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Evaporation Behaviour of Biodiesel Droplets on Heated Wall Surfaces

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Biodiesel, evaporation, heated surface, fuel droplet

Abstract

The rising demand for renewable energy sources has increased interest in biodiesel as a sustainable alternative to conventional diesel fuel. This study investigates the evaporation characteristics of diesel, pure biodiesel, and biodiesel blends using a Hot Surface Evaporation Test (ET) to simulate conditions similar to those inside a diesel engine. The main objective is to evaluate the influence of biodiesel concentration on evaporation behaviour when fuel droplets are deposited on heated aluminum surfaces. Key parameters examined include surface temperature, blend ratio, and droplet lifespan. Results reveal that higher biodiesel content leads to increased fuel film thickness and elevated boiling points, which collectively slow down the evaporation process. The Maximum Evaporation Point (MEP) for each fuel type was calculated and compared. These findings offer valuable insights into the combustion behaviour of biodiesel fuels and support their broader implementation in Malaysia's transportation sector, aligning with the country's renewable energy development goals. This work provides a foundation for future research into biodiesel combustion dynamics under engine-relevant conditions.

1. Introduction

The global transition toward renewable energy sources has increased interest in biodiesel as a sustainable and environmentally friendly alternative to conventional petroleum-based diesel fuel. In Malaysia, the widespread use of palm-based biodiesel is actively promoted due to its abundant domestic supply, biodegradability, and potential to reduce greenhouse gas emissions. As the adoption of biodiesel grows, particularly in the transportation sector, understanding its physical and chemical behaviour under engine-relevant conditions becomes essential to ensure optimal performance, reliability, and compliance with emission standards. One of the key processes influencing the combustion efficiency of biodiesel in compression ignition engines is evaporation. Efficient evaporation of fuel droplets facilitates thorough air–fuel mixing, which directly affects ignition quality, combustion stability, fuel consumption, and pollutant formation. However, high-blend biodiesel fuels pose challenges due to their inherently higher boiling points, greater viscosity, and increased latent heat of vaporization compared to

petroleum diesel, as noted by Jikol et al., [1]. These properties may hinder fuel atomization and delay the vaporization process, particularly under standard engine operating conditions.

Several experimental and numerical studies have been conducted to better understand the evaporation characteristics of biodiesel fuels. Jikol et al., [1] employed a Hot Surface Deposition Test (HSDT) to simulate internal engine conditions and observed the behaviour of palm biodiesel blends (B10–B50) on heated aluminium alloy surfaces. Their results indicated that as biodiesel concentration increased, evaporation slowed, necessitating higher surface temperatures to achieve complete vaporization. Furthermore, the study introduced the concept of the Maximum Evaporation Point (MEP) defined as the temperature at which the evaporation rate is at its peak which was shown to increase proportionally with biodiesel content. Complementary numerical simulations by Amsal et al., [2] analysed palm biodiesel evaporation under varying ambient conditions. Their findings demonstrated that higher temperatures significantly enhanced evaporation rates, while elevated pressures delayed vaporization by limiting diffusion. Oxygen concentration in the combustion environment also played a modest role in promoting evaporation through enhanced oxidation, underscoring the complex interaction between fuel properties and engine conditions.

Physical characteristics such as thermal conductivity, surface tension, and volatility differ significantly between diesel and biodiesel fuels, thereby affecting droplet behaviour on hot surfaces. Putra et al., [3] reported that biodiesel's high surface tension and viscosity reduce droplet spreading and alter the fuel–air interface, which can prolong droplet lifetime and delay evaporation. These thermophysical differences necessitate further investigation, particularly in the context of fuel deposition and droplet evaporation on engine-representative surfaces. To address these challenges, the Hot Surface Evaporation Test (ET) offers a controlled and repeatable method for isolating evaporation behaviour from other droplet impact phenomena such as splashing or rebound [4]. By maintaining constant surface temperatures and standardized droplet parameters, ET enables accurate assessment of droplet lifetime, evaporation rate, and fuel volatility key metrics for optimizing engine combustion processes [5]. This study aims to experimentally investigate the evaporation characteristics of palm oil biodiesel and its blends with petroleum diesel using a hot surface evaporation setup. By analyzing the effects of surface temperature, blend ratio, and droplet behaviour, this work seeks to determine the Maximum Evaporation Point (MEP) for each fuel type and identify how increasing biodiesel content alters the evaporation process. The findings contribute valuable insights for enhancing combustion efficiency, refining fuel injection strategies, and supporting Malaysia's policy goals for greater biodiesel integration in the transportation sector.

2. Methodology

The experimental setup used in this study as shown in Figure 1 is designed to investigate the evaporation characteristics of biodiesel-diesel blends on a controlled heated surface using the Evaporation Test (ET) method. This setup enables precise control of surface temperature, droplet size, and fuel blend composition to observe the evaporation behaviour and determine the Maximum Evaporation Point (MEP) for each fuel type. An aluminium alloy plate was selected as the heated surface due to its excellent thermal conductivity and resistance to deformation at elevated temperatures. The plate was mounted on a laboratory-grade hot plate equipped with a digital temperature controller. Surface temperatures were varied between 250 °C and 340 °C in incremental steps appropriate for analyzing the evaporation behavior of biodiesel and its blends. To ensure accurate thermal conditions, a K-type thermocouple was affixed directly to the surface of the aluminium plate. Real-time temperature readings were displayed via a digital controller. Additionally, an infrared (IR) thermometer was used to cross-verify surface temperatures prior to each test, ensuring consistency and reliability throughout the experiment. Fuel droplets were dispensed using a precision micro-pump fitted with a fine needle, capable of delivering uniform droplets ranging from 2 to 5 μL. The system ensured consistent droplet volume and placement for each test. Droplets of diesel, B10, B20, B30, B50, and B100 were deposited onto the heated surface. A high-resolution video camera was positioned above the hot plate to capture the full evaporation process of each droplet in real-time and the video footage was used to analyze key droplet behaviors, such as the onset of evaporation rate, bubble formation, retraction, and total droplet lifetime. On the other hand, multiple trials were conducted for each temperature setting and fuel type to ensure repeatability accuracy. The shortest droplet lifetime observed at a given temperature was used to determine the Maximum Evaporation Point (MEP) for each fuel blend. Prior to conducting the evaporation tests, all fuel samples including diesel and biodiesel underwent preliminary characterization. Key physical properties such as density, kinematic viscosity, and thermal stability were measured under controlled conditions to ensure comparability between fuel types and to support interpretation of evaporation results.

