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Droplet Evolution and Stability of Water-in-Biodiesel Emulsion with Biosurfactant

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ABSTRACT

Use of an alternative water-in-diesel emulsion (WiDE) fuel instead of pure diesel in a diesel engine reduces emissions and environmental pollution. However, as time passes, water from the emulsified fuel separates. Emulsion stability is affected by the amount of water, type of surfactant, and emulsion technique. Since biodiesel and biosurfactants are environmentally friendly as compared to pure diesel and chemical surfactants, biodiesel-emulsified fuel can reduce emissions, improve combustion, and improve engine performance. Water-in-diesel droplets split into tiny droplets during secondary atomization, which is believed to be caused by microexplosions. In this study, the effect of biosurfactant on the stability and microscopic behaviour of water-in-biodiesel emulsion (WiBDE) fuel were examined. A mixture of B10 biodiesel, 5% water, and a mixture of surfactant (63% lecithin and 37% TWEEN 85 (0.5–3%)) was emulsified for 20 minutes by using a magnetic stirrer at 1500 rpm. Six WiBDE fuel samples were observed for 10 days, and the microscopic behaviour of fuel droplets was examined. The evolution of droplets leading to micro-explosions was captured at 200 °C, 300 °C, and 400 °C. WiBDE-5, having a 2.5% surfactant concentration, is highly stable and reduces the time of micro-explosion of droplets, which can improve combustion and engine performance.

1. Introduction

A well-known source of energy used for sea transportation, industrial sectors, and road vehicles is the diesel engine. The increasing usage of diesel engines in the present period unfortunately produces environmental pollutions that harm all living species across the universe. Researchers have been trying to figure out how to lower diesel engines' emissions of harmful gases. To do so appropriate amount of water is mixed with pure diesel using emulsion techniques that reduce emission of Particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO) and soot emissions [1]. Furthermore, emulsion fuel technology boosts the diesel engine's thermal efficiency [2]. A suitable alternative fuel, WiDE fuel can decrease emissions of nitrogen oxide (NOx) and particulate matter (PM) while increasing combustion efficiency [3,4]. Study suggest by Using Water-

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in-diesel (W/D) emulsified fuel as an alternative fuel in CI engines may help meet emission requirements. Because it improves combustion efficiency, helps to reduce NOx emissions and fuel consumption. The performance of a diesel engine using W/D emulsified fuel was found to be somewhat lower than when using clean diesel fuel [5]. In W/D emulsion the water and diesel are emulsified using an emulsifying agent known as surfactant. The surfactants can lower the surface tension of diesel and water molecules and stabilize emulsion [6]. Since the passage of time, water separates from emulsified fuel and affects the fuel's properties, so for commercializing WiDE fuel, it is important to investigate the emulsion stability before use in engines and storage in tanks [7-10]. The stability of the emulsion fuel depends on the method of emulsification, the duration of the process, the amount of water, the speed of the stirrer, and the amount of surfactant [11,12]. Biosurfactants offer a wide variety of uses. They have recently been tested as an alternative to chemical surfactants in the production of fuel emulsions and microemulsions. Hybrid fuel systems are becoming more popular because to their better fuel characteristics, higher engine performance, and minimal pollutant emissions. Biosurfactants have qualities including lower manufacturing costs, environmental friendliness, and long-term sustainability [4,13-15]. When used in place of a chemical surfactant, the biosurfactant improves the quality of emulsified diesel fuel and decreases pollutant concentrations [15]. Biodiesel is a good alternative fuel for diesel engines, and it is biodegradable, sulfur-free, oxygenated as well as renewable. It provides a number of advantages, such as reduced carbon dioxide emissions, decreased engine wear, reduced engine oil use, and comparable thermal efficiency [16]. Dissociation of water in W/D emulsions at high temperatures creates hydroxyl radicals, which help oxidise soot and minimise soot emissions [17]. as a means of reducing diesel engine pollution, water injection into the combustion chamber has gained widespread use. Canfield claims that the combustion process is affected by water contact because it extends the period between ignition and combustion. This method may be used to create carbon dioxide and reduce pollution, especially nitrogen oxide (NO) (CO2) [18]. Advantages of using water in emulsified fuel: first, water evaporation lowers in-cylinder temperature, which lowers NOx emissions [19]. Second, water may provide more free radicals to speed up the oxidation of soot, lowering PM emissions [20]. Third, there is the micro-explosion phenomenon in water-emulsified diesel owing to preferred water evaporation, which breaks droplets and produces several tiny sub-droplets. This encourages fuel evaporation and air-fuel mixing, which improves thermal efficiency [21,22].

Micro-explosions have been interconnected to the combustion of WiDE as a result of the significant differences between the boiling points of water and diesel [23]. Micro explosions cause secondary atomization of the fuel into smaller droplets, which burn more effectively because of to their increased surface area [24]. Various research has been conducted using WiDE fuel micro explosion processes [25-27]. These experiments have shown that huge, isolated droplets of emulsified fuel may cause puffing and/or micro-explosions. One of the most crucial elements is how emulsions coalesce and phase separation. Other aspects to consider include the kind and quantity of surfactant, the amount of water in the emulsion, and the size of the dispersed water droplets. It was discovered that a greater surfactant concentration prevented micro-explosions [28]. Contrarily, it was discovered that a higher water content in the emulsion decreased its stability and increased the severity of micro-explosion [29]. It was discovered in research using a single suspended droplet that the parent droplet's size had an impact on the timing of the micro-explosion phenomenon. There is still needed to understand the microscopic behavior of emulsified fuel droplets on its stability and micro explosion. Therefore, in this article, the stability and microscopic behavior of water-in-biodiesel emulsified (WiBDE) fuel particles are analyzed. For the preparation of WiBDE fuel, the mixture of B10 biodiesel, 5% water, and 0.5 to 3% surfactant mixture (63% lecithin and 37% Tween 85) was emulsified for 20 minutes by using a magnetic stirrer at 1500 rpm. Six WiBDE fuel samples were observed for 10 days, and the microscopic behavior of fuel droplets was examined by using a polarizing microscope with 50x magnification. The droplet size measurement of the emulsion showed that different amounts of added surfactant caused different droplet sizes. Also, WiBDE fuel with 2.5% surfactant was more stable and the fuel particles behaved better when looked at under a microscope. Moreover, the micro-explosion of these six different WiBDE fuel droplets is analyzed using a hot plate, a high-speed camera, and PCC 3.1 software.

