i, and H. Y. Nanlohy, “Artificial neural network-based modeling of performance spark ignition engine fuelled with bioethanol and gasoline,” *Journal of Mechanical Engineering Science and Technology (JMEST)*, vol. 7, no. 2, p. 190, 2023, doi: 10.17977/um016v7i22023p190.

[7] X. Wang, M. Dai, J. Yan, C. Chen, G. Jiang, and J. Zhang, “Experimental investigation on the evaporation and micro-explosion mechanism of jatropha vegetable oil (JVO) droplets,” *Fuel*, vol. 258, no. August, p. 115941, 2019, doi: 10.1016/j.fuel.2019.115941.

[8] A. Ashok, S. K. Gugulothu, R. V. Reddy, and B. Burra, “Influence of 1-pentanol as the renewable fuel blended with jatropha oil on the reactivity controlled compression ignition engine characteristics and trade-off study with variable fuel injection pressure,” *Sustainable Energy Technologies and Assessments*, vol. 52, p. 102215, Aug. 2022, doi: 10.1016/J.SETA.2022.102215.

[9] F. Declerck, P. Hikouatcha, G. Tchoffo, and R. Tédongap, “Biofuel policies and their ripple effects: An analysis of vegetable oil price dynamics and global consumer responses,” *Energy Economics*, vol. 128, p. 107127, Dec. 2023, doi: 10.1016/J.ENECO.2023.107127.

[10] M. Muhammed Niyas and A. Shaija, “Effect of repeated heating of coconut, sunflower, and palm oils on their fatty acid profiles, biodiesel properties and performance, combustion, and emission, characteristics of a diesel engine fueled with their biodiesel blends,” *Fuel*, vol. 328, p. 125242, Nov. 2022, doi: 10.1016/J.FUEL.2022.125242.

[11] X. Zhang, N.T. Lan Chi, C. Xia, A.S. Khalifa, and K. Brindhadevi, “Role of soluble nano-catalyst and blends for improved combustion performance and reduced greenhouse gas emissions in internal combustion engines,” *Fuel*, vol. 312, p. 122826, Mar. 2022, doi: 10.1016/J.FUEL.2021.122826.

[12] E. David, “Upgrading the corn cob pyrolysis vapors by processing over catalysts based on aluminium slag and the assessment of the produced bio-oil,” *Journal of Analytical and Applied Pyrolysis*, vol. 175, p. 106197, Oct. 2023, doi: 10.1016/J.JAAP.2023.106197.

[13] J. Du, L. Su, D. Zhang, C. Jia, and Y. Yuan, “Experimental investigation into the pore structure and oxidation activity of biodiesel soot,” *Fuel*, vol. 310, Feb. 2022, doi: 10.1016/j.fuel.2021.122316.

[14] D. Luning Prak, M. Hamilton, R. Banados, and J. Cowart, “Combustion and physical properties of blends of military jet fuel JP-5 with fifteen different methyl ester biodiesels synthesized from edible and nonedible oils,” *Fuel*, vol. 311, p. 122503, Mar. 2022, doi: 10.1016/J.FUEL.2021.122503.

[15] B. Kazmi, S. A. A. Taqvi, S. R. Naqvi, A. A. Mirani, M. Shahbaz, M. Naqvi *et al.*, “Techno-economic assessment of sunflower husk pellets treated with waste glycerol for the Bio-Hydrogen production– A Simulation-based case study,” *Fuel*, vol. 348, p. 128635, Sep. 2023, doi: 10.1016/J.FUEL.2023.128635.

[16] M. Nibin, J.B. Raj, and V.E. Geo, “Experimental studies to improve the performance, emission and combustion characteristics of wheat germ oil fuelled CI engine using bioethanol injection in PCCI mode,” *Fuel*, vol. 285, no. April 2020, p. 119196, 2021, doi: 10.1016/j.fuel.2020.119196.