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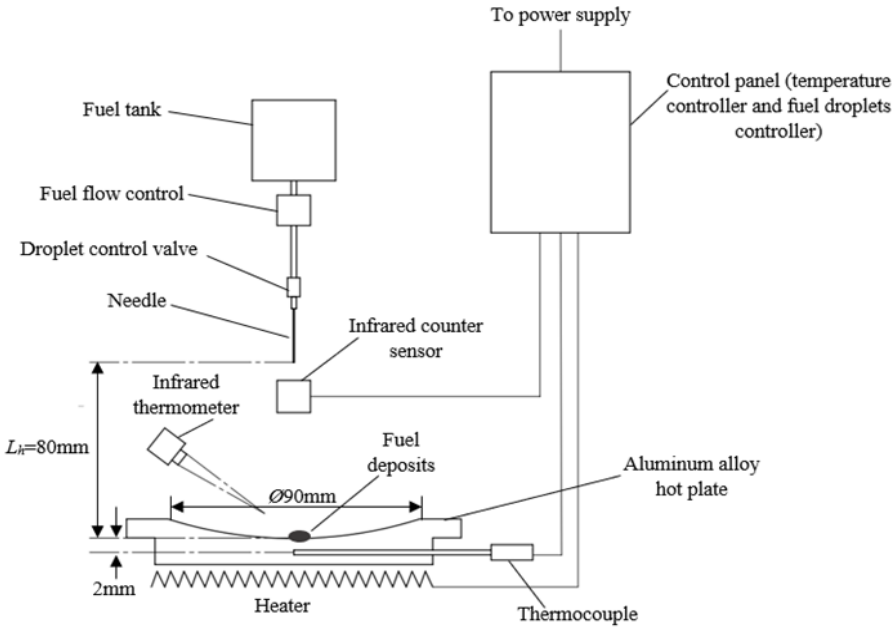

Fig. 1 *Schematic diagram of HSDT setup*

3. Results

Evaporation tests were conducted for various biodiesel blends namely Diesel (B0), B10, B20, B30, B40, B50, and B100 on a heated aluminium surface, with surface temperatures ranging from 250 °C to 340 °C. Across this temperature range, significant changes in droplet behaviour were observed. At lower temperatures, droplet evaporation was characterized by gradual shrinkage and intermittent bubble formation. As the surface temperature increased, some droplets exhibited a rapid transition to film boiling, particularly at the higher end of the temperature spectrum. At 250 °C, all fuel samples demonstrated relatively slow evaporation rates, with droplets persisting on the surface for extended periods. This effect was particularly pronounced in high biodiesel blends such as B50 and B100, which exhibited the longest droplet lifetimes. As the surface temperature increased, droplet lifetime consistently decreased for all blends, indicating an acceleration of the evaporation process. For lower biodiesel blends specifically Diesel (B0), B10, and B20 evaporation occurred much more rapidly. These fuels vaporized with minimal delay and left little to no residue on the surface. In contrast, higher blends exhibited delayed vaporization and more substantial fuel remnants, suggesting incomplete or slower evaporation processes. The observed differences in evaporation behaviour are primarily attributed to the distinct physicochemical properties of the fuel blends, as summarized in Table 1. Higher biodiesel blends possess greater viscosity and density, which hinder efficient heat transfer and reduce evaporation rates. Additionally, the lower heating value (LHV) of biodiesel-rich blends results in less energy being released per unit mass, further contributing to slower droplet evaporation. These findings underscore the strong influence of fuel composition on evaporation dynamics under elevated temperature conditions.

Table 1 *Physicochemical properties of DF and blended malaysian palm oil biodiesel*

Properties	DF	B10	B20	B30	B40	B50	B100
Density (kg/m^3)	847	850	853	857	860	863	880
Kinematic Viscosity (mm^2/s)	3.80	3.86	3.91	3.95	4.00	4.61	5.80
Heating Value (MJ/kg)	45.21	44.23	44.12	43.13	42.95	42.74	41.20
Acid Value (mg KOH/g)	0.16	0.18	0.22	0.26	0.30	0.33	0.42

At a surface temperature of 340 °C, the high-viscosity blends B40, B50, and B100 exhibited noticeably faster evaporation rates compared to lower temperature conditions. However, their evaporation was still slower than that of Diesel and B10, which continued to show more rapid vaporization and shorter droplet lifetimes. This observed trend indicates that higher surface temperatures are required for biodiesel-rich blends to achieve evaporation performance comparable to that of lower biodiesel content fuels. The underlying reason lies in the intrinsic physicochemical properties of these fuels, including higher viscosity, density, and lower heating value, which collectively impede heat transfer and delay phase change. These findings are consistent with trends reported in the existing literature, reinforcing the conclusion that biodiesel content significantly influences evaporation behaviour. Understanding this relationship is critical for optimizing the use of biodiesel in compression ignition engines, where rapid fuel vaporization is essential for effective air–fuel mixing and efficient combustion. The results underscore the need for temperature-specific calibration in engine systems operating with high-blend biodiesel fuels to achieve desired combustion performance and emission standards.

To more clearly visualize the behaviour of evaporation of the diesel, and biodiesel blends, three characteristic surface temperatures were chosen 250 °C (low), 295 °C (mid) and 340 °C (high) as shown in Figure 2 to 8. At 250 °C (low temperature phase) evaporation, although still relatively slow, occurs for all fuels within this phase. Droplets lose their shape at a much slower rate and may smoke or bubble lightly. Higher biodiesel blends such as B50 and B100 as depicted in Figure 7 and 8 demonstrate droplet bodies that are thicker, take longer to boil, and have more surface tension due to their relationship in viscosity. Diesel and lower blends (B10, B20) begin to show initial shrinkage but still evaporate at a slower rate as illustrated in Figure 2 and 3. Whereas at 295 °C (mid temperature phase) which is the transitional boiling phase, where visible changes to the droplets motion are apparent, moderate boiling will be occurring and droplets will begin to shrink at an increased rate. For mid-blends, such as B20 and B30, the vapour escape rate is steady, and small bubbling may be present. High blends (B50 and B100) may take longer to begin boiling, but more pronounced boiling will occur versus 250 °C. Meanwhile at 340 °C (high temperature phase) at this high phase, evaporation is at its most vigorous and rapid across all fuels. Diesel and B10 droplets vaporized quickly without any visible smoke or residue as can be seen in Figure 2 and 3. Biodiesel blends like B40, B50, and B100 eventually vaporized, although the process took slightly longer. In nearly every case, visible evidence of active boiling and a rapid phase change were noted.