1.1 Motivation of the Study

This research was inspired by the idea that by combining two eco-friendly solutions, soy lecithin biosurfactants and biodiesel, we could develop emulsified fuel that is more environmentally friendly. The benefits of combining lecithin biosurfactants with biodiesel to create emulsified fuel are the major focus of this study. Study interest is especially in the effects of surfactant concentration on droplet evolution, micro-explosion occurrences, and emulsion stability. The potential of emulsified fuel combustion to lower emissions and lessen environmental pollution is highlighted. Motivating more research into ecologically friendly transportation solutions is the primary objective of this in-depth examination of this fascinating alternative fuel blend. The long-term objective of this study is to help develop an emulsified fuel that is less harmful to the environment and more sustainable.

2. Materials and Methods

Figure 1 illustrates an experimental flow chart, including the preparation of a WiBDE fuel sample and analyzing the stability, microscopic behavior, and droplet evolution of WiBDE fuel.

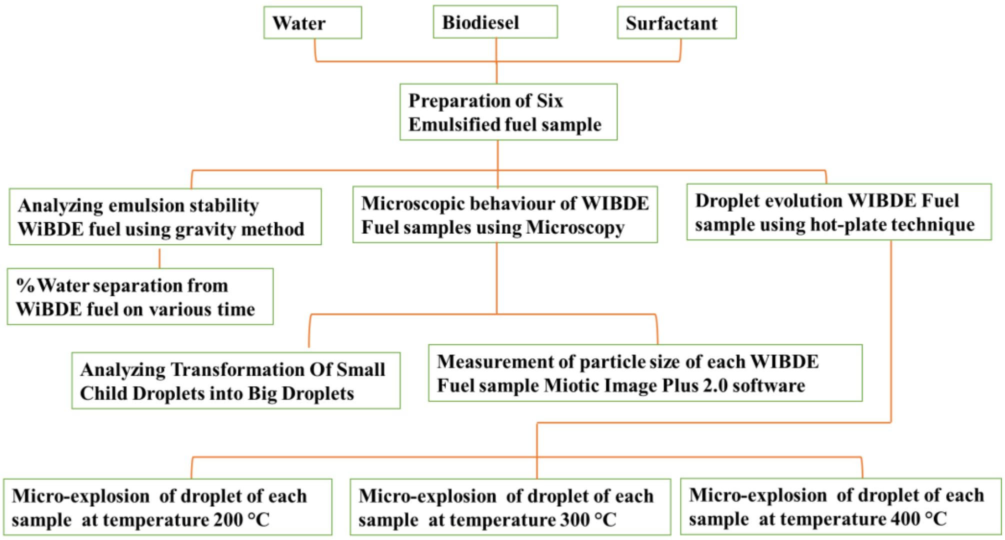


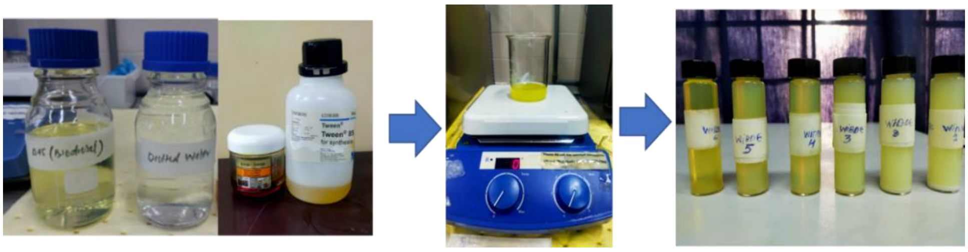
Fig. 1. Experimental flow chart

2.1 Emulsion Preparation

Six different types of WiBDE fuel were made with 5% water, biodiesel (B10), and a mixture of surfactants with a 0.5% increase. The surfactant mixture was composed of 63% Soy lecithin (biosurfactant and 37% Tween 85 by volume. For the emulsification process as shown in Figure 2, a magnetic stirrer has been utilized, and it is operated at a speed of 1500 rpm. The time for emulsification is kept at 20 minutes for each sample. The properties of biodiesel (B10) are given in Table 1 [30].

Table 1
The properties of biodiesel (B10)

Properties of biodiesel at ambient temperature			
Density (g/cm^3)	0.8355	Calorific value (MJ/kg)	41.84
Kinematic Viscosity (cP)	0.8355	Cetane number	48.35



Biodiesel (B10), distilled water and surfactant — Emulsion of mixture on magnetic stirrer — WIBDE Fuel

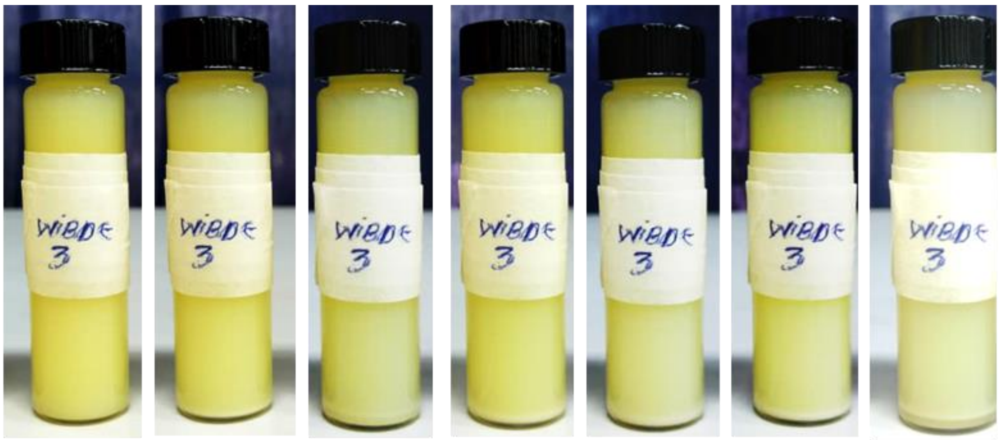
Fig. 2. Emulsion process

2.2 Emulsion Stability Test using Gravity Method

Since water and biodiesel have different densities, and water is denser than biodiesel, as the separation of water occurs from the emulsion, the water settles down with the appearance of a white layer. On various occasions the percentage of water that was separated from the emulsion was measured using a scale and compared to the total amount of water used in the emulsion. Outcomes are detailed in the results and discussion sections.

