# Comparative Analysis of Performance and Emission Characteristics of Jatropha Biodiesel and Emulsified Jatropha Biodiesel in a Diesel Engine

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***Abstract.*** The main aim of this study is to investigate the performance and emission characteristics of Jatropha biodiesel blends in a diesel engine and to explore the potential of water-in-biodiesel emulsification as a strategy to enhance efficiency and reduce harmful emissions, particularly nitrogen oxides ($NO_X$). To achieve these objectives, Jatropha biodiesel blends (B10, B20, B30) were first tested in a single-cylinder diesel engine under standard operating conditions to determine the optimum blend. Based on a balance between Brake Thermal Efficiency (BTE) and emissions, B20 was identified as the most suitable blend and was subsequently used as the base fuel to prepare emulsified biodiesel blends with 5%, 10%, and 15% water by volume (B20W5, B20W10, and B20W15). The utmost important results are that the emulsified blends exhibited prominent improvements in performance and emission characteristics compared to B20. Specifically, B20W10 achieved a 4% higher BTE than B20 and a reduced Brake Specific Fuel Consumption (BSFC), while B20W15 recorded reductions in Hydrocarbon (HC) emissions by 31.42%, Carbon Monoxide (CO) by 55.55%, and Smoke Opacity by 36.11% relative to B20. Furthermore, B20W10 demonstrated a 9% decrease in $NO_X$ emissions than diesel. The significance of the obtained results is that water-in-biodiesel emulsification, particularly the B20W10 blend, offers an applied and sustainable solution for improving combustion efficiency, lowering fuel consumption, and mitigating harmful emissions, thereby promoting cleaner compression Ignition (CI) engine operation and supporting the transition toward renewable energy use in the transportation sector.
***Keywords:*** Jatropha biodiesel, emulsified biodiesel, performance, emission, surfactant.

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**Analiza comparativă a caracteristicilor de performanță și emisii ale biodieselului din Jatropha și ale biodieselului emulsionat din Jatropha într-un motor diesel**

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***Abstract.*** Scopul principal al acestui studiu este de a investiga caracteristicile de performanță și emisii ale amestecurilor de biodiesel cu Jatropha într-un motor diesel și de a explora potențialul emulsificării apă-în-biodiesel ca strategie pentru creșterea eficienței și reducerea emisiilor nocive, în special a oxizilor de azot (NOX). Pentru a atinge aceste obiective, amestecurile de biodiesel cu Jatropha (B10, B20, B30) au fost testate mai întâi într-un motor diesel monocilindric în condiții standard de funcționare pentru a determina amestecul optim. Pe baza unui echilibru între eficiența termică la frânare (BTE) și emisii, B20 a fost identificat ca fiind amestecul cel mai potrivit și a fost ulterior utilizat ca și combustibil de bază pentru a prepara amestecuri de biodiesel emulsionate cu 5%, 10% și 15% apă în volum (B20W5, B20W10 și B20W15). Cele mai importante rezultate sunt că amestecurile emulsionate au prezentat îmbunătățiri proeminente ale caracteristicilor de performanță și emisii în comparație cu B20. Mai exact, B20W10 a obținut un BTE cu 4% mai mare decât B20 și un Consum Specific de Combustibil la Frânare (BSFC) redus, în timp ce B20W15 a înregistrat reduceri ale emisiilor de hidrocarburi (HC) cu 31,42%, ale monoxidului de carbon (CO) cu 55,55% și ale opacității fumului cu 36,11% față de B20. În plus, B20W10 a demonstrat o scădere cu 9% a emisiilor de NOX față de motorina. Semnificația rezultatelor obținute constă în faptul că emulsificarea apă-în-biodiesel, în special amestecul B20W10, oferă o soluție aplicată și durabilă pentru îmbunătățirea eficienței arderii, reducerea consumului de combustibil și atenuarea emisiilor nocive, promovând astfel o funcționare mai curată a motorului cu aprindere prin compresie (CI) și sprijinind tranziția către utilizarea energiei regenerabile în sectorul transporturilor.
***Cuvinte-cheie:*** biodiesel din Jatropha, biodiesel emulsionat, performanță, emisie, surfactant.

