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Comparative Study of a Biomass-Derived Activated Carbon Catalyst and a Synthetic Silica–Alumina Catalyst on the Heat Transfer Rate Characteristics of Coconut Oil Droplet Combustion

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Abstract

This study compares the effect of a biomass-derived catalyst (areca-husk activated carbon, hereafter termed the biocatalyst) and a synthetic catalyst (silica–alumina) on the combustion characteristics and heat transfer rate of crude coconut oil (CCO) droplets, a renewable fuel that is difficult to burn because of its high viscosity. Each catalyst was blended into CCO at 1, 2, and 3 ppm, and 0.001 mL droplets suspended at a K-type thermocouple junction were ignited by a Ni–Cr wire heated at 12 V. Flame evolution was recorded with a digital camera and temperature–time data with a data logger, with five repetitions per condition; the heat transfer rate was estimated from the measured temperature using Newton's law of cooling. The biocatalyst blends burned for 1.68–2.00 s and reached peak flame temperatures of about 700–720 °C and peak heat transfer rates of 0.94–0.96 W, whereas the synthetic-catalyst blends burned longer (1.92–2.16 s) but peaked lower, at about 650–665 °C and 0.87–0.88 W. The biocatalyst blends also had a lower kinematic viscosity (27.37–27.46 cSt) than the synthetic-catalyst blends (30.54–32.52 cSt). Within the range tested, the biocatalyst mainly accelerates and intensifies heat release, with 2 ppm giving its longest flame (2.00 s), while silica–alumina mainly prolongs and stabilises combustion, with 3 ppm giving the longest flame of all blends (2.16 s). These findings indicate that low-cost activated carbon from agricultural waste can be used to improve the ignitability of raw vegetable-oil fuels in burners and small-scale combustion systems, whereas silica–alumina is better suited where a steady, sustained flame is required.

Keywords: Bio-derived catalyst; Areca husk activated carbon; Silica–alumina; Coconut oil droplet; Heat transfer rate

1. Introduction

The growing global population and rising productivity have increased human mobility, leading to a corresponding increase in the number of motor vehicles and, consequently, fossil fuel demand. Fossil fuels are formed from the compaction of hydrocarbon deposits within the earth over hundreds of millions of years, whereas the growth of fuel consumption driven by the rising number of vehicles is not matched by a comparable growth in production, since the natural formation of petroleum requires geological timescales far beyond the pace of extraction [1], [2], [3] . This widening gap between fossil energy supply and demand underlines the need for alternative, more readily renewable fuel sources.

One option is to shift toward fuels derived from vegetable oil, generally referred to as biofuel (bahan bakar nabati, BBN). Vegetable oils extracted from plant sources-including palm oil, corn oil, sunflower seed, kapok, candlenut, and jatropha-have increasingly been explored worldwide as fossil fuel substitutes, reducing dependence on petroleum-based energy. Recent studies have examined coconut, palm, sunflower, and jatropha oils and their derivatives as fuels in burners and compression ignition engines, and have shown that their combustion behaviour is governed largely by fatty acid composition, viscosity, and volatility [4], [5], [6], [7]. Coconut oil (crude coconut oil, CCO) is one such alternative, obtained from the flesh of mature coconuts through the extraction of coconut milk. However, coconut oil cannot be used directly as fuel because of its high viscosity, which makes it difficult to ignite. Blending the oil with a catalyst is one way to reduce this viscosity and improve its combustion behavior. More generally, fuel additives and catalysts-ranging from oxygenated bio-additives to metal-oxide and carbon-based nanoparticles-have been widely reported to modify fuel properties, shorten ignition delay, and intensify heat release [8], [9], [10]. A catalyst accelerates the reaction rate by opening a reaction pathway with a lower activation energy, without being consumed and without altering the thermodynamic equilibrium of the reaction [11]; the catalysts used in fuel studies may be either bio-derived (natural) or synthetic (chemical) materials.

In the strict biochemical sense, a biocatalyst is a biologically derived catalytic system, such as an enzyme or a whole microbial cell, that accelerates reactions with high stereo-, regio-, and chemoselectivity. In combustion studies, however, the term has also been applied to carbon materials prepared from biomass. To avoid ambiguity, the term biocatalyst is used in this paper only as shorthand for a biomass-derived (bio-derived) activated-carbon catalyst: a solid, predominantly carbonaceous material (carbon with smaller amounts of oxygen, hydrogen, and mineral ash) obtained by carbonizing and activating lignocellulosic biomass, whose catalytic action is attributed to its large specific surface area, pore structure, surface defects, and oxygen-containing functional groups rather than to any enzymatic activity [12], [13]. Carbon-based catalysts have been reported to lower the activation energy of thermochemical processes; in hospital-waste carbonization, for example, the reactive temperature of the waste was reduced from about 2,400 °F under high pressure to about 800 °F (200–400 °C) under normal pressure [14]. Synthetic catalysts, by contrast, are manufactured to optimize catalytic activity, selectivity, stability, and cost, and can be produced from materials such as MgO and zeolite, kaolin, natural Maredan clay, $Al_2(SO_4)_3$, or polyglycerol dendrimers; silica–alumina, an amorphous aluminosilicate bearing Brønsted and Lewis acid sites, is one of the most widely used synthetic solid acid catalysts for cracking hydrocarbon molecules [30]. Biomass-derived porous carbons are particularly attractive as low-cost catalysts because activation develops a large specific surface area and pore volume that favour interaction with reactant molecules [12].