2.2.1 WiBDE fuel sample

The fuel sample, WiBDE1 (1.5 % surfactant), was observed at different times for two days to observe the separation of water, biodiesel, and emulsifier. The complete separation of the water took place on the second day of preparation, as shown in Figure 3.

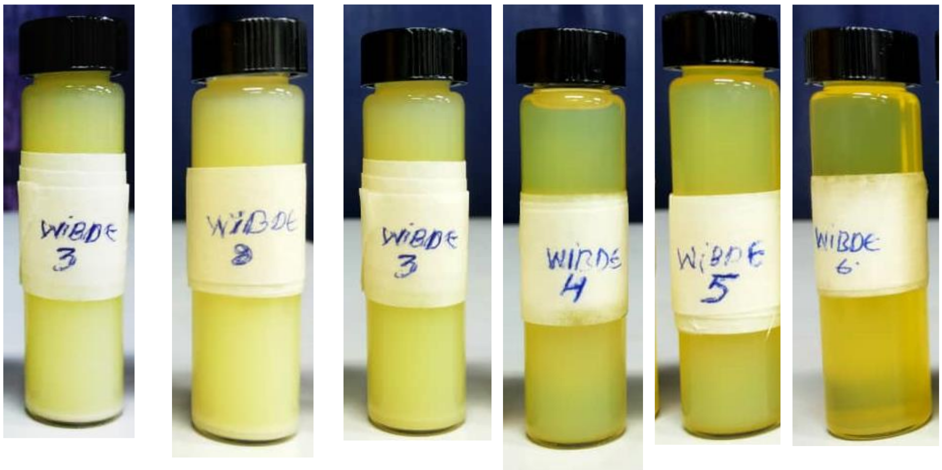


0 15minutes 30 min 1 hour 2 hours 1st day 2nd day

Fig. 3. Physical appearance of WiBDE fuel sample on different time

2.2.2 Different WiBDE fuel samples

To test emulsion stability, six samples of WiBDE fuel were made with increments of 0.5% of the surfactant mixture. Also, after making these samples, the samples were observed for one day to see how the different surfactant concentrations affected the fuel's stability. Figure 4 clearly shows that the sample WiBDE 1, with a lower surfactant concentration, is less stable than WiBDE 6, which has a higher surfactant concentration.



WiBDE1 WiBDE2 WiBDE3 WiBDE4 WiBDE5 WiBDE6

Fig. 4. Physical appearance of different WiBDE fuel samples after one day

2.3 Microscopic Behaviour of WiBDE Fuel Droplets

To know the microscopic behaviour of WIBDE fuel samples. Droplets of each sample were examined using an electronic microscope (Olympus BX51, Model U LHOOL-3, Tokyo, Japan), as shown in Figure 5 [15-31]. A single emulsified WiBDE fuel droplet was put on a thin, clear plate and seen under a microscope at a magnification of x50. For post-processing, images of multiple distinct droplet positions were captured, and the diameter of 100 partials of each sample was measured using Miotic Image Plus 2.0 software, as shown in the Figure 6(a) to Figure 6(f).

