Jurnal Teknosains: Jurnal Ilmiah Sains dan Teknologi
ISSN 2088-5415 (Print) | ISSN 2443-1311 (Online)
Vol. 16, No. 1, 14-23, December 2025
https://doi.org/10.22146/teknosains.110521
Submitted: 2025-08-19; Revised: 2025-09-26; Accepted:2025-09-29

JURNAL TEKNOSAINS

The role of bio-additive and attractive magnetic fields on flame behavior and hydrocarbon gas in palm oil droplets combustion

Indonesian title: Peranan bio-aditif dan medan magnet tarik terhadap perilaku api dan gas hidrokarbon pada pembakaran tetesan minyak sawit

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ABSTRAK

Ketersediaan bahan bakar fosil semakin menipis sebaliknya semakin meningkat akan kebutuhan energi didunia ini. Sumber energi alternative yang tersedia saat ini dari berbagai minyak nabati diantaranya minyak jarak pagar, minyak sawit, minyak kapuk, minyak kelapa, minyak kapas sebagai pengganti bahan bakar fosil. Namun, penggunaannya secara langsung pada mesin diesel masih menghadapi kendala berupa viskositas tinggi, titik nyala yang besar, pembakaran yang sulit berlangsung optimal, serta pembentukan endapan karbon pada ruang bakar. Permasalahan tersebut dapat diatasi melalui pemanasan bahan bakar, pencampuran dengan solar, penambahan aditif, sirkulasi gas buang, dan modifikasi ruang bakar. Studi ini bertujuan untuk memperoleh informasi peranan bioaditif dan medan magnet tarik tentang perilaku nyala api dan gas hidrokarbon dipembakaran tetesan minyak sawit. Pengujian secara langsung yang digunakan dalam metode penelitian ini pada minyak sawit dengan penambahan bioaditif minyak kayu putih dengan persentasi 3% dan medan magnet tarik (U-S) dengan diameter tetesan berkisar 0.3-0.4 mm. Termokopel dengan diameter 0.12 mm ditempatkan disisi kanan kiri medan magnet dengan intensitas medan magnet 1.1 Tesla dan kawat pemanas sebagai sumber panas diletakkan dibawah termokopel. Dalam Penelitian ini telah ditemukan bahwa peranan bioaditif minyak kayu putih dan medan magnet tarik (U-S) menghasilkan waktu evolusi nyala api paling singkat sebesar 1760 ms. Disisi lain tinggi nyala api dan gas HC menghasilkan terendah masing masing sebesar 5.74 mm dan 296 ppm. Sedangkan pada penambahan bioaditif minyak kayu putih dan medan magnet tarik (U-S) menghasilkan suhu paling tinggi sebesar 846.5 ^{o}C dibanding dengan perlakuan yang berbeda.

Kata kunci: *Minyak sawit murni; Gas hidrokarbon; Minyak kayu putih; Medan magnet tarik; Pembakaran tetesan.*

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ABSTRACT

The availability of fossil fuels is increasingly diminishing, while the global energy demand continues to rise. Alternative energy sources currently available from various vegetable oils include jatropha, palm, kapok seed, coconut, and cottonseed oil as substitutes for fossil fuels. When used directly in diesel engines, these oils can lead to several issues, including high viscosity and elevated flash points, which hinder proper fuel combustion and result in carbon deposits within the combustion chamber. Several solutions have been proposed to address these issues, including blending vegetable oils with diesel fuel at various ratios, preheating the vegetable oils, mixing them with additives, and utilizing exhaust gas recirculation and combustion chamber modification. This study investigates the role of bio-additive and applied magnetic fields in influencing flame characteristics and hydrocarbon gas emissions during palm oil droplet combustion. The experimental procedure involved direct testing on palm oil by incorporating a 3% eucalyptus oil-based bio additive and applying an attractive magnetic field (U-S), with droplet diameters ranging between 0.3-0.4 mm. Thermocouples diameter of 0.12 mm were placed on both sides of the magnet with a magnetic field intensity of 1.1 Tesla, and heating wires as the heat source were positioned beneath the thermocouples. The study found that combining eucalyptus oil bio-additive and an attractive magnetic field (U-S) resulted in the shortest flame evolution time of 1760 ms. The flame height and hydrocarbon gas concentration also reached their lowest values at 5.74 mm and 296 ppm, respectively. Meanwhile, the same treatment produced of highest temperature of 846.5 °C compared to other experimental conditions.