Nanlohy *et al.* [13] characterized nano-activated bio-carbon derived from sago waste as a homogeneous combustion catalyst for coconut oil droplets at room temperature. The nano-biocatalyst was found to enhance the fuel's mechanical properties and facilitate rapid heat absorption, evidenced by a reduction in flash point and viscosity, together with an increase in fuel mass, broader molecular contact, higher reactivity, and greater heat absorption that eased ignition. Related work on diffusion combustion of pure coconut oil blended with clove-oil bio-additive similarly demonstrated that modifying the fuel with a bio-based additive can offset the poor combustion properties associated with the high viscosity and oxygen content of raw vegetable oils [15]. Prior studies on crude vegetable oil droplets treated with a rhodium (Rh^{3+}) catalyst have also shown that catalytic modification of the triglyceride chain geometry increases molecular reactivity, accelerates ignition and burning rate, and raises the combustion temperature of the fuel droplet [16]. Subsequent work showed that rhodium-based liquid catalysts alter the bond angles of triglyceride molecules and shorten the ignition time of crude vegetable oil droplets [17], [18], and that aromatic bio-additives such as eugenol and cineol increase the reactivity of crude coconut oil droplets [19]. Carbon-based additives have also been examined: nanocarbon shortened the ignition and burning time of CCO droplets [20], and activated carbon from areca shell waste improved the heat absorption and ignition of CCO droplets, with 2 ppm giving the best performance [21]. Beyond vegetable oils, metallic and carbon nanoparticles have been shown to increase the droplet burning rate through enhanced thermal conductivity and radiation absorption [22], [23], while Al_2O_3 nano-additives increased the heat release and cylinder pressure of biodiesel blends in engines [24], [25].

Because both catalysts studied here are insoluble solids dispersed in a liquid fuel, the catalysed droplet is a heterogeneous system in which the catalyst and the fuel occupy different phases, and this is particularly important at the droplet scale. In a suspended droplet, ignition and burning are controlled by coupled heat and mass transfer: heat from the hot wire and the flame is conducted into the droplet, the liquid is heated to its boiling range, and fuel vapour diffuses outward to meet oxygen in a thin diffusion flame [26], [27]. Solid particles located inside the droplet or at its surface can influence each step of this sequence. They can change the effective thermal conductivity and radiative absorption of the liquid [22], [23], provide surface sites at which triglyceride molecules are adsorbed and their bonds weakened [16], [17], and act as nucleation sites that promote internal boiling and micro-explosion [6], [28]. Because a millimetre-sized droplet has a very large surface-to-volume ratio and burns within a few seconds, these interfacial processes, rather than bulk reaction kinetics, govern ignition and heat release, so even a few ppm of catalyst can produce measurable changes in flame behaviour. Comparing a porous carbon catalyst with an acidic oxide catalyst on the same droplet is therefore a useful first step toward distinguishing heat-absorption effects from bond-weakening effects.

Despite this body of work, direct comparisons between a natural (bio-based) catalyst and a synthetic catalyst on the same fuel, under identical experimental conditions, remain limited-particularly with respect to droplet-scale heat transfer characteristics. Previous droplet studies have examined either metal-based liquid catalysts [16], [17], [18], [29], [30] or bio-derived additives [13], [15], [19], [20], [21] separately and with different set-ups, so their

relative effects cannot be compared directly, and it remains unclear whether a porous bio-derived carbon and a synthetic acid catalyst modify droplet combustion in the same way. Based on this background, the present study directly compares the effect of biocatalyst and synthetic catalyst addition on the heat transfer rate and combustion characteristics of coconut oil droplet combustion, and examines how long the combustion process lasts, from the moment of ignition until the flame is fully extinguished. Specifically, it quantifies the burn duration, flame width and height, flame temperature, and heat transfer rate of CCO droplets containing 1–3 ppm of each catalyst and relates them to the measured flash point, density, and viscosity of the blends.