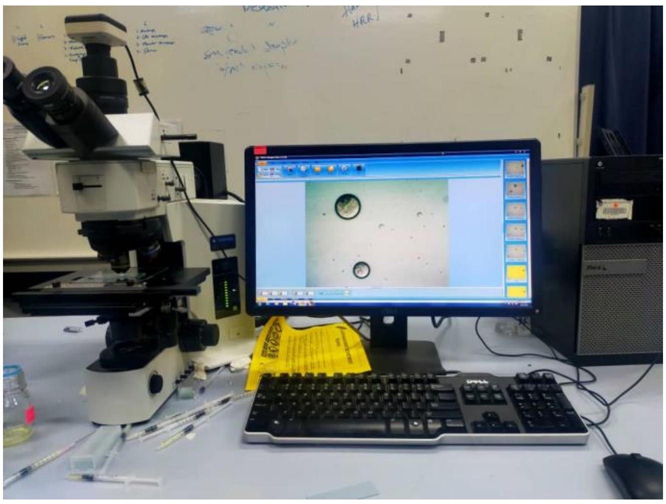


Fig. 5. Polarizing microscope with 50x magnifications

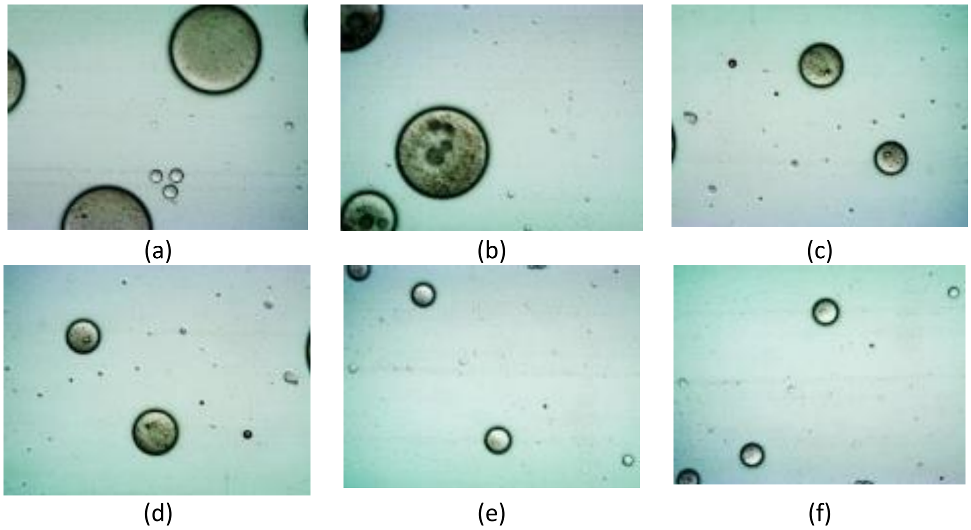


Fig. 6. Microscopic visualization of WiBDE fuel droplets' particles

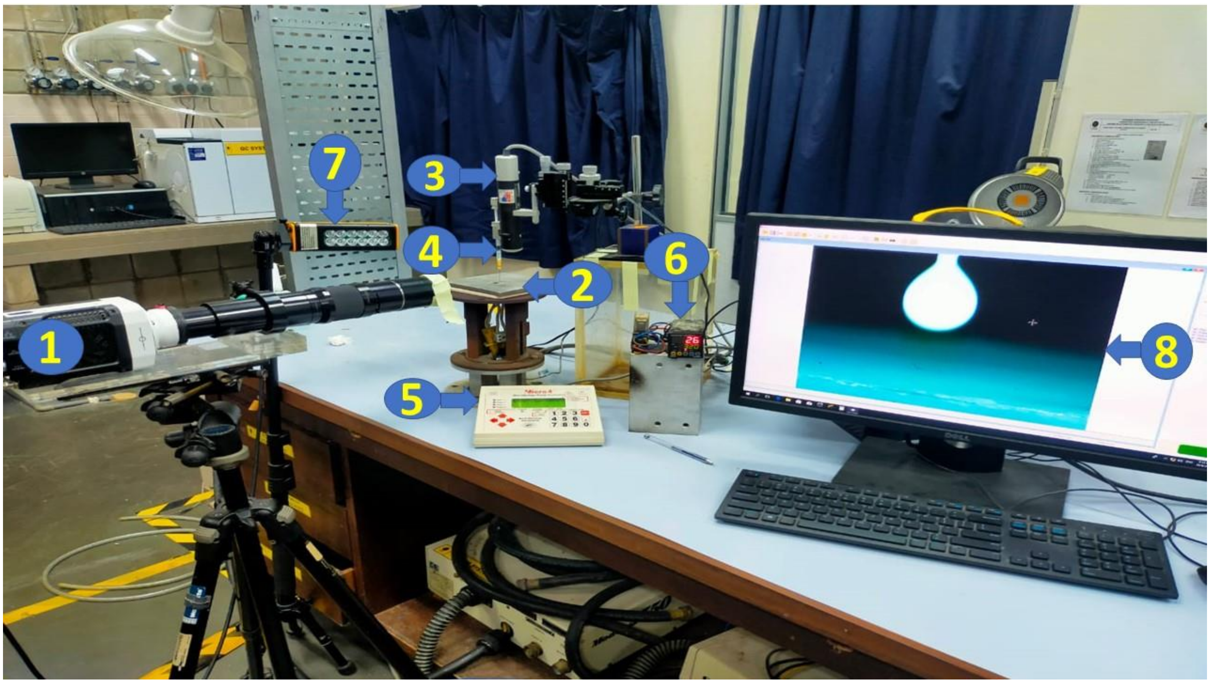
It can be observed in the above Figure 6(a) to Figure 6(f) that in the fuel particle, water is dispersed in biodiesel. Moreover, at different locations, there is variation in the size of the fuel particle.

2.4 Droplet Evolution of WIBDE Fuel Samples

A hot plate is heated with the help of an electric heater and controlled by a temperature controller. The fuel droplet of each sample is injected with the help of a micropump, which is controlled by a microcontroller. As the fuel droplet touches the surface, the evolution of the droplet occurs, including boiling, puffing, and microexplosions within microseconds. To record and capture the droplet evolution, a high-speed camera was used with the help of Phantom Camera Control (PCC 3.1) software. The image acquisition rate was set at 50 fps with a resolution of 1280 x 1024 pixels throughout the experiment. Single droplets of each sample were captured at three different temperatures: 200 °C, 300 °C, and 400 °C. The procedure is repeated three times under the same conditions for accuracy.

2.4.1 The occurrence of micro-explosions

Figure 7 shows the schematic experimental setup for the micro-explosion visualization technique. A high-speed camera is adjusted with extra light and connected to a PC to capture the images. A syringe filled with WiBDE sample is filled and connected to the micro-fuel controller. This micropump is connected to a microcontroller. A hot plate is heated with electric current, and its temperature is controlled through a temperature controller.



1	High Speed Camera	2	Hot plate	3	Micro-pump
4	Syringe	5	Micro-controller	6	Temperature adjust controller
7	Light	8	PC for data acquisition and Image processing		

Fig. 7. Schematic illustration of experimental setup (Visualization Lab UTP Malaysia)

3. Results and Discussion
3.1 Transformation of Small Child Droplets into Big Droplets

Under a microscope with a x50 magnification, a single droplet of WiBDE fuel from each sample was looked at, and it was seen that the droplet's particle size varies in different places. Also, as shown in Figure 8, small particles of emulsified fuel started to join to form a bigger particle. It was assumed that it happens because of the instability of particles in emulsified fuel. Since the stability of an emulsion increases with the concentration of surfactant, it was found that stable emulsions have less particle transformation and take more time. From Figure 8, at time 5 sec, one big particle and three small particles were nearby, but after 55 sec, two particles merged into the big one. Literature suggests that small emulsions with small particles are more stable than those with larger particles, so transforming small particles into big ones causes instability in the emulsion. Therefore, it can be overcome by using an appropriate concentration of surfactant.

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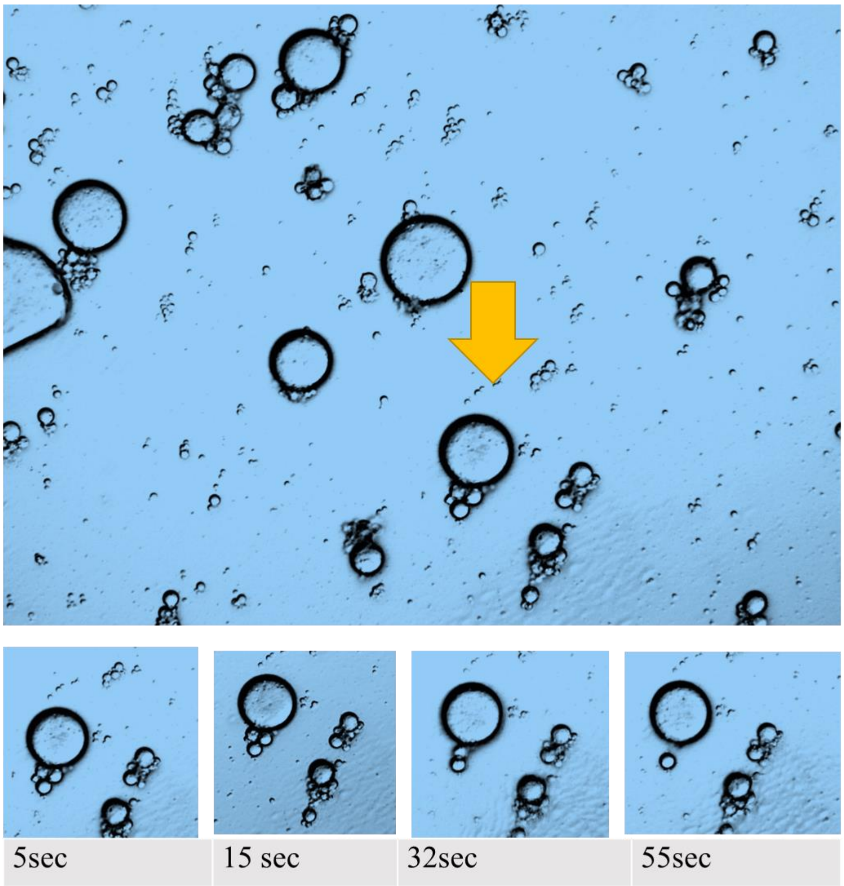