# Сравнительный анализ эксплуатационных характеристик и характеристик выбросов биодизеля из Ятрофы и эмульгированного биодизеля из Ятрофы из дизельного двигателя

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***Аннотация.*** Основная цель данного исследования – изучение эксплуатационных характеристик и характеристик выбросов смесей биодизеля на основе ятрофы в дизельном двигателе, а также изучение потенциала эмульгирования воды в биодизеле как стратегии повышения эффективности и снижения вредных выбросов, в частности оксидов азота (NOX). Для достижения этих целей смеси биодизеля на основе ятрофы (B10, B20, B30) были сначала испытаны в одноцилиндровом дизельном двигателе в стандартных условиях эксплуатации для определения оптимальной смеси. На основе баланса между термической эффективностью тормозов (BTE) и выбросами, смесь B20 была признана наиболее подходящей и впоследствии использовалась в качестве базового топлива для приготовления эмульгированных биодизельных смесей с 5%, 10% и 15% воды по объему (B20W5, B20W10 и B20W15). Наиболее важным результатом является то, что эмульгированные смеси продемонстрировали значительное улучшение эксплуатационных характеристик и характеристик выбросов по сравнению с B20. В частности, масло B20W10 показало на 4% более высокую удельную теплотворную способность (BTE), чем B20, и сниженный удельный расход топлива (BSFC), в то время как B20W15 зафиксировал снижение выбросов углеводородов (HC) на 31,42%, оксида углерода (CO) на 55,55% и дымности на 36,11% по сравнению с B20. Кроме того, B20W10 продемонстрировал снижение выбросов NOX на 9% по сравнению с дизельным топливом. Значимость полученных результатов заключается в том, что эмульгирование воды в биодизельном топливе, особенно в смеси B20W10, представляет собой практичное и устойчивое решение для повышения эффективности сгорания, снижения расхода топлива и сокращения вредных выбросов, тем самым способствуя более чистой работе двигателей с воспламенением от сжатия (CI) и поддерживая переход к использованию возобновляемых источников энергии в транспортном секторе.

***Ключевые слова:*** биодизель из ятрофы, эмульгированный биодизель, производительность, выбросы, поверхностно-активное вещество.

## INTRODUCTION

The growing demand for energy on a global scale at an exponential rate, combined with the fast-depleting fossil fuel resources and increasing environmental pressure, has hastened the quest for cleaner and greener alternatives to traditional fuels [1]. The industrial and transport sectors depend largely on petroleum-derived fuels, most notably diesel, which are heavy polluters that emit high levels of greenhouse gases, particulate matter, and nitrogen oxides ($NO_X$) [2]. The use of diesel fuel in compression ignition (CI) engines though efficient has been found to be linked with toxic emissions that cause harm to human health and the environment. Therefore, there exists a pressing need for the creation of environment-friendly fuels that can be easily used in current engines with little or no alterations [3].

Among the array of alternative fuels researched, biodiesel is found to be a sustainable and useful alternative to traditional diesel. It is a biodegradable, oxygenated, and renewable fuel that is produced from vegetable oils or animal fats by transesterification. Biodiesel has some benefits such as reduced sulfur content, better lubricity, and lower CO, HC, and particulate emissions. Some of the limitations like increased viscosity, poor volatility, and higher NOx emissions, particularly at higher blending levels, are obstacles to its widespread use. These drawbacks necessitate further modifications to improve the fuel's combustion characteristics and emission behavior [4].

Jatropha curcas, which is a non-food oilseed crop, is a good feedstock for biodiesel use, especially in the tropics and subtropics. The crop adapts to poor land, is easy to maintain, and does not compete with food crops, hence a good option in resolving the food-versus-fuel conflict. Biodiesel from Jatropha has shown good combustion characteristics; however, its use in blends over 20% can have a negative impact on engine performance and raise specific emissions [5].