2. Method

This research was carried out experimentally at the Fuel Engineering and Combustion Technology Laboratory, Department of Mechanical Engineering, Universitas Sains dan Teknologi Jayapura (USTJ). The raw materials used in this study were coconut oil (crude coconut oil, CCO), a biocatalyst prepared from areca (betel nut) husk activated carbon, and a synthetic catalyst in the form of silica-alumina. Each catalyst was blended into the coconut oil at concentrations of 1, 2, and 3 ppm, giving six fuel-blend variations in total. The suspended-droplet technique was adopted because it isolates the vaporization, ignition, and burning processes of a single droplet under controlled conditions [26], [27], [31], and comparable configurations have been used in recent droplet- and flame-scale studies of vegetable-oil fuels with additives and catalysts [21], [29], [32].

The apparatus used to prepare and test each sample is shown in **Figure 1**: (a) a 5 A step-down transformer that reduces the 220 V AC mains supply to 12 V, used to heat the Ni-Cr wire; (b) a 0.9 mm diameter Ni-Cr wire, which acts as the heating element that ignites the fuel droplet; (c) a data logger connected to a laptop, used to record and store the temperature-time data as it is generated; (d) a K-type thermocouple, used to detect and measure the flame temperature at the droplet location; (e) a high-speed camera (Canon EOS M50), used to visually record the evolution of the flame from ignition to extinction; and (f) a 1 cc syringe, used to draw up and deposit a precise 0.001 mL volume of the fuel blend onto the thermocouple junction.

These components were arranged into the complete experimental set-up shown in **Figure 2**. The laptop (1) and data logger (2) were placed together on the workbench and connected to the thermocouple (6) to capture the temperature signal in real time. The 5 A transformer (4) was wired through an MCB (5) to the Ni-Cr wire (7), which was mounted directly above the thermocouple junction so that the fuel droplet, once deposited with the syringe (8), would be heated and ignited at a fixed, repeatable position. The high-speed camera (3) was mounted on a tripod facing the ignition point to record each combustion event from a consistent angle and distance.

Data collection followed these steps: (1) the coconut oil was blended with the catalyst at the target concentration (1, 2, or 3 ppm); (2) 0.001 mL of the blended sample was drawn into the syringe; (3) the sample was deposited onto the Ni–Cr wire at the thermocouple junction; (4) the transformer and camera were switched on simultaneously to heat the wire and record the flame; (5) the entire combustion process, from ignition to extinction, was documented on video and as temperature-time data; and (6) the procedure was repeated five times for each of the six fuel-blend variations, with all temperature data logged directly to the laptop.

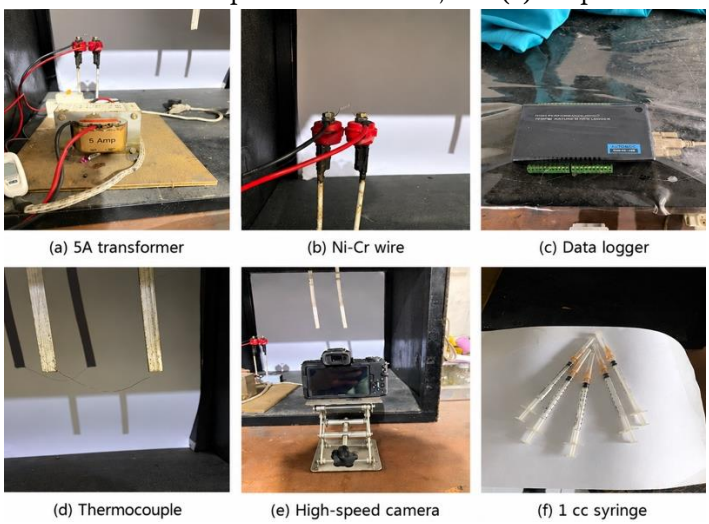


Figure 1. Experimental apparatus: (a) 5 A transformer, (b) Ni-Cr wire, (c) data logger, (d) thermocouple, (e) digital high-speed camera, (f) 1 cc syringe

Three types of variables were examined. The independent variables, deliberately varied by the researcher, were the catalyst type (areca-husk activated carbon biocatalyst or silica-alumina synthetic catalyst) and the catalyst concentration (1, 2, and 3 ppm). The controlled variables, held constant throughout all tests, were the applied voltage (12 V), the Ni-Cr wire diameter (0.9 mm), and the sample volume (0.001 mL). The dependent variables, whose values were measured, were the flame duration, flame width and height, flame temperature, and heat transfer rate.