Fig. 8. Transformation of small child droplets into big droplets

3.2 Effect Surfactant on Particle Size

Under a microscope with a magnification of x20, a droplet of each sample is magnified. And, using Moti Image Plus 2.0 software, the diameters of 100 particles from different places were measured to see how the concentration of surfactant affected the size of emulsified fuel particles. The concentration of the surfactant also has a role in determining the particles' ultimate size. A high concentration of surfactant facilitates homogenization and the formation of smaller particles by reducing surface tension and stabilising newly created surfaces [32-34]. WiBDE 1 fuel has a lower surfactant concentration (0.5%) than WiBDE-5 fuel (2.5%), as can be seen in Figure 9. Particles of WiBDE1 are larger in size than those of WiBDE5. So, increasing the concentration of surfactants helps to develop small particles with more stability and more particles of the same size Moreover, it can be observed that the larger particle in WiBDE 1 is 17.74 µm whereas that in WiBDE 5 is 4.62 µm. It is because in WiBDE 1, a greater number of particles merged into one, whereas in WiBDE 5, a smaller number of particles merged to form one.

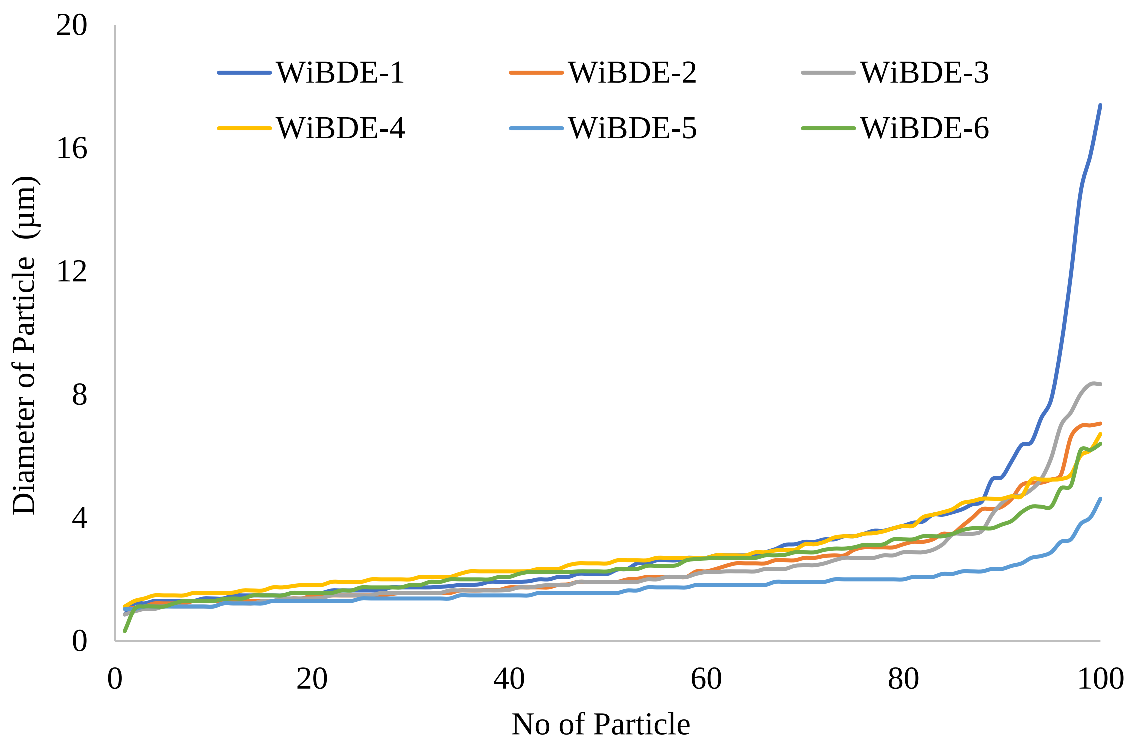
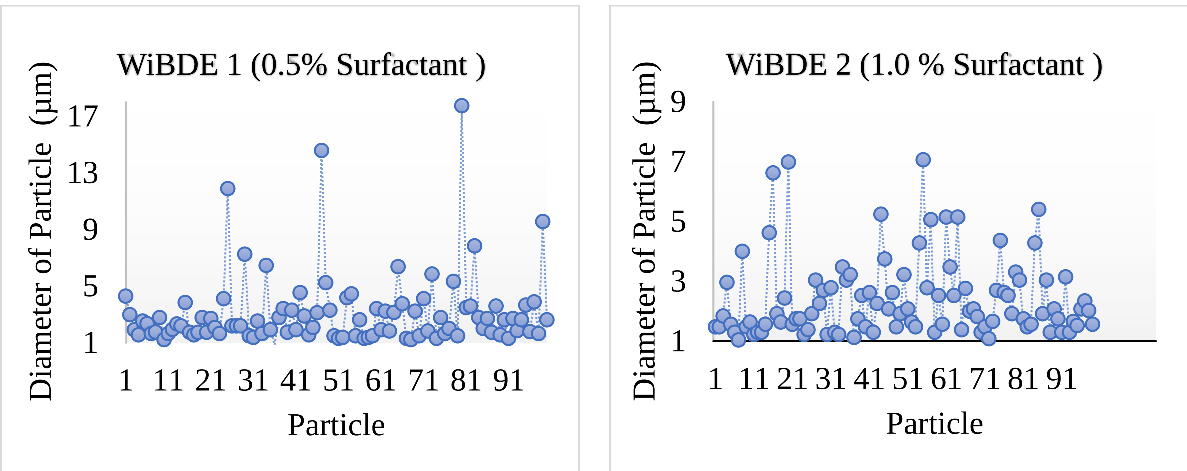