Keywords: *Pure palm oil; Hydrocarbon gas; Eucalyptus oil; Attractive magnetic field; Droplets combustion.*

INTRODUCTION

Global energy consumption has risen rapidly due to population growth, accelerated socio-economic development, and rapid urbanization. Among various contributors, the transportation sector plays a major role in environmental degradation. Diesel engines release substantial amounts of nitrogen oxides (NOx) and particulate matter (PM), both of which significantly contribute to environmental pollution and pose serious health risks (Dobrzyńska et al., 2020). Biofuels are considered a promising solution to the current global crises, which include energy shortages, the sharp increase in petroleum prices, and pressing environmental challenges such as pollution and rising global temperatures (Zhen et al., 2020).

Addressing these challenges requires the identification of suitable alternatives capable of producing renewable, efficient, biodegradable, and environmentally friendly fuels that are also compatible with existing engine technologies (Alalwan et al., 2019). Various feedstocks have been identified for biodiesel production, including Jatropha curcas oil, Calophyllum inophyllum oil, Ceiba pentandra oil, waste cooking oil, as well as animal-derived fats such as tallow and lard (Silitonga et al., 2020). However, biodiesel oil exhibits certain limitations when applied to diesel engines, including high density, inadequate fuel atomization, and poor cold flow characteristics (Soudagar et al., 2024). Blocking biodiesel with petroleum diesel at low percentages can mitigate these limitations.

Nevertheless, such blends may adversely affect certain emission characteristics, which can be alleviated using suitable additives. Incorporating additives has been shown to improve engine performance while reducing exhaust emissions from diesel engines (Khan et al., 2020). The present study focuses on fuel modification techniques through additive blends with diesel fuel to enhance engine performance and reduce emission characteristics (Raju et al., 2020). Using nanoparticles as biodiesel additives has demonstrated promising outcomes, including enhanced engine performance and substantial reductions in emissions (Mujtaba, Masjuki, et al., 2020). Nanoparticle additives have been known to reduce diesel engine emissions (Mujtaba, Kalam, et al., 2020). Nano-additives contribute to reducing diesel engine emissions as metal particles interact with water molecules to generate hydroxyl radicals during combustion. These radicals promote the complex oxidation of soot particles by reacting with their carbon atoms, decreasing the oxidation temperature (Akram et al., 2020).

In general, cerium oxide (CeO_2) nanoparticles enhance combustion efficiency on diesel engines, thereby contributing to the reduction of CO and HC emissions while simultaneously decreasing brake specific fuel consumption (BSFC) (Kumar et al., 2019). This effect was attributed to the reaction of base-metal nanoparticles with H_2O, leading to the formation of hydroxyl radicals that promote soot oxidation and consequently reduce combustion temperature (Sivakumar et al., 2018). Incorporation of iron nanoparticles into biodiesel has been reported to influence diesel engine performance and emission characteristics. Specifically, the addition of 1% (v/v) ferrofluid nano-additives to B20 resulted in the highest brake thermal efficiency (BTE), while simultaneously lowering fuel consumption as well as carbon monoxide (CO) and hydrocarbon (HC) emissions (Kumar et al., 2017).