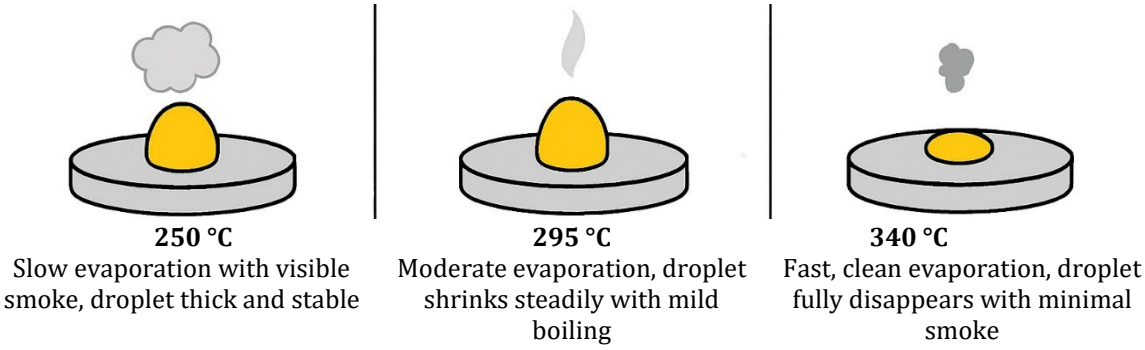

Fig. 2 *Diesel (DF) droplet evaporation behavior*

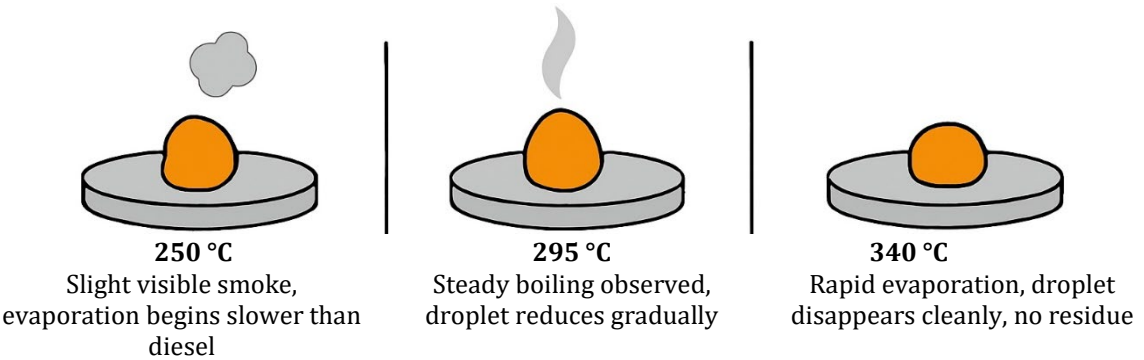

Fig. 3 *B10 droplet evaporation behaviour*

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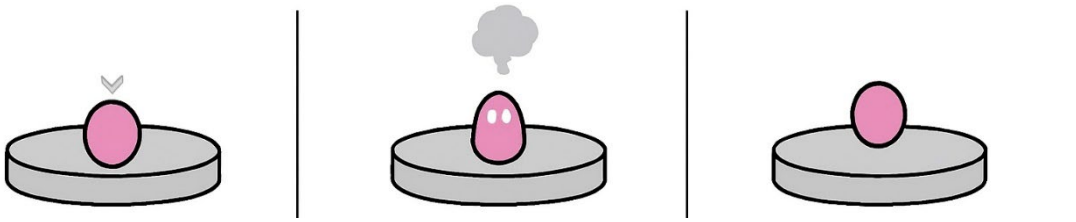
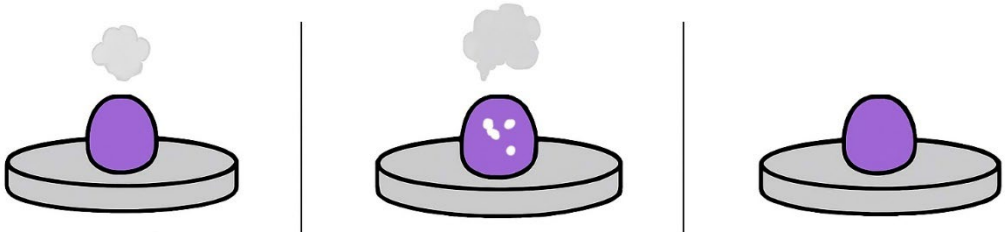