Fig. 9. Particles size distributions of WIBDE fuel sample

3.2.1 Fluctuations in size of the particles in WiBDE fuel sample

In a microscopic visualization study, it was observed that there is variation in the size of particles. For this study, hundred particles from each sample were collected from different locations, and Efgfect of Surfacntant the particale size. The graphs in Figure 10 show that there is a fluctuation in particle size. WiBDE 1 shows that most of the particle diameters are between 1 and 5 µm, but a few particles fluctuate and range from 5 to 17.74 µm. Moreover, by increasing the surfactant concentration as shown in WiBDE 5, most of the particle diameters are between 1 and 3 µm, which are smaller in size compared to WiBDE 1, and a few particles fluctuate in the range near 4.6 µm. In a nutshell, increasing the concentration of the surfactant reduces particle size and enhances stability by reducing particle fluctuation.



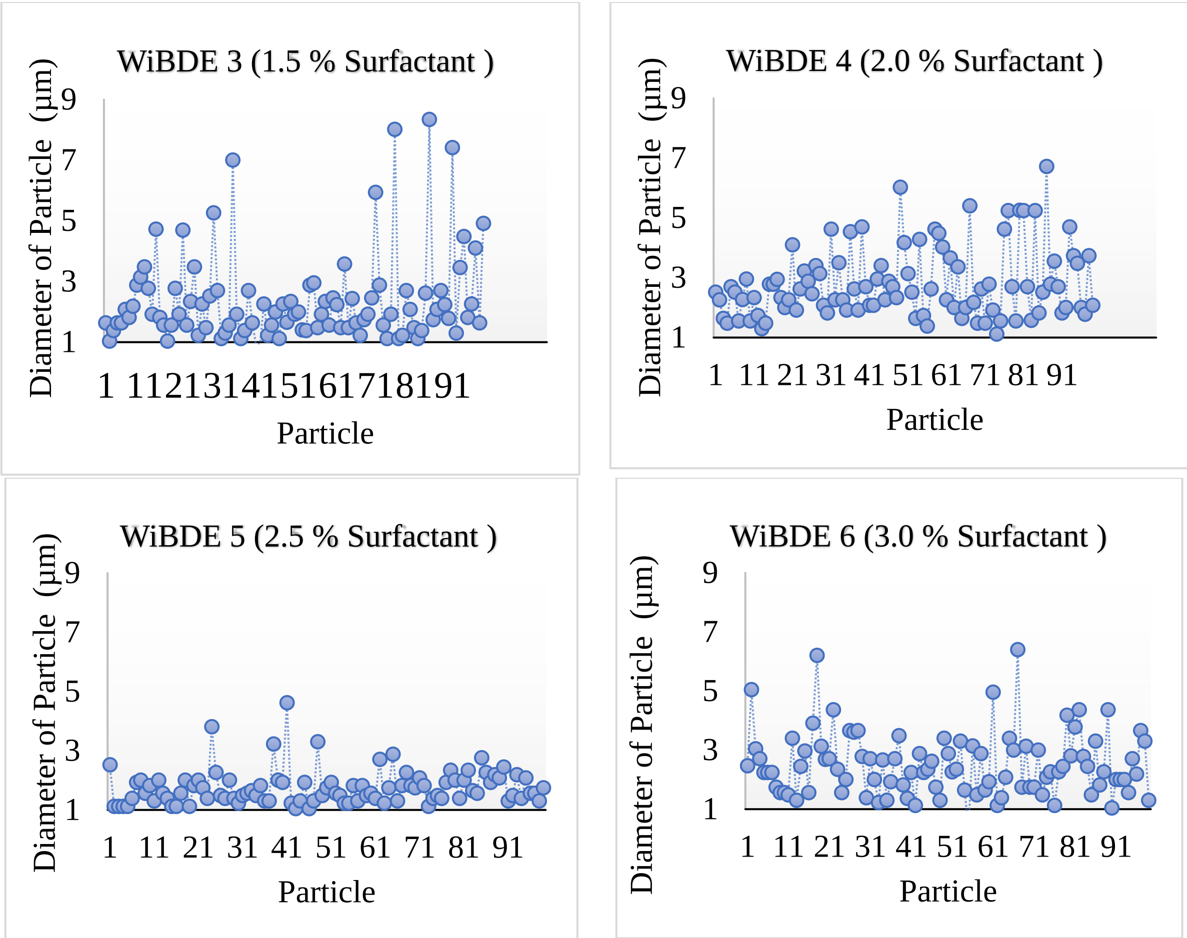


Fig. 10. Fluctuation in the size of the WiBDE fuel samples

3.3 Water Separation in Different Samples of WiBDE

When non mixable liquids are emulsified, after a certain time, these liquids get separated. The stability of an emulsion depends upon various factors, such as time for emulsion, quantity of water, and an emulsifying agent known as a surfactant. Furthermore, a highly stabilized emulsion takes longer to separate than a less stabilized liquid. The current data, collected by Nie *et al.,* [35] show a linear relationship between the percentage of water separation from different emulsions over time and the concentration of surfactant used. It was observed that by increasing surfactant concentration, stability in emulsion increased and water separation decreased [35].

In this study, six different WiBDE fuel samples with different percentages of surfactant are studied to analyze the stability and water separation duration. These samples were observed for ten days, and during this period the water separation percentage was calculated as shown Table 2 and in Figure 11. By increasing the surfactant concentration, it reduces the percentage of water separation or delay in separation in emulsified fuels. Furthermore, as shown in Table 2 and Figure 11, WiBDE 1, 2, and 3 separate more quickly than WiBDE 4, 5, and 6. Furthermore, the stability of WiBDE 4, 5, and 6 samples is nearly identical. And for an economical solution, WIBDE5 is suitable for study and is more stable than others.