The operational characteristics of conventional diesel engines utilizing alumina (Al_2O_3) and cerium oxide (CeO_2) nanoparticles have been investigated. The findings revealed that Al_2O_3 as a nano-additive produced higher brake thermal efficiency (BTE) than CeO_2, while generally reducing ignition delay and advancing the onset of combustion (Prabu, 2018). Another experimental investigation examined the effects of biodiesel–diesel blend containing titanium dioxide (TiO_2) and n-butanol on engine performance and emissions characteristics. The incorporation of TiO_2 was found to increase combustion pressure, heat release rate (HRR), torque, and brake power (BP) up to 10%. Brake specific fuel consumption (BSFC) was reduced by approximately 30% (Örs et al., 2018). Experimental investigations are carried out on diesel engines to evaluate the effects of nano particles blending with diesel fuel. Findings indicated that BSFC decreased to 20%, while BTE increased by 19%. Moreover, the SiO_2 blend was more effective than the alumina blend, as it enhanced combustion pressure, BSFC, and BTE, and reduced CO emissions.

In contrast, incorporating carbon nanotubes into diesel fuel increased NOx emissions (Chen et al., 2018). In addition to the advantages of nanoparticle additives described above, several negative effects have also been identified. First, increase NOx emission due to the provision of oxygen molecules in chain reactions; second, variations in the features of nanoparticles used as additives (such as type, size, morphology, oxide layer thickness, and volume fraction), which require special treatment; and third, injector clogging caused by unburned nanoparticle additives. In addition to the use of metal nano particles, several studies have employed liquid bio-additive to reduce the viscosity of biodiesel and to enrich the fuel with oxygenated compounds such as diethylene glycol dimethyl ether (DGM), dimethoxy methane (DMM), dimethyl ether (DME), methyl tert-butyl ether (MTBE), dibutyl ether (DBE), dimethyl carbonate (DMC), methanol, ethanol, and diethyl ether (DEE). Several characteristics of diethyl ether offer advantages, including a high cetane number, significant oxygen content, low flash point, and rapid miscibility (Jaya et al., 2022).

A study on the combustion of waste cooking oil biodiesel with diethyl ether as an oxygenated additive in droplet combustion revealed that the addition of diethyl ether at concentrations of 0%, 10%, 15%, and 20% had a significant influence on flame evolution, flame height, and exhaust gas emissions. Diethyl ether (20%) blend yielded the shortest flame duration of 592 milliseconds, the lowest flame height of 7.41 mm, and the lowest NOx emission at 137 ppm (Putra & Perdana, 2025). Subsequent research on the effect of magnetic fields and eucalyptus oil blends in palm oil droplet combustion demonstrated that applying repulsive magnetic fields and variations in eucalyptus oil bio-additive significantly influenced flame evolution. Bio-additive concentration 10% blend produced the shortest flame duration of 1600 milliseconds, the lowest flame height of 5.74 mm, and the highest temperature of 894.25 °C compared to other bio-additive variations. CO emissions at a bio-additive concentration 6% yielded the lowest value of 33 ppm, whereas NOx emissions at a bio-additive concentration (10%) reached the lowest level of 545 ppm (Taufik & Perdana, 2024).

In addition to oxygen enrichment, fuel efficiency can be further enhanced by applying a magnetic field. The magnetic field induces significant alterations in flame structure and results in distinct temperature variations (Perdana, 2023). The orientation of the magnetic field plays a role in transporting O_2 and facilitating heat transfer carried by H_2O in the form of reaction products, which determine flame stability and the achievement of complete combustion. Combining appropriate field strength and magnetic field direction is crucial in determining combustion quality (Winarko et al., 2022). The role of the magnetic field surrounding the flame induces airflow magnetically, thereby enhancing heat transfer around the flame and resulting in variations in flame height during the combustion process (Perdana et al., 2023).

Furthermore, flame characteristics, which play a crucial role in combustion stability and significantly affect engine performance, have been discussed only to a limited extent. Special attention should therefore be directed toward investigating the effects of magnetic fields and eucalyptus oil blends in palm oil droplets combustion on flame behavior and exhaust gas emission as alternative fuels. This study discusses the role of eucalyptus oil, attractive magnetic fields, and the absence of magnetic fields in palm oil droplet combustion concerning combustion characteristics and exhaust gas emissions in the combustion chamber, particularly in industrial furnaces and transportation equipment during long-term operation.