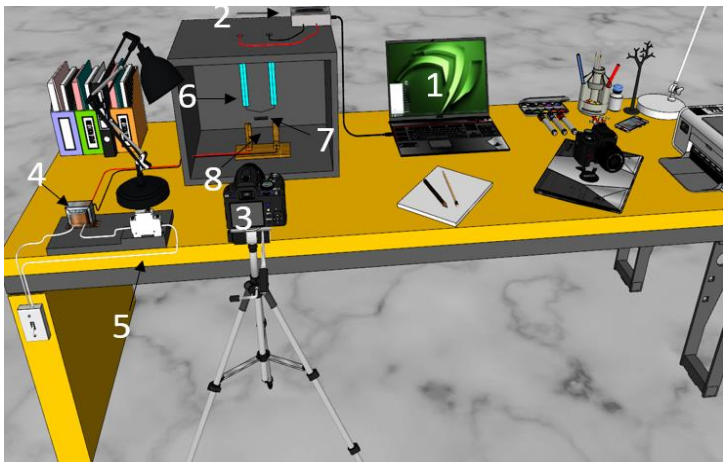


Figure 2. Experimental set-up: (1) laptop, (2) data logger, (3) camera (EOS M50), (4) 5 A transformer, (5) MCB, (6) thermocouple, (7) Ni-Cr wire, (8) syringe for oil drople

The heat transfer rate from the combustion zone at the thermocouple junction to the surrounding air was calculated from the measured temperature history using Newton's law of cooling, $q = h \cdot A \cdot (T - T\infty)$, where q is the heat transfer rate (W), h is the convective heat transfer coefficient (W/m²·K), $A = \pi \cdot d \cdot L$ is the lateral surface area of the Ni-Cr wire (m²), d is the wire diameter (0.9 mm), L is the heated wire length (m), T is the measured flame temperature, and T∞ is the ambient temperature (≈ 28 °C). For the values of h and L used in this set-up, the product $h \cdot A$ is approximately 1.38×10^{-3} W/K, so the heat transfer rate is directly proportional to the excess temperature ($T - T\infty$). The resulting heat transfer rate is reported in watts (W) and is designated Q_{bio} for the biocatalyst blends and Q_{sin} for the synthetic-catalyst blends.

3. Result and Discussion

3.1. Flame Characteristics and Burning Duration

All combustion tests were performed using a 0.9 mm diameter Ni-Cr wire at an applied voltage of 12 V. Table 1 summarizes the burning duration recorded for each catalyst type and concentration.

Table 1. Burning duration of coconut oil droplets with biocatalyst and synthetic-catalyst variations.

Fuel Blend	Sample Volume (mL)	Voltage (V)	Burn Duration (s)
CCO + areca husk carbon, 1 ppm	0.001	12	1.68
CCO + areca husk carbon, 2 ppm	0.001	12	2.00
CCO + areca husk carbon, 3 ppm	0.001	12	1.76
CCO + silica-alumina, 1 ppm	0.001	12	2.04
CCO + silica-alumina, 2 ppm	0.001	12	1.92
CCO + silica-alumina, 3 ppm	0.001	12	2.16

Figure 3 shows the flame evolution sequence recorded for all six fuel-blend variations, from ignition to extinction. For the 1 ppm biocatalyst blend (Figure 3a), ignition occurred at 0.08 s, with an initial flame width of 4.2 mm and height of 13.4 mm and a light orange color. The flame reached its peak at 1.32 s, with a width of 6.0 mm and a height of 41.9 mm, before gradually shrinking and extinguishing at 1.68 s. The active-carbon biocatalyst is understood to make the coconut oil's molecular bonds more reactive and thus easier to break down, promoting faster vaporization and reaction; part of this effect arises because carbon atoms from the coconut oil are drawn toward the activated carbon to compensate for surface defects caused by its own carbon deficiency. This behaviour agrees with reports that nanocarbon and areca-shell activated carbon make crude coconut oil droplets more reactive and easier to ignite [20], [21], and with the general role of a catalyst in opening a reaction pathway with a lower activation energy [11].

As the biocatalyst concentration increased from 1 to 3 ppm (Figure 3a-c), the flame duration changed non-monotonically-1.68 s, 2.00 s, and 1.76 s, respectively (Table 1)-while the flame width and height at each stage varied with concentration, reflecting the combined effect of catalyst loading on fuel viscosity and reactivity. A similar optimum at 2 ppm was reported by Raehan et al. [21] for areca-shell activated carbon in CCO, who attributed the weaker performance at 3 ppm to the increase in molecular mass, which strengthens carbon bonding and delays ignition. A similar pattern was observed for the synthetic (silica-alumina) catalyst (Figure 3d-f), which produced a generally longer overall burn duration than the biocatalyst at the same concentration (Table 1). At 1 ppm, the synthetic-catalyst flame lasted 2.04 s, reaching a peak width of 10.6 mm and height of 30.4 mm at 1.84 s, and at 3

ppm the flame lasted 2.16 s-the longest duration recorded among all six variations, consistent with the synthetic catalyst's role in slowing vaporization and stabilizing the combustion process.