Table 2
Water separation from different WiBDE fuel sample

Time	WiBDE1 (0.5% surfactant)	WiBDE2 (1% surfactant)	WiBDE3 (1.5% surfactant)	WiBDE4 (2% surfactant)	WiBDE5 (2.5% surfactant)	WiBDE6 (3% surfactant)
0 min	0	0	0	0	0	0
15 min	60	20	15	0	0	0
30 min	80	30	25	5	0	0
1 hour	100	40	30	5	0	0
2hour	100	60	45	5	0	0
1st day	100	100	60	15	5	0
2nd day	100	100	100	20	10	0
3rd day	100	100	100	25	15	0
10th day	100	100	100	30	20	10

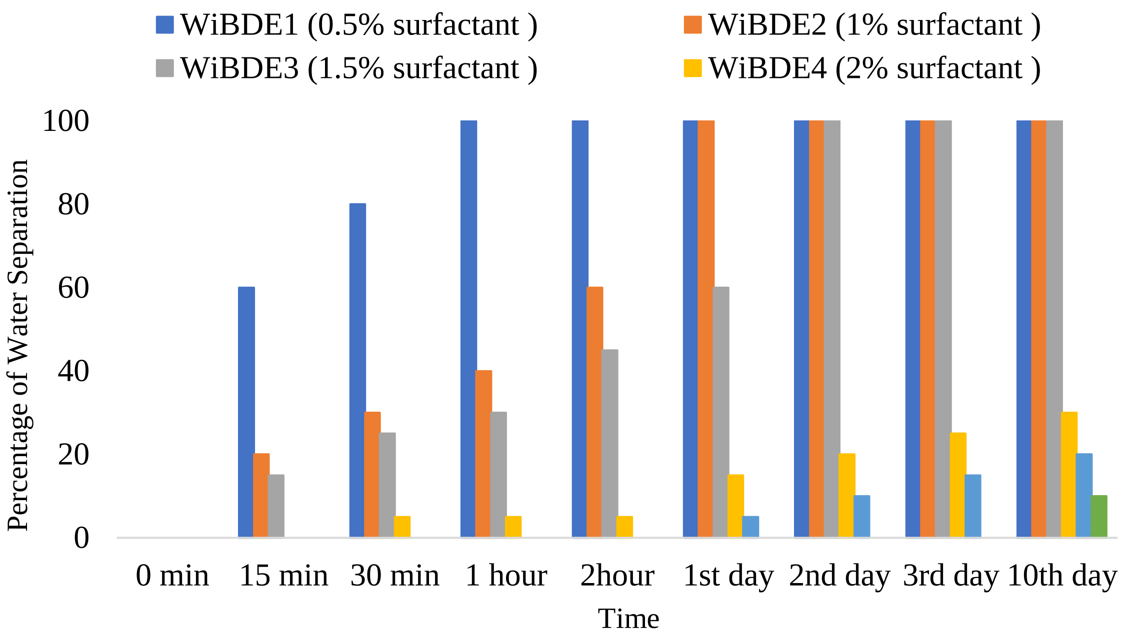


Fig. 11. Water separation from various WiBDE fuel samples on different time

3.4 Droplet Evolution of WiBDE Fuel

The droplet evolution of each sample at 300 °C was captured using a high-speed camera at 950 frames per second. After categorizing these morphological changes into six separate phases based on their shared characteristics. As can be seen in Figure 12, beginning on the left, the droplet begins its transformation from its initial milky white liquid state—typical of an emulsion—into its final. Droplet color shifts are caused by the greater separation of water and biodiesel in the droplet, which occurs at higher temperatures.