Method

Physical Properties of Palm Oil

The fuel tested was a vegetable-based fuel, palm oil, obtained from commercial products. The physical properties of palm oil are presented in Table 1, as reported in previous studies (Perdana et al., 2018). Meanwhile, as reported in previous studies, the physical properties of eucalyptus oil bio-additive are shown in Table 2 (Marlina et al., 2020).

Table 1.
Physical Properties of Palm Oil

Vegetable oil	Physical properties	Value
Palm oil	Kinematic viscosity at 38°C (mm^2/s)	39,6
	Calorific value (MJ/kg)	36,9
	Density at 20°C (kg/m^3)	910
	Cloud point (°C)	31
	Pour point (°C)	31
	Flash Point (°C)	267–330

Source: Authors' Experimental Results, 2018

Table 2.
Physical Properties of Eucalyptus Oil

Bio additive	Physical properties	Value
Crude Eucalyptus Oil	Kinematic viscosity at 40°C (mm^2/s)	2.197
	Density at 15°C (kg/m^3)	900-930
	Flash Point (°C)	49 closes up

Source: Marlina, 2020

Experimental Apparatus

The experimental investigation was conducted using an apparatus schematically illustrated in Figure 1. During droplet combustion, 4 ml of palm oil was blended with 3% eucalyptus oil bio-additive under an attractive magnetic field. Fuel droplets were manually prepared using a conventional 1 mL syringe to obtain a droplet diameter of approximately 0.3–0.4 mm. The fuel droplets were then placed at the junction of a K-type thermocouple (Pt/Rh13%, 0.1 mm in diameter). Meanwhile, the MQ-2 sensor module was positioned above the droplet combustion zone to measure the resulting exhaust gas emissions. All instruments were interfaced with an Arduino Uno module for recording temperature and hydrocarbon (HC) emissions. A NiCr electric coil wire (0.7 mm in diameter and 30 mm in length) was employed to heat the thermocouple.

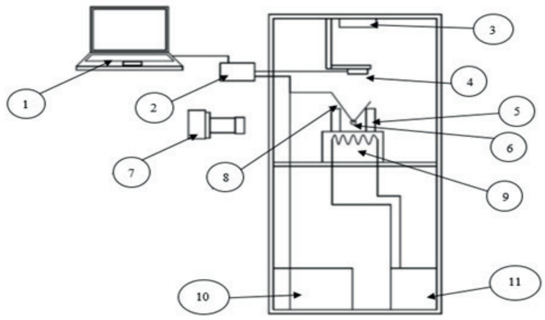

Figure 1.
Experimental Equipment Setup; (1) Laptop, (2) Data logger, (3) Lamp, (4) Sensor HC, (5) Magnet, (6) Droplet, (7) High-speed camera, (8) Thermocouple. (9) Electrical heater, (10) Temperature controller, (11) Power supply
Source: Research Documentation

Magnetic Field

The droplet formed on the thermocouple was positioned within the gap between two permanent bar magnets, generating a north–south (N–S) attractive magnetic field with an intensity of 1.1 T. Neodymium magnets of type N52, with dimensions of 40 × 25 × 10 mm and a spacing of 10 mm, were employed, as illustrated in Figures 2-3 as reported in previous studies (Winarko et al., 2022).