250 °C
Delayed evaporation starts, mild smoke present

295 °C
Moderate bubbling, some residue may be visible

340 °C
Complete evaporation, slightly faster than B30 and above

Fig. 4 *B20 droplet evaporation behaviour*

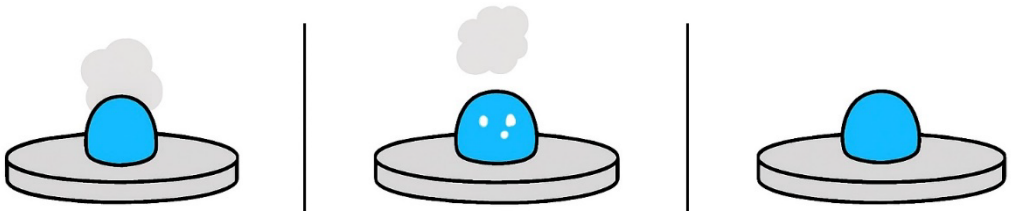


250 °C
Smoky, thicker droplet, slower shrinkage

295 °C
Moderate boiling with slow vapor release

340 °C
Full evaporation occurs, but slower than B20

Fig. 5 *B30 droplet evaporation behavior*

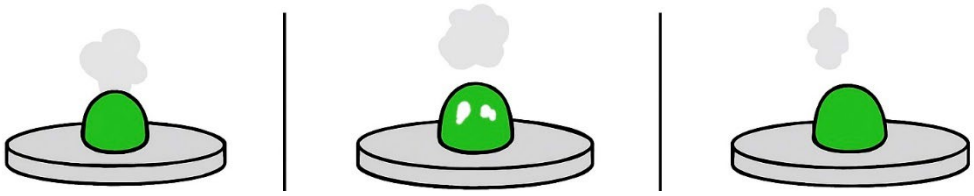


250 °C
Thick droplet with visible smoke, evaporates slowly

295 °C
Slow boiling, slight residue ring may form

340 °C
Complete evaporation, but takes longer than lower blends

Fig. 6 *B40 droplet evaporation behavior*



250 °C
Heavy droplet; very slow to react, visible smoke

295 °C
Late bubbling, prolonged evaporation time

340 °C
Full evaporation achieved, though slower and smokier

Fig. 7 *B50 droplet evaporation behavior*

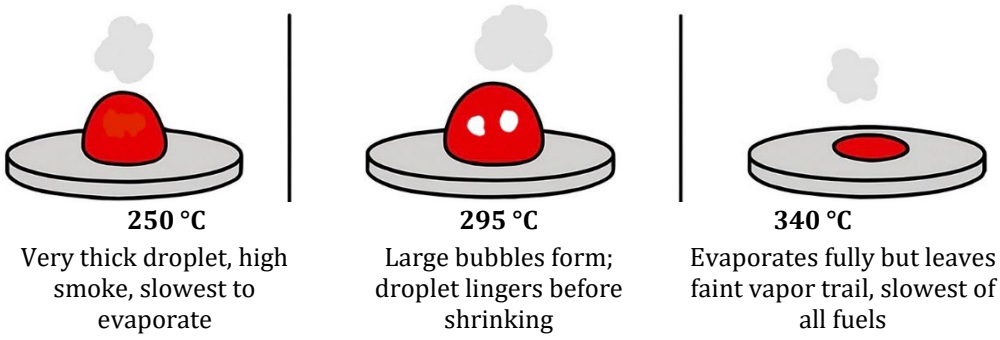


Fig. 8 *B100 droplet evaporation behaviour*

Each biodiesel blend Diesel (DF), B10, B20, B30, B40, B50, and B100 were tested for evaporation performance at surface temperatures ranging from 250 °C to 340 °C. For all tests, the droplet volume and needle height were kept constant (3–5 µL and 90 mm, respectively), and droplets were deposited onto a heated aluminium surface with an average roughness of 0.9 µm. The average droplet lifetime was recorded for each temperature and fuel type. General trend was observed across all blends as surface temperature increased, droplet lifetime decreased, indicating a faster evaporation rate at higher temperatures as shown in Table 2-8. However, the rate of evaporation varied significantly depending on the biodiesel content of the fuel. Conventional diesel exhibited the shortest evaporation times across all temperatures as listed in Table 2, attributable to its low viscosity and high volatility. In Table 3 and 4 for blends with lower biodiesel content, such as B10 and B20, showed only slight increases in droplet lifetime compared to pure diesel, indicating minimal impact on evaporation behaviour at these blending ratios. As the biodiesel concentration increased (B30, B40, B50) as depicted in Table 5-7, a noticeable reduction in evaporation rate was recorded, requiring higher surface temperatures to achieve complete vaporization. Whereas as revealed in Table 8, the B100 blend (pure biodiesel) exhibited the longest droplet lifetimes, especially at the lower temperature range (250 °C–280 °C). This behaviour is explained by biodiesel's higher viscosity, higher boiling point, and lower heating value, which collectively reduce heat absorption and slow down the evaporation process. These results highlight the strong dependence of evaporation behaviour on biodiesel content and reinforce the importance of accounting for fuel properties when designing combustion strategies for engines running on biodiesel or its blends.

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Table 2 *Average evaporation times of diesel fuel (DF) at different surface temperatures (Needle height: 90 mm; Surface roughness: 0.9 μm)*

Surface Temperature, T_s (°C)	Evaporation Time, T_{life} (s)			Average Evaporation Time, T_{life} (s)	Evaporation Characteristic
	Reading				
	1	2	3		
250	22.0	21.8	21.3	21.7	Moderate boiling observed, visible smoke, evaporation slow but complete
255	21.4	21.6	22.1	21.7	
260	20.8	20.6	20.1	20.5	
265	20.1	19.9	19.4	19.8	
270	19.5	19.3	20.2	19.7	
275	18.9	19.1	19.6	19.2	Single droplet shrinks gradually, moderate to fast evaporation
280	18.2	18.4	17.6	18.1	
285	17.6	17.8	16.9	17.4	
290	17.0	17.2	17.7	17.3	
295	16.4	16.2	15.7	16.1	
300	15.8	15.6	15.1	15.5	Rapid boiling, slight sizzling, evaporates completely
305	15.1	15.3	15.8	15.4	
310	14.5	14.7	15.2	14.8	
315	13.9	14.1	14.6	14.2	
320	13.2	13.1	12.6	13.0	
325	12.6	12.8	11.9	12.4	
330	12.0	11.8	12.7	12.2	Very fast evaporation, minimal smoke, stable clean burn
335	11.4	11.6	10.7	11.2	
340	10.8	10.9	10.1	10.6	

Table 3 *Average evaporation times of B10 fuel at different surface temperatures (Needle height: 90 mm; Surface roughness: 0.9 μm)*

Surface Temperature, T_s (°C)	Evaporation Time, T_{life} (s)			Average Evaporation Time, T_{life} (s)	Evaporation Characteristic
	Reading				
	1	2	3		
250	22.6	22.8	21.9	22.4	Slight smoke, slower boiling start than diesel
255	22.0	21.8	22.7	22.2	
260	21.4	21.6	20.7	21.2	
265	20.7	20.5	20.0	20.4	
270	20.1	20.3	19.4	19.9	
275	19.5	19.7	18.8	19.3	
280	18.9	19.1	19.6	19.2	Boils steadily, moderate droplet lifetime
285	18.2	18.0	18.9	18.4	
290	17.6	17.4	16.9	17.3	
295	17.0	17.2	16.3	16.8	
300	16.4	16.6	17.1	16.7	
305	15.7	15.9	15.0	15.5	Faster boiling, droplet completely disappears
310	15.1	15.3	14.4	14.9	
315	14.5	14.7	13.8	14.3	
320	13.8	14.0	13.2	13.7	
325	13.2	13.0	13.9	13.4	
330	12.6	12.8	13.3	12.9	Rapid phase change, clean evaporation
335	12.0	12.2	12.7	12.3	
340	11.3	11.5	12.0	11.6	

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Table 4 *Average evaporation times of B20 fuel at different surface temperatures (Needle height: 90 mm; Surface roughness: 0.9 μm)*

Surface Temperature, T_s (°C)	Evaporation Time, T_{life} (s)			Average Evaporation Time, T_{life} (s)	Evaporation Characteristic
	Reading				
	1	2	3		
250	23.2	23.0	22.5	22.9	Mild smoke, delayed evaporation starts
255	22.6	22.4	21.9	22.3	
260	21.9	21.8	22.6	22.1	
265	21.3	21.5	20.6	21.1	
270	20.7	20.9	21.4	21.0	
275	20.1	20.3	19.4	19.9	
280	19.4	19.6	18.8	19.3	Moderate bubbling, slight residue
285	18.8	19.0	18.1	18.6	
290	18.2	18.4	17.5	18.0	
295	17.6	17.4	18.3	17.8	
300	16.9	17.1	16.2	16.7	
305	16.3	16.5	15.6	16.1	Stronger boiling, clear droplet shrinking
310	15.7	15.9	16.4	16.0	
315	15.1	15.3	14.4	14.9	
320	14.4	14.2	13.8	14.1	
325	13.8	13.6	14.5	14.0	
330	13.2	13.4	13.9	13.5	Full evaporation, faster than B30
335	12.6	12.4	13.3	12.8	
340	11.9	11.8	12.6	12.1	