[17] F. Fairuddin, H. Riupassa, and H.Y. Nanlohy, “Karakteristik pembakaran difusi campuran bahan bakar minyak kelapa murni dengan bioaditif minyak cengkeh,” *Jurnal Rekayasa Material, Manufaktur dan Energi*, vol. 7, no. 1, pp. 1–8, 2024.

[18] H.Y. Nanlohy, I.N.G. Wardana, N. Hamidi,and L. Yuliati, “Karakteristik pembakaran droplet minyak jarak dengan menggunakan katalis pembakaran homogen,” *Prosiding SENIATI*, vol. 3, no. 2, pp E15. 1-4, 2017

[19] H. Riupassa, H.Y. Nanlohy, and S. Suyatno, “Effects of eugenol and cineol compound on diffusion burning rate characteristics of crude coconut oil droplet,” *Automation in Construction*, vol. 6, no. 1, pp. 59–67, 2023.

[20] H. Riupassa, Trismawati, and H.Y. Nanlohy, “The effect of graphene oxide nanoparticles as a metal based catalyst on the ignition characteristics of waste plastic oil,” *AIP Conference Proceedings*, vol. 2440, pp. 1–9, 2022, doi: 10.1063/5.0075009.

[21] A. Dhanda, R. Raj, S.M. Sathe, B.K. Dubey, and M.M. Ghangrekar, “Graphene and biochar-based cathode catalysts for microbial fuel cell: Performance evaluation, economic comparison, environmental and future perspectives,” *Environmental Research*, vol. 231, p. 116143, Aug. 2023, doi: 10.1016/J.ENVRES.2023.116143.

[22] H.Y. Nanlohy, H. Riupassa, and M. Setiyo, "Characterizing of nano activated bio-carbon of Sago waste as a homogeneous combustion catalyst," *Automotive Experiences*, vol. 7, no. 1, pp. 77–85, 2024.

[23] C.C. Lee, M.V. Tran, B.T. Tan, G. Scribano, and C.T. Chong, "A comprehensive review on the effects of additives on fundamental combustion characteristics and pollutant formation of biodiesel and ethanol," *Fuel*, vol. 288, no. September, p. 119749, 2021, doi: 10.1016/j.fuel.2020.119749.

[24] H. Riupassa, S. Suyatno, and H.Y. Nanlohy, "Identifying the effect of aromatic compounds on the combustion characteristics of crude coconut oil droplet," *Eastern-European Journal of Enterprise Technologies*, vol. 2, no. 6–122, pp. 6–14, 2023, doi: 10.15587/1729-4061.2023.272289.

[25] H.Y. Nanlohy and H. Riupassa, "An experimental study on the ignition behavior of blended fuels droplets with crude coconut oil and liquid metal catalyst," *Automotive Experiences*, vol. 3, no. 2, pp. 39–45, 2020.

[26] I.R. Sugara, N. Ilminnafik, S. Junus, M.N. Kustanto, and Y. Hermawan, "The combustion characteristics of calophyllum inophyllum fuel in the presence of magnetic field," *Journal of Mechanical Engineering Science and Technology (JMEST)*, vol. 7, no. 1, p. 28, May 2023, doi: 10.17977/um016v7i12023p028.

[27] D.H.T. Prasetiyo, N. Ilminnafik, and S. Junus, "The Flame Characteristics of Diesel Fuel Blend with Kepuh (Sterculia Foetida) Biodiesel," *Journal of Mechanical Engineering Science and Technology (JMEST)*, vol. 3, no. 2, pp. 70–80, Nov. 2019, doi: 10.17977/um016v3i22019p070.

[28] H.Y. Nanlohy, I.N.G. Wardana, M. Yamaguchi, and T. Ueda, "The role of rhodium sulfate on the bond angles of triglyceride molecules and their effect on the combustion characteristics of crude jatropha oil droplets," *Fuel*, vol. 279, p. 118373, Nov. 2020, doi: 10.1016/J.FUEL.2020.118373.