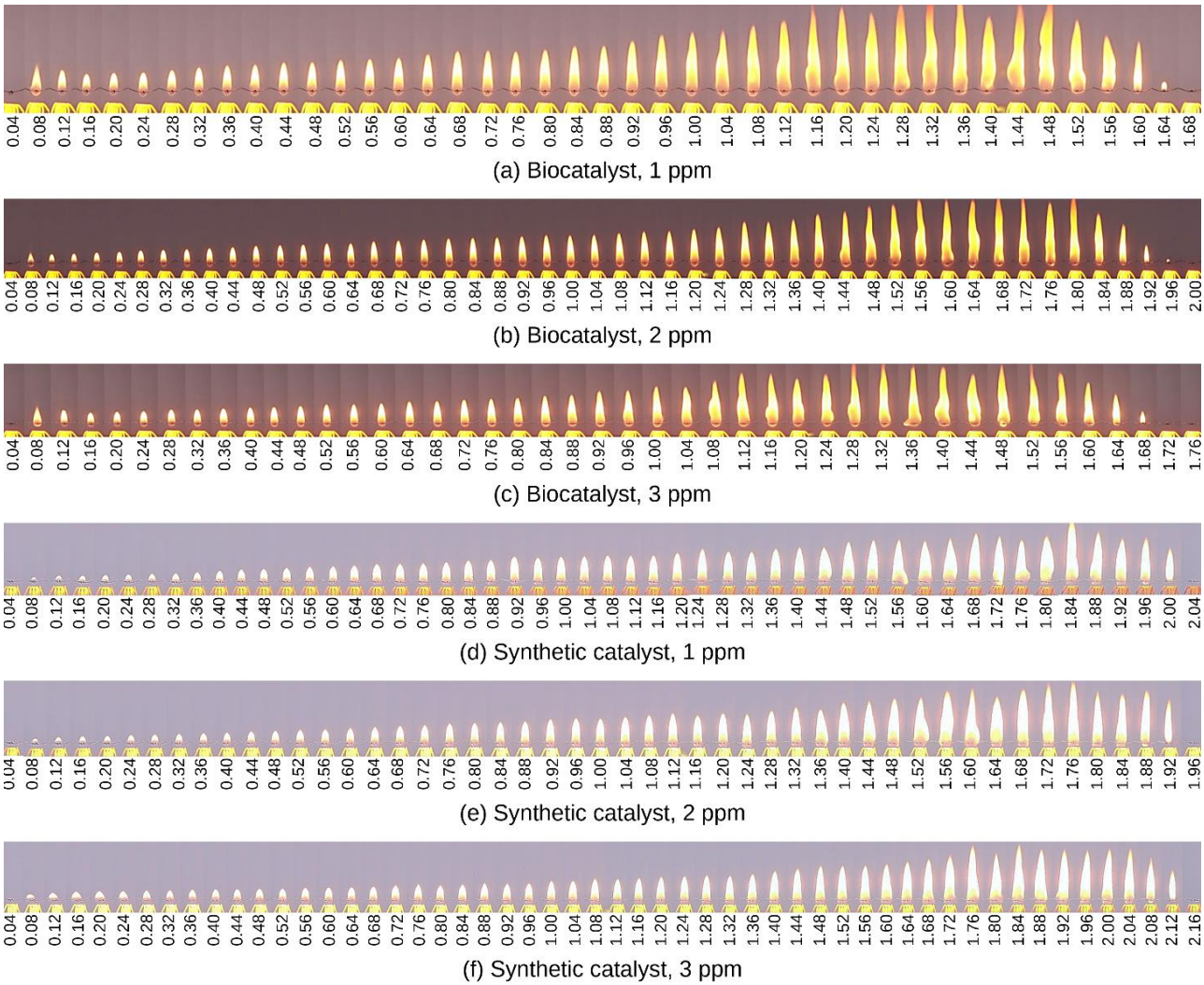


Figure 3. Flame evolution sequence of coconut oil droplet combustion for all six fuel-blend variations (time in seconds): (a) biocatalyst 1 ppm, (b) biocatalyst 2 ppm, (c) biocatalyst 3 ppm, (d) synthetic catalyst 1 ppm, (e) synthetic catalyst 2 ppm, (f) synthetic catalyst 3 ppm