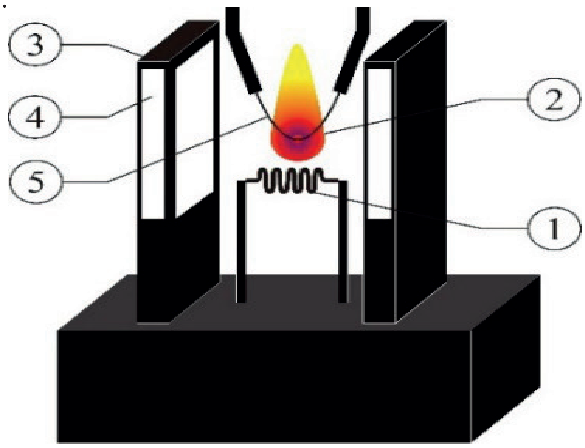

Figure 2.
Apparatus in the Combustion Chamber; (1) Electrical heater, (2) Droplet, (3) Magnet Holder, (4) Magnet, (5) Thermocouple
Source: Present Study, 2022

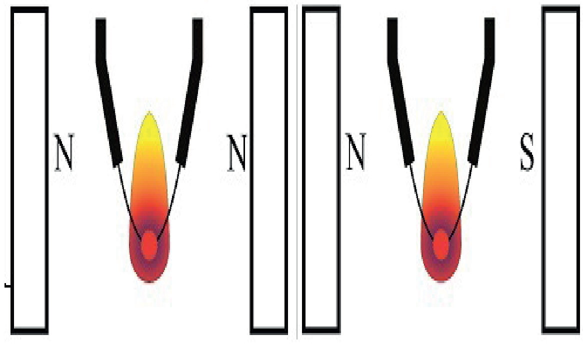

Figure 3.
Magnetic Field Position
Source: Present Study, 2022

Data Acquisition

Flame development was recorded from ignition to extinction using a Fuji ZR high-speed camera operating at 250 fps. The captured footage was subsequently processed with Free Video to JPG Converter, with time measured in milliseconds (ms). CorelDRAW software was utilized to analyze flame evolution and determine flame height. Data acquisition was conducted over ten repeated trials.

RESULTS AND DISCUSSION

Influence to Eucalyptus Oil Bio-additive and Attractive Magnetic Field on the Temporal Evolution of Flame

Figures 4-6 depict the flame evolution of pure palm oil under three conditions: without eucalyptus oil bio-additive, with 3% bio-additive, and under the influence of a north-south (N-S) attractive magnetic field. The sample without the bio-additive exhibited the longest ignition duration, measuring 2400 ms, followed by the 3% eucalyptus oil blend, which exhibited an ignition duration of 2240 ms.

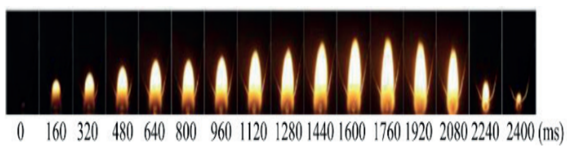

Figure 4.
Flame without eucalyptus oil bio-additive and on the absence an attractive magnetic field
Source: Researchers, 2024

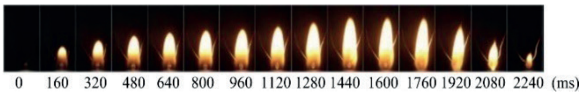

Figure 5.
Flame with 3% eucalyptus oil bio-additive blend on absence an attractive magnetic field
Source: Researchers, 2024

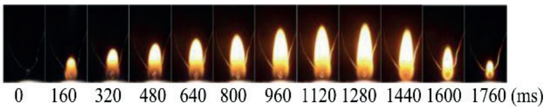

Figure 6.
Flame with 3% eucalyptus oil bio-additive blend under influence an attractive magnetic field
Source: Researchers, 2024

The shortest flame evolution was observed for the blend of 3% eucalyptus oil bio-additive with an attractive magnetic field, measuring 1760 ms. Adding eucalyptus oil bio-additive and applying the magnetic field led to a shorter flame evolution time. This effect is primarily due to the high viscosity of palm oil (as shown in Table 1); the incorporation of eucalyptus oil bio-additive reduces the overall viscosity (as shown in Table 2). The decrease in viscosity occurs because eucalyptus oil has a lower viscosity than palm oil (Marlina et al., 2020). Second, as the concentration of eucalyptus oil bio-additive increases, which contains 50%–65% cineole ($C_{10}H_{18}O$) contains oxygen, which facilitates the cleavage of molecular chains in palm oil, thereby accelerating the combustion rate of palm oil (Musyaroh, 2016).