Table 5 *Average evaporation times of B30 fuel at different surface temperatures (Needle height: 90 mm; Surface roughness: 0.9 μm)*

Surface Temperature, T_s (°C)	Evaporation Time, T_{life} (s)			Average Evaporation Time, T_{life} (s)	Evaporation Characteristic
	Reading				
	1	2	3		
250	23.8	24.0	24.5	24.1	Smoky droplet, takes longer to shrink
255	23.2	23.0	23.9	23.4	
260	22.6	22.4	21.9	22.3	
265	21.9	22.1	22.6	22.2	
270	21.3	21.1	20.6	21.0	
275	20.7	20.9	20.0	20.5	Moderate boiling, vapor escapes slowly
280	20.1	19.9	19.4	19.8	
285	19.4	19.6	18.7	19.2	
290	18.8	18.6	18.1	18.5	
295	18.2	18.0	17.5	17.9	
300	17.6	17.8	18.2	17.9	Increased bubbling, slower phase-out
305	16.9	16.7	17.6	17.1	
310	16.3	16.5	15.6	16.1	
315	15.7	15.9	15.0	15.5	
320	15.1	15.2	15.8	15.4	
325	14.4	14.2	13.7	14.1	Complete evaporation, delayed compared to B20
330	13.8	13.6	14.5	14.0	
335	13.2	13.0	13.9	13.4	
340	12.6	12.4	11.9	12.3	

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Table 6 *Average evaporation times of B40 fuel at different surface temperatures (Needle height: 90 mm; Surface roughness: 0.9 μm)*

Surface Temperature, T_s (°C)	Evaporation Time, T_{life} (s)			Average Evaporation Time, T_{life} (s)	Evaporation Characteristic
	Reading				
	1	2	3		
250	24.4	24.6	23.7	24.2	Visible smoke and thick droplet body
255	23.8	24.0	23.1	23.6	
260	23.1	23.3	23.8	23.4	
265	22.5	22.3	23.2	22.7	
270	21.9	21.7	21.2	21.6	
275	21.3	21.5	22.0	21.6	
280	20.6	20.8	19.9	20.4	
285	20.0	20.2	20.7	20.3	Boils slowly, may leave small residue ring
290	19.4	19.2	20.1	19.6	
295	18.8	18.6	18.1	18.5	
300	18.1	18.3	18.8	18.4	
305	17.5	17.3	16.8	17.2	
310	16.9	16.7	17.6	17.1	Moderate to vigorous boiling, takes time to disappear
315	16.3	16.5	17.0	16.6	
320	15.7	15.5	16.4	15.9	
325	15.0	14.8	15.7	15.2	
330	14.4	14.6	15.1	14.7	Boils completely but still slower than lower blends
335	13.8	13.6	14.5	14.0	
340	13.2	13.3	12.5	13.0	

Table 7 *Average evaporation times of B50 fuel at different surface temperatures (Needle height: 90 mm; Surface roughness: 0.9 μm)*

Surface Temperature, T_s (°C)	Evaporation Time, T_{life} (s)			Average Evaporation Time, T_{life} (s)	Evaporation Characteristic
	Reading				
	1	2	3		
250	25.0	25.2	24.3	24.8	Heavy droplet, slower response to heat
255	24.4	24.2	23.7	24.1	
260	23.8	23.6	24.4	23.9	
265	23.1	23.3	23.8	23.4	
270	22.5	22.7	23.2	22.8	
275	21.9	21.7	21.2	21.6	
280	21.2	21.4	20.6	21.1	
285	20.6	20.8	19.9	20.4	Delayed boiling onset, bubbling later in test
290	20.0	19.8	19.3	19.7	
295	19.4	19.6	20.1	19.7	
300	18.8	18.9	19.4	19.0	
305	18.1	17.9	18.8	18.3	
310	17.5	17.3	18.2	17.7	Takes longer to evaporate fully, moderate smoke
315	16.9	16.7	17.6	17.1	
320	16.2	16.1	16.9	16.4	
325	15.6	15.4	14.9	15.3	
330	15.0	15.2	15.7	15.3	Complete evaporation, requires longer time
335	14.4	14.2	13.7	14.1	
340	13.8	13.9	14.4	14.0	

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Table 8 *Average evaporation times of B100 fuel at different surface temperatures (Needle height: 90 mm; Surface roughness: 0.9 μm)*

Surface Temperature, T_s (°C)	Evaporation Time, T_{life} (s)			Average Evaporation Time, T_{life} (s)	Evaporation Characteristic
	Reading				
	1	2	3		
250	25.6	25.4	26.3	25.8	High viscosity, droplet thick, slow boiling, more smoke
255	25.0	25.2	24.3	24.8	
260	24.4	24.2	23.7	24.1	
265	23.7	23.9	23.0	23.5	
270	23.1	22.9	23.8	23.3	
275	22.5	22.7	21.8	22.3	
280	21.9	22.1	22.6	22.2	
285	21.2	21.0	20.5	20.9	
290	20.6	20.8	21.3	20.9	Larger bubbles, extended lifetime
295	20.0	19.8	19.3	19.7	
300	19.4	19.6	20.1	19.7	
305	18.7	18.5	18.0	18.4	
310	18.1	17.9	18.8	18.3	
315	17.5	17.7	16.8	17.3	Boiling begins actively droplet shrinks steadily
320	16.9	16.7	16.2	16.6	
325	16.2	16.4	15.5	16.0	
330	15.6	15.8	16.3	15.9	Still takes time to fully evaporate, some visible vapor trail
335	15.0	14.8	14.3	14.7	
340	14.3	14.2	13.7	14.1	

The Maximum Evaporation Point (MEP) is defined as the surface temperature at which the average evaporation time (droplet lifetime) reaches its minimum for a given fuel. Identifying the MEP is critical for understanding how different biodiesel blends behave during fuel injection and combustion, particularly under thermal conditions representative of internal combustion engines. Due to biodiesel's distinct physical properties such as higher viscosity and lower volatility compared to conventional diesel the MEP tends to shift toward higher temperatures as the biodiesel content increases. In this study, the MEP was determined for each tested fuel which are Diesel, B10, B20, B30, B40, B50, and B100. For each blend, droplet lifetime was experimentally measured across a temperature range of 250 °C to 340 °C, using three repeated trials at each temperature setting to ensure statistical reliability. The average evaporation times were then plotted as a function of surface temperature, and the MEP for each blend was identified as the temperature corresponding to the lowest point on the evaporation curve as shown in Figure 9 to 15. This analysis reveals how increasing biodiesel content influences the thermal evaporation behaviour of fuel droplets. Blends with higher biodiesel concentration consistently demonstrated MEPs at higher temperatures, confirming the need for elevated thermal energy to overcome biodiesel's lower volatility and higher latent heat of vaporization. These findings have practical implications for fuel optimization, combustion timing, and the development of mitigation strategies for wall film deposition in engines operating with biodiesel blends. Understanding the MEP behaviour aids in tailoring injection parameters to maximize evaporation efficiency and improve overall engine performance.