3.2. Discussion

Figure 4 compares the flame width over time for the synthetic catalyst (Synthetic 1-3 ppm) and the biocatalyst (Biocatalyst 1-3 ppm). During the early stage, all variations show an increase in flame width, with the synthetic catalyst-particularly the 3 ppm variation-producing consistently larger values than the biocatalyst. In the middle stage, the synthetic-catalyst flames stabilize in the 5-7 mm range, while the biocatalyst flames increase more gradually from a lower baseline. At the peak stage, the 2 ppm synthetic catalyst produces the largest flame width, around 10-11 mm, followed by the 3 ppm and 1 ppm synthetic variations, while the biocatalyst variations remain within 5-7 mm. After the peak, all variations decline until extinction, with the 3 ppm synthetic catalyst sustaining the longest burn duration. Overall, the synthetic catalyst produces a larger flame width, higher combustion intensity, and better flame stability than the

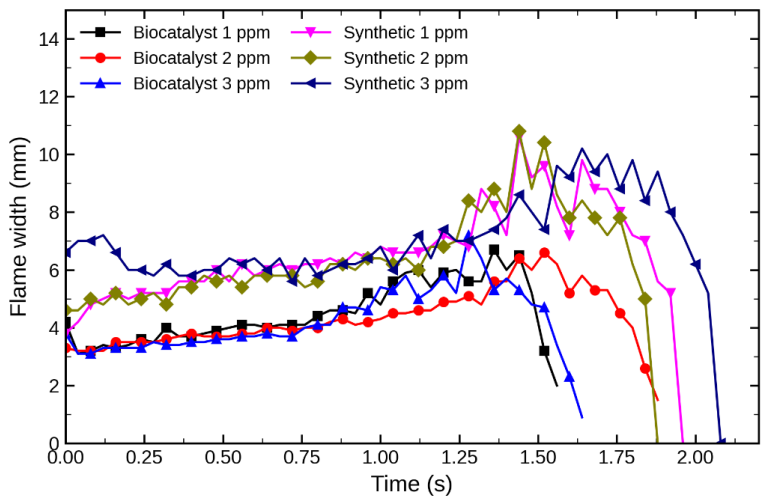


Figure 4. Flame width versus time for synthetic-catalyst and biocatalyst variations

biocatalyst, which tends to produce a smaller, shorter-duration flame. The larger and more sustained flames of the silica-alumina blends are consistent with engine studies in which Al_2O_3 -based nano-additives improved fuel-air mixing and the combustion of biodiesel blends [24], [33], [34].

Figure 6 shows the corresponding flame height over time. In the early stage, the biocatalyst-especially at 1 ppm-shows a slightly greater flame height than the synthetic catalyst, while the middle stage shows the biocatalyst fluctuating more than the more consistent rise of the synthetic catalyst. At the peak, the synthetic catalyst is more dominant: the 2 ppm and 3 ppm variations reach the highest flame heights, around 40-45 mm, followed by the 1 ppm variation, while the biocatalyst variations remain slightly below or near these values but with lower stability, rising quickly and then dropping more sharply. In the final stage, the 3 ppm synthetic catalyst sustains the longest burn time, whereas the 1 ppm and 3 ppm biocatalyst flames decline and extinguish earlier. This indicates that the synthetic catalyst produces a more stable and longer-lasting flame height, while the biocatalyst produces a faster but less stable rise that extinguishes sooner. Flame width and height are commonly used as indicators of the burning intensity and stability of vegetable-oil droplet flames [29], [32].

Figure 5 presents the temperature-time history of both catalyst types. In the early stage (≈1.5 s), all variations show a gradual temperature rise from preliminary heating; the 1 ppm synthetic catalyst and the 2 ppm biocatalyst show the fastest initial response, whereas the 3 ppm synthetic catalyst rises most slowly. In the transition-to-peak stage (≈1.5-2.5 s), where the main oxidation reaction takes place, the 2 ppm and 3 ppm biocatalyst variations reach the highest peak temperatures, around 700-730 °C, followed closely by the 1 ppm biocatalyst and 2 ppm synthetic catalyst, while the 1 ppm and 3 ppm synthetic-catalyst variations peak somewhat lower. This indicates that the biocatalyst has a greater capacity to intensify heat release during the main combustion stage. Comparable increases in peak heat release have been reported for metal-oxide and carbon-based additives, which act as thermal bridges inside the fuel [23], [35], and changes in fuel composition are known to alter the timing and intensity of heat release through chemical kinetic interactions [36]. After the peak, all variations cool down, but at different rates. Between the peak and 5.15 s, the biocatalyst blends cool at roughly 120-150 °C/s, whereas the synthetic-catalyst blends cool more slowly, at roughly 100-110 °C/s, so the synthetic catalyst retains its temperature somewhat longer after the peak. It should be noted that temperature recording for the biocatalyst blends ended at 5.15 s, at which point the 1 ppm biocatalyst was still at about 418 °C-higher than any synthetic blend at that instant-whereas the synthetic blends were recorded up to 6.5-6.9 s. Differences beyond 5.15 s therefore reflect the recording length rather than the combustion behaviour and are not used to compare the two catalysts. A slower, steadier decay of this kind has also been associated with additives that suppress disruptive micro-explosions and promote more uniform droplet evaporation [28], [37].