Oxygen is essential for the combustion process as it mixes with fuel, promoting more complete combustion. Third, O_2 from the air surrounding the flame is attracted by the magnetic field (N–S), while the H_2O produced from the combustion is repelled by the magnetic field (N–S). This phenomenon accelerates and enhances the combustion reaction with the fuel, leading to a faster and more complete process (Perdana et al., 2020). The attracted oxygen flows to the lower region on both sides of the flame, increasing the concentration of oxygen and fuel molecules in the reaction zone, thereby promoting a more reactive and shorter combustion process that influences the flame evolution time.

Effect to Eucalyptus Oil Bio-additive and Attractive Magnets on Flame Heigh

The effect of eucalyptus oil bio-additive and attractive magnets on flame height is shown in Figure 7. The highest flame height was observed without eucalyptus oil bio-additive, measuring 7.74 mm, followed by 3% bio-additive and the attractive magnet, which recorded 7.2 mm and 5.74 mm, respectively. The flame height tended to increase with the evolution time until its peak, then decreased before the flame was extinguished. The differences in flame height were caused by oxygen enrichment, affecting the reaction between the fuel and the oxidizer, leading to an incomplete combustion process. Second, the attractive magnetic fields (U-S) drew oxygen in the air since oxygen is paramagnetic toward the fuel, facilitating the combustion reaction.

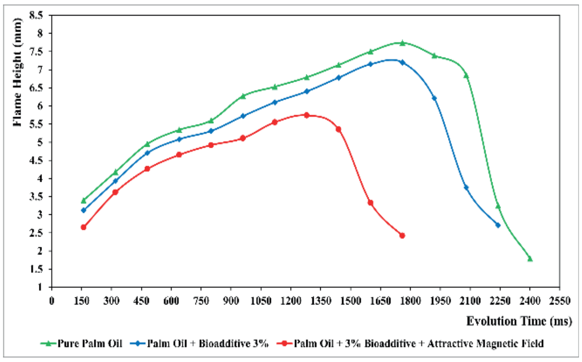

Figure 7.
Effect to Eucalyptus Oil Bio-additive and Attractive Magnetic Fields on Flame Height
Source: Researchers, 2024

Effect on Eucalyptus Oil Bio-additive and Attractive Magnetic Fields on Flame Temperature

Figure 8 shows the effect of eucalyptus oil bio-additive and attractive magnets on flame temperature. The flame temperature generally increased with evolution time, then decreased after reaching the peak before the flame extinguished. Adding eucalyptus oil bio-additive and the magnetic field produced varying flame temperatures. The highest temperature, 846.5 °C, was obtained from a mixture of 3% eucalyptus oil bio-additive and an attractive magnetic field (U-S), followed by 3% bio-additive alone and without bio-additive, which recorded 771 °C and 747.75 °C, respectively. The attractive magnetic field (U-S) showed a very sharp increase in temperature after an evolution time of 750 ms, compared to the cases without the magnetic field and bio-additive mixture. This indicates that the magnetic field influences the peak flame temperature in droplet combustion; without it, the temperature is lower due to oxygen deficiency, resulting in incomplete combustion. Second, oxygen contained in the cineole compound within the eucalyptus oil bio-additive also helps increase the temperature, as oxygen is essential in combustion.