[29] A. Sanata, I. Sholahuddin, and H.Y. Nanlohy, "Characterization of biogas as an alternative fuel in micro-scale combustion technology," *International Journal of Integrated Engineering*, vol. 15, no. 4, pp. 64–76, 2023, doi: 10.30880/ijie.2023.15.04.006.

[30] B. Panchal, Q. Zhao, B. Liu, Y. Sun, C. Zhao, K. Bian *et al.*, "Surface area and porosity development of catalyst using agricultural waste Chestnut shell biomass as a bio-source for ethyl oleate production," *Molecular Catalysis*, vol. 548, p. 113458, Sep. 2023, doi: 10.1016/J.MCAT.2023.113458.

[31] H.Y. Nanlohy, "Comparative studies on combustion characteristics of blended crude Jatropha oil with magnetic liquid catalyst and DEX under normal gravity condition," *Journal of Mechanical Engineering Science and Technology (JMEST)*, vol. 5, no. 2, pp. 79–88, 2021, doi: 10.17977/um016v5i22021p079.

[32] O. Awogbemi and D.V. Von Kallon, "Recent advances in the application of nanomaterials for improved biodiesel, biogas, biohydrogen, and bioethanol production," *Fuel*, vol. 358, p. 130261, Feb. 2024, doi: 10.1016/J.FUEL.2023.130261.

[33] H. Tang, T. Yang, L. Chen, Y. Zhang, Y. Zhu, C. Wang *et al.*, "Surface chemistry of graphene tailoring the activity of digestive enzymes by modulating interfacial molecular interactions," *Journal of Colloid and Interface Science*, vol. 630, pp. 179–192, Jan. 2023, doi: 10.1016/J.JCIS.2022.10.030.

[34] Suyatno, H. Riupassa, S. Marianingsih, and H.Y. Nanlohy, "Characteristics of SI engine fueled with BE50-Isooctane blends with different ignition timings," *Heliyon*, vol. 9, no. 1, p. e12922, Jan. 2023, doi: 10.1016/J.HELIYON.2023.E12922.

[35] S. Cheng, S.S. Goldsborough, C. Saggese, S.W. Wagnon, and W.J. Pitz, “New insights into fuel blending effects: Intermolecular chemical kinetic interactions affecting autoignition times and intermediate-temperature heat release,” *Combustion and Flame*, vol. 233, p. 111559, Nov. 2021, doi: 10.1016/J.COMBUSTFLAME.2021.111559.

[36] H.Y. Nanlohy, I.N.G. Wardana, N. Hamidi, L. Yuliati, and T. Ueda, “The effect of Rh3+ catalyst on the combustion characteristics of crude vegetable oil droplets,” *Fuel*, vol. 220, no. December 2017, pp. 220–232, 2018, doi: 10.1016/j.fuel.2018.02.001.

[37] R.S. Timang, H. Riupassa, and H.Y. Nanlohy, “Study eksperimental karakteristik penyalaan minyak kelapa sebagai bahan bakar alternatif dengan penambahan bioaditif minyak kayu putih,” *Jurnal Rekayasa Material, Manufaktur dan Energi*, vol. 7, no. 2, pp. 184–191, 2024.

[38] H.Y. Nanlohy and Trismawati, “The role of fatty acid of Morinda citrifolia oil as surface-active chemicals on the deinking process of waste paper,” *Materialia*, vol. 23, p. 101436, Jun. 2022, doi: 10.1016/J.MTLA.2022.101436.

[39] H.Y. Nanlohy, S. Sarikoc, and M. Setiyo, “Dynamical behavior of droplet diffusion flame of blended castor oil with metal based liquid catalyst,” *Automotive Experiences*, vol. 7, no. 2, pp. 310–320, 2024.

[40] M.M. Niyas and A. Shaija, “Effect of repeated heating of coconut, sunflower, and palm oils on their fatty acid profiles, biodiesel properties and performance, combustion, and emission, characteristics of a diesel engine fueled with their biodiesel blends,” *Fuel*, vol. 328, p. 125242, Nov. 2022, doi: 10.1016/J.FUEL.2022.125242.