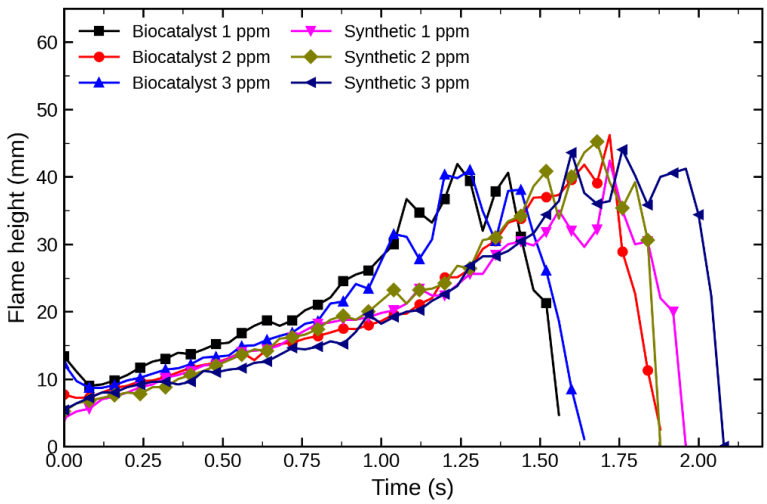


Figure 6. Flame height versus time for synthetic-catalyst and biocatalyst variations

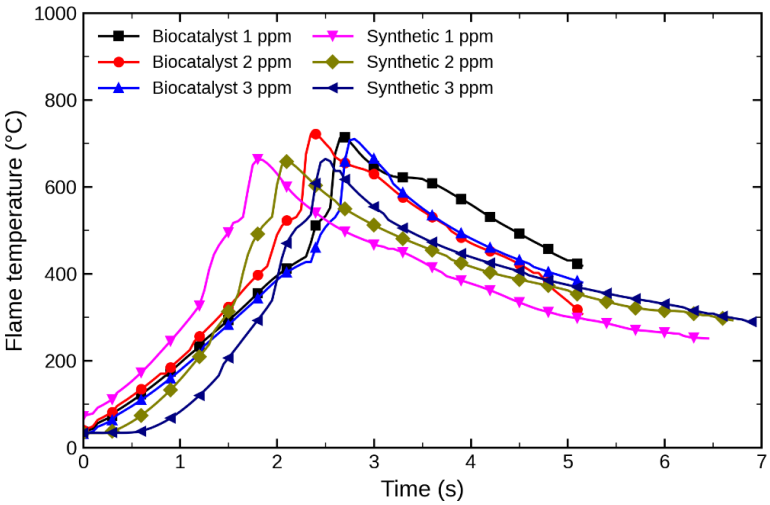


Figure 5. Flame temperature versus time for synthetic-catalyst and biocatalyst variations

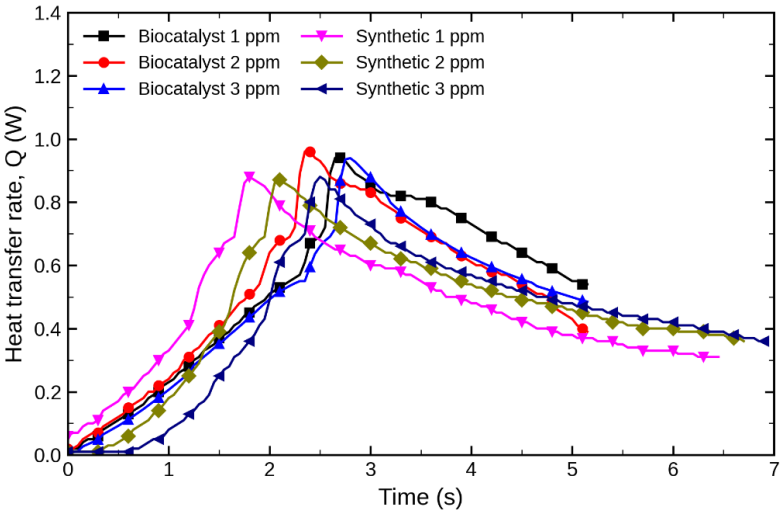


Figure 7. Heat transfer rate versus time for the biocatalyst (Qbio) and synthetic-catalyst (Qsin) blends