The vaporization behaviour of pure diesel fuel was examined on a heated aluminium surface across a temperature range of 250 °C to 340 °C. As expected, higher surface temperatures resulted in shorter droplet evaporation times, indicating that diesel exhibits enhanced evaporation performance at elevated temperatures. As presented in Figure 9, at lower temperatures (250 °C–275 °C), diesel droplets evaporated slowly, producing visible, light smoke. In the mid-temperature range (280 °C–310 °C), the evaporation process accelerated noticeably, with droplets visibly shrinking and exhibiting mild surface boiling. At higher temperatures (330 °C–340 °C), evaporation occurred rapidly and cleanly, with little to no smoke observed—suggesting more efficient phase transition and complete vaporization. The Maximum Evaporation Point (MEP) for diesel was identified between 330 °C and 335 °C, corresponding to the shortest observed droplet lifetime. This behaviour can be attributed to diesel's favourable physicochemical properties, specifically its low kinematic viscosity (3.8 mm^2/s) and high heating value (45.21 MJ/kg) as shown in Table 1, which enhance its ability to absorb heat and transition

into the vapor phase efficiently. The consistent decline in evaporation time with increasing temperature, and the clean vaporization observed at higher thermal conditions, confirms diesel's high volatility and thermal responsiveness. These characteristics distinguish it from higher biodiesel blends and underscore its continued reference value in comparative fuel evaporation studies.

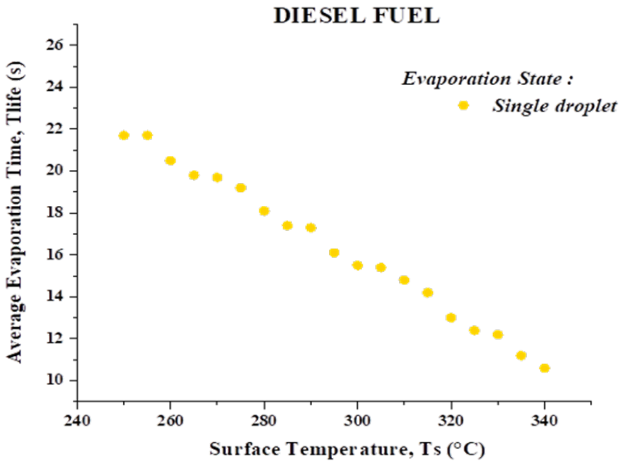

Fig. 9 *Evaporation time of diesel fuel at different surface temperatures*

The B10 fuel blend, consisting of 10% biodiesel and 90% diesel, was evaluated over the same surface temperature range of 250 °C to 340 °C. B10 exhibited an evaporation pattern similar to that of pure diesel, though with slightly longer droplet lifetimes at all temperature levels, indicating a modest delay in evaporation due to the presence of biodiesel. As demonstrated in Figure 10, at lower temperatures (250 °C–275 °C), B10 droplets evaporated gradually, accompanied by the emission of light smoke. In the mid-temperature range (280 °C–310 °C), evaporation proceeded more rapidly, with droplets displaying consistent shrinkage and occasional bubble formation, indicating the onset of boiling. At higher temperatures (330 °C–340 °C), the droplets vaporized cleanly and rapidly, closely resembling the behaviour observed with pure diesel. The Maximum Evaporation Point (MEP) for B10 was identified in the 335 °C to 340 °C range, where the shortest average droplet lifetime was recorded. This efficient evaporation behaviour can be attributed to the relatively low biodiesel concentration in the blend, which does not significantly alter the viscosity**,** boiling point, or **volatility** of the mixture compared to diesel. As a result, B10 maintains favourable thermal and physical characteristics that support rapid vaporization at elevated temperatures, making it a practical low-blend alternative in combustion systems with minimal performance compromise.

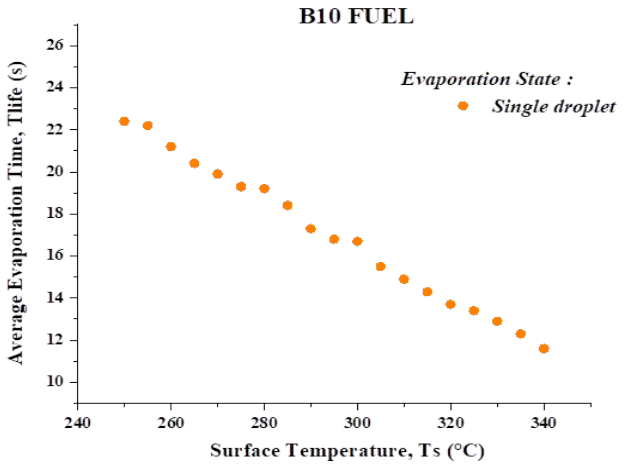

Fig. 10 *Evaporation time of B10 fuel at different surface temperatures*

B20 blend (20% Biodiesel and 80% Diesel) has a significant change in the evaporation time compared to Diesel and B10. Test results have revealed that the evaporation time decreases as temperature increases to 250

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°C to 340 °C. As revealed in Figure 11, the droplet stayed longer on the surface at lower temperatures (250 °C to 275 °C), had light smoke and boiled slowly. During heating in the intermediate temperature interval (280 °C – 310 °C), vigorous boiling and obvious contraction occurred. The droplet also completely evaporated at higher temperatures (330 °C – 340 °C) though taking a little longer than that of B10. The Maximum Evaporation Point (MEP) of B20 happened at 340 °C where evaporation time was the lowest. This decreased viscosity and volatility of the diesel blend makes it slow when compared to diesel.

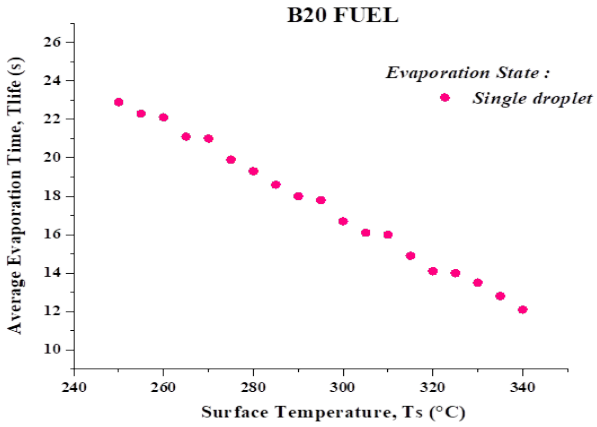

Fig. 11 *Evaporation time of B20 fuel at different surface temperatures*

The B30 mixture (30% biodiesel, 70% diesel) exhibited enhancement of the evaporation time particularly over the lower and medium surface temperature. The experiment in the range of 250 °C to 340 °C indicated that the biodiesel content exercise had a significant influence on the evaporation behaviour as shown in Figure 12. The stability of the droplet at low temperatures (250 °C – 275 °C) was found to last longer with visible smoke and delayed boiling being experienced. At the mid-range (280 °C – 310 °C), moderate bubbling and gradual shrinkage was noted. High temperatures (330 °C – 340 °C) finally completely evaporated the droplet but with less evaporation speed than B20. B30 has been characterized by its Maximum Evaporation Point (MEP) at 340 °C which represented the lowest evaporation time. It is due to the increased viscosity, density and lower heating value of the fuel blend which takes more thermal energy to ensure full phase change.