To mitigate these problems, emulsification of water with biodiesel has been recommended as an innovative solution to improve the combustion process and minimize emissions. Emulsified fuel is created by mixing water with biodiesel or biodiesel-diesel blends using surfactants to facilitate stable formation of an emulsion. Addition of water to the fuel results in micro-explosions in the case of combustion—a phenomenon where the volatile fraction quickly vaporizes with secondary atomization. This enhances air–fuel mixing, decreases peak combustion temperature, and decreases ignition delay, finally leading to cleaner combustion and lower NOx emissions. The application of emulsified biodiesel also has the potential to enhance brake thermal efficiency and decrease carbon monoxide and unburned hydrocarbon emissions because of enhanced fuel atomization and complete combustion.

**Novelty of the Work**

This work exclusively explores the performance and emission properties of water-emulsified Jatropha B20 biodiesel blends (5%, 10%, and 15% water) in a CI engine. In contrast to existing literature focused only on biodiesel or emulsified diesel, this study presents a comparative analysis of neat diesel, B20, and water-emulsified B20 blends. It determines the best content of water that improves combustion efficiency and decreases emissions without any engine modification and helps in sustainable fuel development with non-edible Jatropha oil.

## MATERIALS AND METHODS

*Transesterification of Jatropha Oil*

Jatropha curcas oil was obtained from a nearby biodiesel plant and used as the raw material to produce biodiesel [7]. Transesterification was utilized to convert the crude oil to Jatropha Methyl Ester (JME) form of biodiesel using methanol and sodium hydroxide (NaOH) as a base catalyst. The oil was first filtered and preheated at 60°C to remove moisture and impurities. At the same time, the catalyst solution was prepared by dissolving methanol in NaOH at a 6:1 molar ratio (methanol to oil). The methanolic NaOH was then added to the heated oil and stirred for 90 minutes at 60°C using a magnetic stirrer under the condition of continuous stirring to help the transesterification reaction. The resulting blend was left to settle in a separating funnel for 12 hours and formed two layers: crude biodiesel (top) and glycerol (bottom). The biodiesel was then washed several times with warm distilled water to get rid of any remaining catalyst and methanol [8]. It was finally dried at 110°C to remove moisture content. The resulting biodiesel (JME) was kept for later use in fuel formulations.

*Selection of Maximum Water Content in Biodiesel Emulsions*

In the present research, the highest water content in emulsified biodiesel blends was limited to 15% by volume. This was grounded on both fuel property and engine performance reasons. Initial tests found that blends having higher than 15% water content had poor emulsion stability, with a leaning tendency towards phase separation with time. In addition, increased water content resulted in a significant reduction in brake thermal efficiency. These phenomena undermine the reliability of fuel and safe engine operation. Based on this experience, 15% water addition was chosen as the upper safe and stable limit, providing a compromise between emulsion stability and practical engine usability.

*Preparation of Emulsified Biodiesel Blends*

To improve combustion performance and emissions properties, emulsified biodiesel fuel blends were prepared from JME-based B20 (20% JME and 80% diesel by volume) as the reference fuel. Water was emulsified into the B20 blend with a surfactant system consisting of Span 80 and Tween 80 having a Hydrophilic-Lipophilic Balance (HLB) value of 6.43 for the best emulsion stability. Three fuel samples were made: B20W5 (5% water), B20W10 (10% water), and B20W15 (15% water), each having 2% surfactant by volume [9]. Emulsification was done using a Hielscher UP400St Ultrasonic Processor (400 W, 24 kHz) at continuous flow conditions which was shown in Figure 1. All mixes were sonicated for 10 minutes to achieve uniform dispersion and stabilized emulsion formation. These emulsified mixes were further utilized in subsequent engine performance and emissions studies.

**Fig. 1. Ultrasonication Setup for Emulsified Biodiesel.**

*Fuel Property Analysis*

Fuel properties of B20, diesel, and emulsified biodiesel blends of B20W5, B20W10, and B20W15 were measured according to respective ASTM standards. Table 1 shows the determined properties such as density, viscosity, flash point, fire point calorific value. Measurements were made in triplicates, and the average values were considered for analysis [10].