Overall, the biocatalyst is superior in producing a higher peak temperature and a faster rate of heat build-up, whereas the synthetic catalyst is superior in thermal stability and in sustaining temperature over a longer period. This pattern is mirrored in the heat-transfer-rate data in Figure 7, comparing Qbio (coconut oil + areca-husk activated carbon) and Qsin (coconut oil + silica-alumina). Because the heat transfer rate is proportional to the excess temperature (T - T∞), both blends show the same rise-peak-decay profile as the temperature curves. The biocatalyst blends reach the higher peak heat transfer rate, 0.94-0.96 W at 2.35-2.80 s, compared with 0.87-0.88 W at 1.80-2.50 s for the synthetic-catalyst blends, i.e. about 8-10% higher. After the peak, Qbio decreases at about 0.16-0.20 W/s, slightly faster than Qsin (about 0.14-0.16 W/s). This suggests that the porous, high-surface-area structure of the areca-husk activated carbon intensifies heat release during the main combustion stage and produces a higher peak heat transfer rate, whereas the silica-alumina blend releases heat at a lower peak but more evenly over time, in agreement with its longer flame duration. The higher peak heat transfer rate of Qbio is consistent with reports that carbon-based and metallic particles raise the effective thermal conductivity and radiation absorption of the fuel, thereby accelerating heat release [22], [23].

Table 2 lists the physicochemical properties of both blends. For flash point, the biocatalyst blends at 1 and 2 ppm both reach 251 °C, higher than the synthetic catalyst (233.0 and 250.5 °C, respectively), indicating that the biocatalyst improves the fuel's pre-ignition stability even though it releases energy more rapidly once combustion begins. At 3 ppm, the biocatalyst's flash point drops to 244.5 °C, suggesting that thermal stability decreases as the reaction becomes faster at higher concentration, whereas the synthetic catalyst's flash point rises steadily (233.0 → 241.0 °C), reflecting more controlled and stable combustion.

Kinematic viscosity shows a clearer contrast: the biocatalyst blends remain nearly constant at 27.37-27.46 cSt, while the synthetic-catalyst blends are substantially higher and continue to rise with concentration (30.54 → 32.52 cSt). The biocatalyst's lower viscosity allows easier flow and atomization, accelerating air mixing and reaction-consistent with its faster but shorter combustion-while the synthetic catalyst's higher viscosity slows vaporization, producing slower but more stable and longer-lasting combustion. Density follows a related trend: the biocatalyst blends increase from 0.9181 to 0.9283 g/mL, indicating an effective mass addition from the activated carbon that can accelerate energy release, whereas the synthetic-catalyst blends remain nearly constant (0.9275-0.9278 g/mL), reflecting a more homogeneous fuel that supports steadier combustion. The strong influence of viscosity on the vaporization and burning behaviour of catalysed fuel droplets has also been highlighted in earlier studies [17], [30], [38].

Taken together, the biocatalyst combination of low viscosity, increasing density, and high flash point results in a fuel that vaporizes and reacts quickly, producing fast combustion with a high peak temperature but a shorter, less stable flame duration. The synthetic catalyst's combination of high viscosity, stable density, and a gradually increasing flash point results in slower vaporization and more controlled reaction, producing more stable and longer-lasting combustion. In summary, the biocatalyst is more effective for accelerating the combustion reaction kinetics, whereas the synthetic catalyst is more effective for stabilizing the combustion process.

Table 2. Physicochemical properties of the biocatalyst and synthetic-catalyst fuel blends

Properties	1 ppm Bio	1 ppm Syn	2 ppm Bio	2 ppm Syn	3 ppm Bio	3 ppm Syn
Flash point, PMcc, °C (ASTM D93)	251	233.0	251	250.5	244.5	241.0
Density at 15 °C, g/mL (ASTM D1298)	0.9181	0.9275	0.9281	0.9276	0.9283	0.9278
Kinematic viscosity at 40 °C, cSt (ASTM D445)	27.37	30.54	27.40	32.24	27.46	32.52

4. Conclusion

Based on the results of this study, it can be concluded that the biocatalyst increases fuel reactivity, resulting in faster ignition and a higher peak temperature; however, combustion in the presence of the biocatalyst tends to be faster but less stable, as indicated by its shorter flame duration. In contrast, the synthetic catalyst produces more stable combustion, characterized by a longer flame duration and a greater ability to sustain temperature over time, although it exhibits a slower initial temperature rise. The biocatalyst blends also achieve a higher peak heat transfer rate (0.94-0.96 W) than the synthetic-catalyst blends (0.87-0.88 W), whereas the synthetic-catalyst blends show a slightly slower decline in heat transfer rate after reaching the peak. Overall, the biocatalyst is more effective in accelerating the combustion process, while the synthetic catalyst is more effective in maintaining combustion stability and continuity. Future research should investigate a wider range of catalyst concentrations to determine the optimum composition and explore the combination of biocatalysts and synthetic catalysts to assess whether their respective advantages can be integrated to further enhance combustion performance.

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