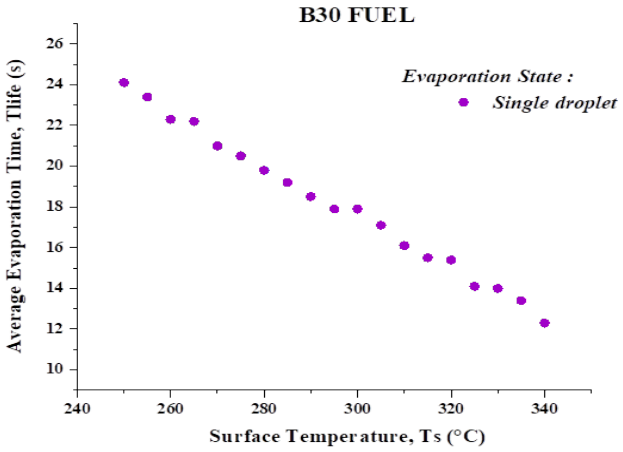

Fig. 12 *Evaporation time of B30 fuel at different surface temperatures*

As shown in Figure 13, B40 blend (40% biodiesel, 60% diesel) had reduced increasing evaporation delay even lower than lower blends. At low and mid temperatures, droplet evaporation at higher biodiesel level became slower and less sensitive to heat. The droplet was on the surface longer at 250 °C to 275 °C with visible smoke and it was thicker. At the mid-range (280 °C – 310 °C) there was slow bubbling and sluggish phase change. The evaporation of the droplet started at high temperatures (330 °C – 340 °C) and occurred entirely, although this process was observed to be slow compared to that of B30.The Maximum Evaporation Point (MEP) of the B40 was

noticed to be 340 °C, where the minimum evaporation time was recorded. This outcome can be attributed to effects of high biodiesel viscosity and thermal resistance, which must be evaporated using higher energy.

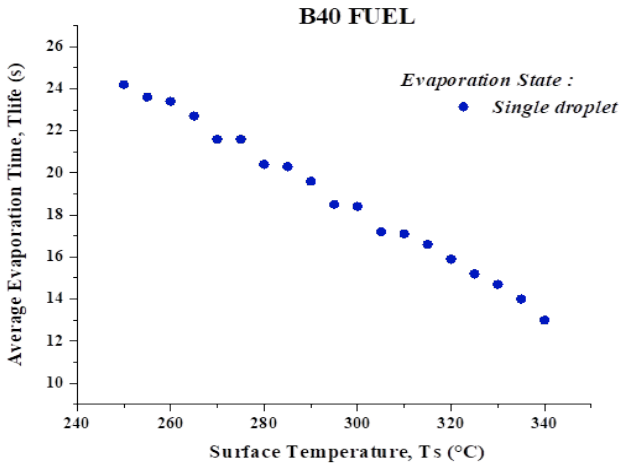

Fig. 13 *Evaporation time of B40 fuel at different surface temperatures*

The B50 blend (50% biodiesel, 50% diesel) showed much longer evaporation times and at the low temperatures. The slower rate of heat absorption and the greater thermal resistance caused by the rise in content of biodiesel influenced the behaviour of droplet evaporation. As illustrated in Figure 14, at the low temperatures (250 °C – 275 °C) the droplet was thick, resisted the boiling, and emitted the visible smoke. Evaporation was observed in the mid-range (280 °C – 310 °C) the process was comparatively slow to B40. At higher temperatures (330 °C – 340 °C), the droplet finally evaporated but at a low rate as compared to all the previous blends. The Maximum Evaporation Point (MEP) for B50 was 340 °C, representing the highest temperature needed at this point to achieve successful evaporation.

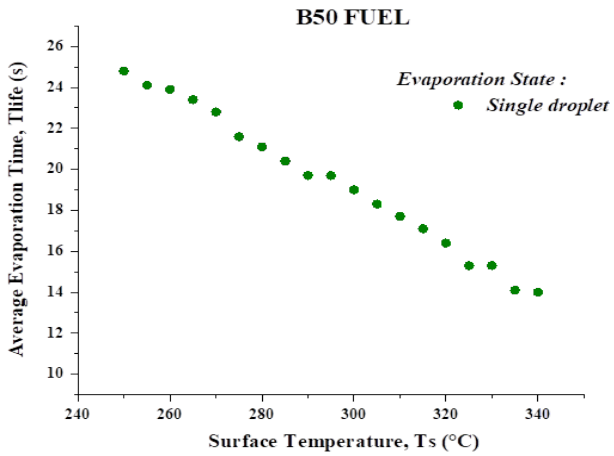

Fig. 14 *Evaporation time of B50 fuel at different surface temperatures*

Finally, the B100 (100% biodiesel) had the longest evaporation times when compared to the other fuel types due to its high viscosity, density, and lower heating value, making it much slower to respond to heat, especially at cooler temperatures. As represented in Figure 15, at 250 °C to 275 °C, the droplet remained stable, and thick structure, boiling was delayed for a considerable amount of time, and smoking was observed. At the mid-range of 280 °C – 310 °C larger bubbles formed, and evaporation began slowly. At higher temperatures (330 °C – 340 °C), the droplet evaporated completely, which was one of the longest evaporation times of all the fuel. The Maximum Evaporation Point (MEP) for B100 was observed at 340 °C, which was the greatest temperature needed across all tested fuels to reach a minimum evaporation time. This indicates a strong influence from biodiesel's physical and thermal properties on evaporation performance.