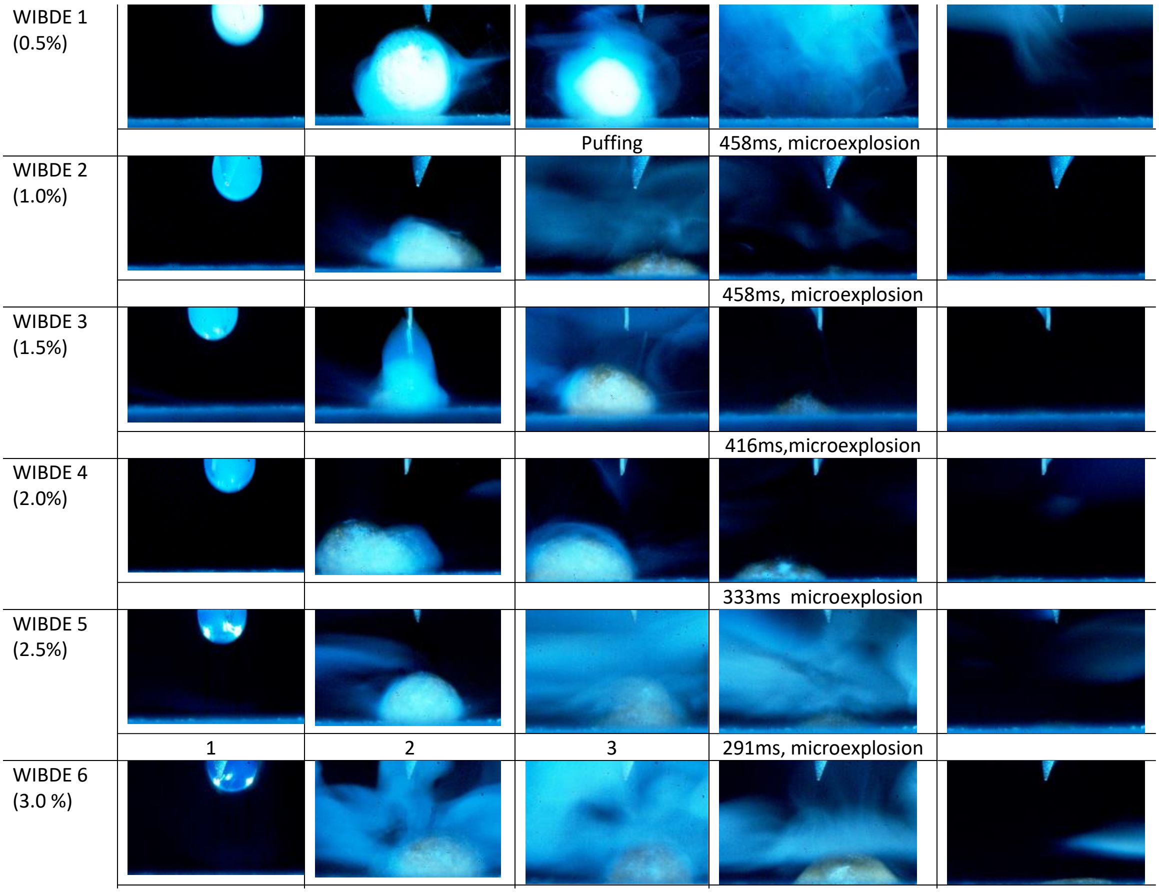


Fig. 12. Micro-explosions of WiBDE fuel at 300 °C

3.4.1 Micro-explosion time profile in various samples droplets on different temperature

The deactivation temperature of surfactant is affected by surfactant concentration. As a result, the micro-explosion may be regulated by varying the quantity of surfactant in emulsified fuels [36]. The micro-explosion delay time decreases as temperature rises, yet it happens near the end of droplet evaporation. The power of the micro-explosion rises as the ambient temperature rises [37]. In this study, droplets of six WiBDE samples were exposed to three different temperatures (200 °C, 300 °C, and 400 °C) to investigate the effect surfactant and temperature on micro-explosion time, as illustrated in Table 3 and Figure 13. It can be observed that the time for micro-explosion is different for the same WiBDE droplet due to variations in exposed temperature. Moreover, high temperatures require more time for micro-explosion because at low temperatures, droplets stick to the surface and are unable to maintain a round shape. This causes a larger surface area of the droplet to contact the hot plate, gaining heat and resulting in a quick micro-explosion. On the other hand, at high temperatures, the droplet maintains its spherical shape, which means that less surface area of the droplet touches the hot plate to gain heat and there is a delay in the micro-explosion. Similarly, the time of micro-explosion for 200 °C, 300 °C, and 400 °C is compared, respectively, as shown in Table 3 and Figure 13 and quick micro-explosion occurs in WiBDE 5 at temperature 300 °C.

Table 3
Micro-explosion time profile in various samples droplets on different temperature

Temperature	Time (ms) at 200 °C	Time (ms) at 200 °C	Time (ms) at 400 °C
WiBDE 1 (0.5%)	1083	458	958
WiBDE 2 (1.0%)	958	458	792
WiBDE 3 (1.5%)	828	416	781
WiBDE 4 (2.0%)	723	333	750
WiBDE 5 (2.5%)	633	291	500
WiBDE 6 (3.0%)	575	333	583

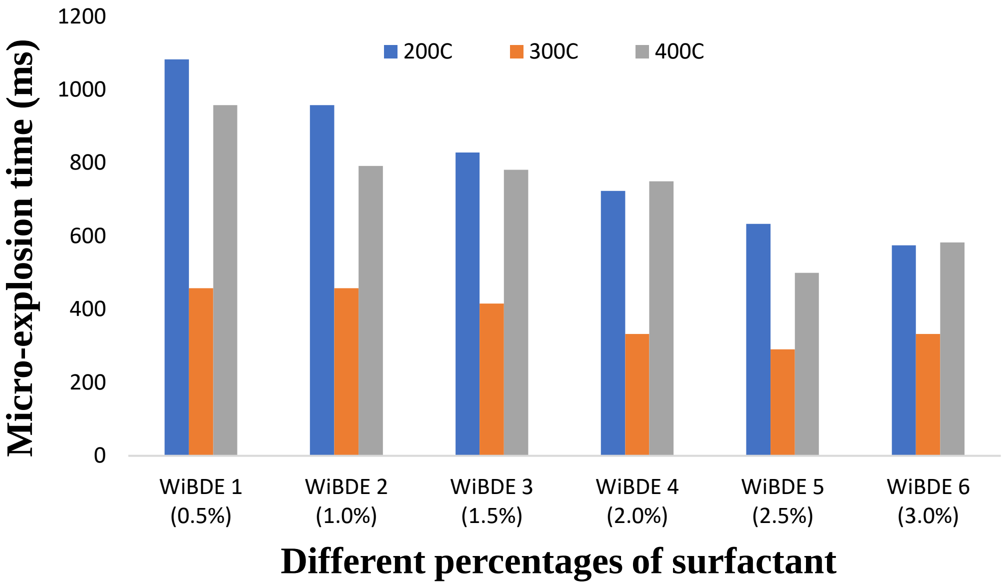


Fig. 13. Micro-explosion of different WiBDE fuel samples

4. Conclusion and Recommendation

The microscopic behaviour of six emulsified fuel samples was studied by changing the amount of surfactant from 0.5 percent to 3.0 percent in six different WiBDE fuel samples. Emulsified fuel with smaller particle sizes is more stable, resulting in better micro-explosion. Increasing surfactant in emulsified fuel helps to develop smaller particles, reduce fluctuations in the size of particles, stabilise fuel, and reduce particle transformation. In emulsified fuel, as the surfactant concentration rises, the percentage of water separation declines, and the separation process is delayed. Varied surfactant dosages were discovered to result in different micro-explosion temperatures. Increasing the hot plate temperature delays the micro-explosion because droplets start dancing and less of the droplet area touches the hot plate. However, at low hotplate temperatures, droplets stick and cover a larger area of the hotplate. So, the fuel should be burned at a recommended temperature for a quick micro-explosion. And increasing or decreasing the recommended temperature of the hot plate can delay the micro-explosion's duration. WiBDE-5 fuel with a surfactant mixture concentration of 2.5% was found to be highly stable and reduce micro-explosion times. A longer micro-explosion and evaporation delay might result in incomplete combustion, which would raise exhaust emissions. The use of biosurfactant instead of chemical surfactant can enhance emulsified fuel quality and stability. Biodiesel and biosurfactants are eco-friendly and can be used to develop an alternative emulsified WIBDE fuel. This sustainable and environmentally friendly fuel reduces harmful emissions and contributes to the preservation of the environment. This environmentally friendly technique is a crucial step towards a cleaner future for our planet.

4.1 Study Limitations and Potential Future Research Avenues

The gradual separation of water from emulsified fuel over time is one of the factors that contributes to the fuel's limited use. Potential benefits of using emulsified fuel in diesel engines are that it reduces harmful emissions during combustion. The presence of water produces a lowering in combustion temperature when this emulsified fuel is burned. Therefore, nitrogen oxide (NOx) generation is reduced, resulting in significant reductions in emissions that contribute to air pollution. Adopting such creative solutions will pave the way for cleaner and more green power techniques, creating a healthier and greener future for our world.

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