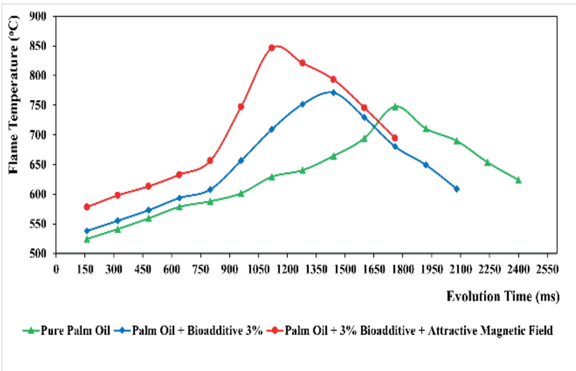

Figure 8.
Effect of Eucalyptus Oil Bio-additive and Attractive Magnetic Fields on Flame Temperature
Source: Researchers, 2024

Effect to Eucalyptus Oil Bio-additive and Attractive Magnetic Fields on Hydrocarbon (HC) Exhaust Emissions

The comparison to hydrocarbon (HC) exhaust emissions with the influence of eucalyptus oil bio-additive and the attractive magnetic fields (U–S) is shown in Figure 9. The HC emission from a 3% eucalyptus oil bio-additive mixture combined with the attractive magnetic field (U–S) produced the lowest value of 296 ppm compared to the other cases. This was followed by 329 ppm for the 3% bio-additive mixture without a magnetic field. The highest HC emission was observed for pure palm oil without eucalyptus oil bio-additive, reaching 389 ppm. The chemical reaction between palm oil and air hydrocarbon (HC) molecules contains very little oxygen (O_2), resulting in incomplete combustion. Excess unburned hydrocarbons (HC) are then released into the surrounding air. In contrast, the 3% eucalyptus oil bio-additive combined with the attractive magnetic field receives additional oxygen from the cineole compound contained in eucalyptus oil and attracts oxygen from the surrounding air, facilitating the breaking of carbon chains in palm oil and resulting in lower HC levels.

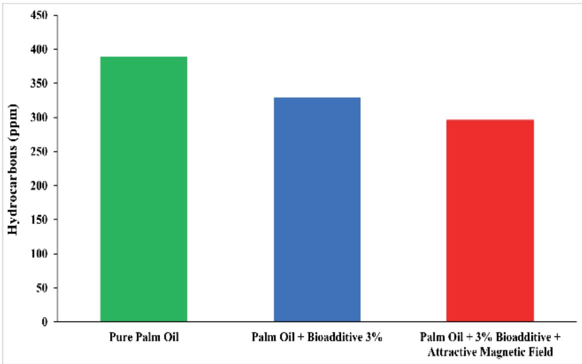

Figure 9.
Effect to Eucalyptus Oil Bio-additive and Attractive Magnetic Fields on Hydrocarbon (HC) Emissions
Source: Researchers, 2024

CONCLUSION

From the research, it can be concluded that the flame evolution with the longest burning time occurred in pure palm oil without bio-additive. The 3% eucalyptus oil bio-additive mixture and the attractive magnetic field produced the lowest flame height. The 3% eucalyptus oil bio-additive mixture obtained the highest temperature with the attractive magnetic field. Pure palm oil generated the highest hydrocarbon (HC) exhaust emissions. Magnetic field enhances the supply of paramagnetic oxygen, and fuel molecules flow to the lower part of the flame, making it more reactive and combustible. At the same time, diamagnetic gases are expelled from the reaction zone. These reactions result in a shorter flame height but an increased temperature. Meanwhile, eucalyptus oil contains cineole ($C_{10}H_{18}O$), which has an oxygen content capable of accelerating the cleavage of molecular chains in palm oil, thereby enhancing the combustion rate of palm oil.

However, this study has limitations regarding vegetable oil types, bio-additive, and magnetic field orientations, partly due to the limited availability of plantation land affecting oil production in Indonesia. Further research is needed to explore all types of vegetable oils, both pure and derived, along with bio-additive and magnetic field variations. This would provide sustainable benefits and valuable data to use magnetic field applications to advance the automotive, power generation, aerospace, and transportation industries.

ACKNOWLEDGMENTS

We would like to express our gratitude to Rector and Head of Mechanical Engineering Study Program at Universitas Maarif Hasyim Latif for their support in completing this research.

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