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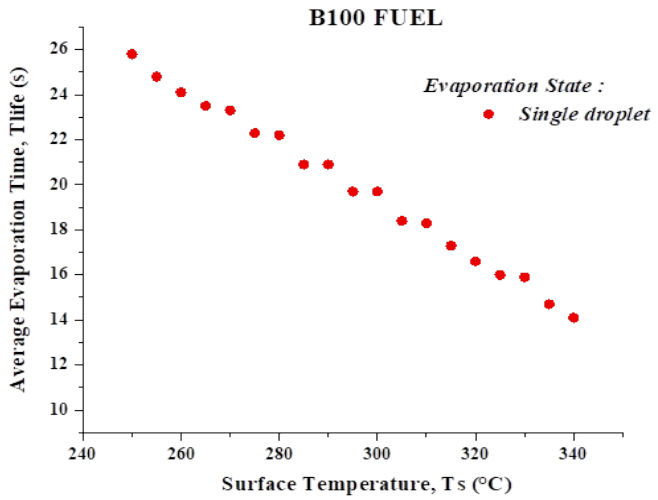

Fig. 15 *Evaporation time of B100 fuel at different surface temperatures*

To give a better comparison of all the fuel types studied, Figure 16 shows a collective graph demonstrating the average evaporation time of every blend (Diesel, B10, B20, B30, B40, B50, B100) at the tested temperature range. These trends indicate clearly that the evaporation time rises with the amount of biodiesel present, especially at lower temperatures. All evaporation times were shorter at diesel and B10 compared with any other temperature and vaporization started speedily at 300 °C. B20 and B30 had the same trends but took a little higher temperature to be completely evaporated. The more biodiesel-based blends, such as B50 and B100, exhibited considerably larger evaporation times, especially in the range under 310 °C and only approached their minimum of evaporation temperature at 340 °C. This graph supports the previously presented results which stated that evaporation performance is directly dependent on the physical properties of each blend which in this case includes viscosity and volatility. It proves visually that biodiesel rich fuels need more investment of thermal energy to fully evaporate, and the maximum evaporation point (MEP) moves with biodiesel ratio. Overall, the trends that were visible across all seven fuels were consistent, as the biodiesel content increased, the Maximum Evaporation Point (MEP) increased surface temperatures. Diesel and B10 evaporated more readily at slightly lower temperatures due to their softer and less viscous characteristics. Higher blends such as B50 and B100 required more heat energy to help achieve complete evaporation. The results were indicative of how fuel composition can impact droplet behaviour, and these results enhance the understanding of optimal engine temperature conditions relative to biodiesel-rich fuels.

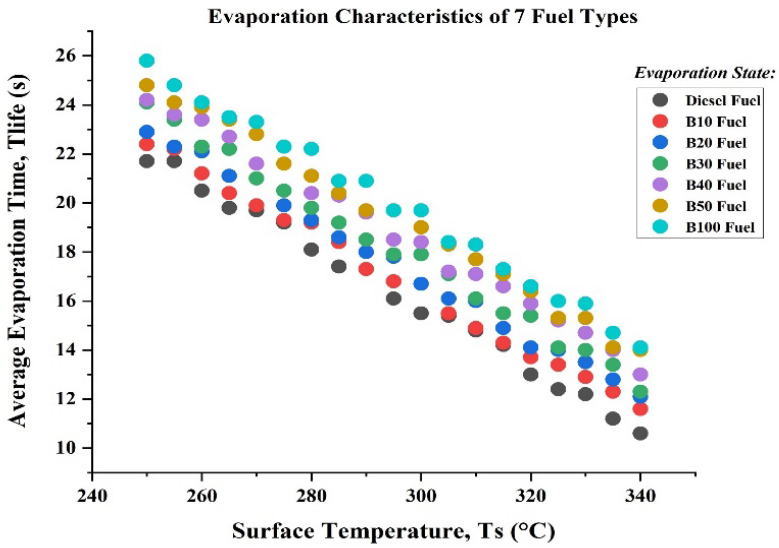

Fig. 16 *Comparison of average evaporation times for all fuel blends (Diesel, B10, B20, B30, B40, B50 and B100) across surface temperatures from 250 °C to 340 °C*

As the concentration of biodiesel in a blend increases, so does the viscosity, which in turn reduces heat transfer efficiency and slows the evaporation rate**.** Additionally, biodiesel exhibits lower volatility compared to diesel, requiring higher surface temperatures to achieve complete phase change. These characteristics result in longer droplet lifetimes, particularly at lower temperatures, and shift the MEP to higher thermal thresholds for biodiesel-rich blends. These findings carry important implications for real-world engine operation. In particular, higher biodiesel blends such as B50 or B100 may experience incomplete vaporization if the combustion chamber temperature is insufficient. This can lead to problems such as increased carbon deposits, fuel wastage, and delayed ignition, ultimately affecting engine performance, emissions, and fuel economy. Despite these challenges, biodiesel remains a viable and attractive alternative fuel due to its renewable nature, lower net carbon emissions, and superior lubricating properties. By understanding how biodiesel behaves thermally, engine designers and operators can implement compensatory strategies such as optimizing fuel injection timing, adjusting blending ratios, or integrating preheating systems to ensure efficient combustion. In brief, while biodiesel-rich fuels require higher thermal input to achieve efficient evaporation and combustion compared to petroleum diesel, they can still be effectively utilized in compression ignition engines. This study confirms that with well-defined temperature control and engine calibration, biodiesel blends particularly up to B50 can support reliable engine operation and align with sustainable fuel initiatives.

4. Conclusions

In this research, the researcher investigated the behaviour of various biodiesel mixtures at high temperatures on a heated aluminium plate. The tested types of fuel were pure diesel fuel, B10, B20, B30, B40, B50 and B100. As the temperature ranged between 250 °C to 340 °C, it was noticed that all the fuel droplets evaporated more rapidly as the temperature increased. Diesel took the shortest time to evaporate followed by B10 and B20. Droplets evaporated slowly with an increase in biodiesel content, resulting in higher evaporation time at lower temperatures. Mixes such as B30 and above required increased heating before fully vaporizing, as shown in the evaporation time results. All fuels were observed to have a maximum evaporation point of about 340 °C, indicating that greater blends are heavier and therefore require more energy to evaporate. The visual tests also indicated that the droplets containing greater amounts of biodiesel were slower to shrink and may cause minimal residue or vapour clouds. These research results indicate that biodiesel, particularly in stronger blends, requires improved thermal management to understand it can execute successfully under engine-type conditions. Findings of this study provide a better understanding of the impact of fuel composition on evaporation and may inform future efforts at bettering the use of biodiesel.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhammad Haikal Favian Jikol, Yusmady Mohamed Arifin;* ***data collection:*** *Theebenraj Rajosagran, Muhammad Haikal Mukhtar;* ***analysis and interpretation of results:*** *Mohd Azli Salim, Safarudin Gazali Herawan;* ***draft manuscript preparation:*** *Theebenraj Rajosagran, Mohd Zaid Akop. All authors reviewed the results and approved the final version of the manuscript.*

Data Availability

The data that support the findings of this study are openly available in zenodo at https://zenodo.org/records/17180952.

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