Table 1 Fuel properties.

| Properties | Diesel | B10 | B20 | B30 | B20W5 | B20W10 | B20W15 |
|---|---|---|---|---|---|---|---|
| Density (kg/m³) | 813 | 815 | 829 | 837 | 835 | 840 | 845 |
| Viscosity at 40°C (cSt) | 2.8 | 3.1 | 3.3 | 3.6 | 3.4 | 3.5 | 3.7 |
| Flash Point (°C) | 52 | 56 | 59 | 58 | 61 | 63 | 66 |
| Fire Point (°C) | 56 | 62 | 65 | 68 | 67 | 69 | 71 |
| Calorific Value (kJ/kg) | 42, 100 | 41,500 | 40,900 | 40,200 | 39,600 | 38,900 | 38,100 |

## EXPERIMENTAL SETUP DESCRIPTION

Experimental study was performed on a Kirloskar, single-cylinder, four-stroke, direct injection diesel engine rated at 3.5 kW at 1500 rpm. The engine is water-cooled and attached to an eddy current hydraulic loading system, which provides accurate loading over a wide range of test conditions. The engine specifications are given in Table 2.

Table 2 Specifications of Research Engine.

| Parameter | Specification |
|---|---|
| Engine Make | Kirloskar |
| Engine Type | Single-cylinder, 4-stroke, CI engine |
| Cooling System | Water-cooled |
| Rated Power | 3.5 kW |
| Rated Speed | 1500 rpm |
| Bore × Stroke | 87.5 mm × 110 mm |
| Compression Ratio | Variable (16:1 to 18:1) |
| Ignition Type | Compression Ignition |
| Starting Method | Manual start |
| Fuel Injection System | Direct injection |
| Loading Type | Eddy current hydraulic dynamometer |
| Dynamometer Capacity | 3.7 kW |

To measure exhaust emissions, an AVL Di-Gas 444 analyzer was used to monitor CO, HC, and $NO_X$ levels. Smoke opacity was assessed using an AVL 437 Smoke Meter. The above instruments provided real-time measurements of the typical exhaust characteristic of the engine within accuracy.

The base fuel utilized was B20 comprising 20% tamarind seed oil biodiesel and 80% diesel. Emulsified fuels were made by the addition of 5%, 10%, and 15% water to the B20 using a mechanical homogenizer, along with appropriate surfactants for stability.

The entire experimental arrangement, comprising the engine test rig, loading system, emission analyzers, and smoke meter, is shown in Figure 2.

**Fig. 2. Schematic of the experimental setup comprising Kirloskar 3.5 kW diesel engine.**

## RESULTS AND DISCUSSION

The study was carried out in two stages. During the first stage, performance BTE and BSFC) and emission characteristics (HC, CO, $NO_X$, and Smoke Opacity) were tested with Jatropha biodiesel blends (B10, B20, and B30) and compared with diesel. In the second stage, emulsified biodiesel samples (B20W5, B20W10, and B20W15) were evaluated. Emulsified fuels were focused on enhancing combustion and decreasing emissions.

Comparative findings from the two stages are presented to identify the impact of emulsification on engine performance and emissions.

*Phase 1*

*Brake Thermal Efficiency (BTE)*

Figure 3 illustrates the variation in BTE with respect to BP. It can be seen from the graph that BTE rises with brake power in all fuel types, reflecting increased combustion efficiency at higher loads because of better atomization and air-fuel mixing.

Diesel has the highest BTE under all loads with an all-time peak value of 29.5% at 3.5 kW. The biodiesel blends, B20 ranks better than B10 and B30, achieving an all-time maximum BTE of 27.5%, which is only slightly lower than diesel.

This improvement in BTE for B20 can be explained by the ideal oxygen content enhancing combustion without unnecessarily raising fuel viscosity [11]. Conversely, B10 is comparatively less thermal efficient because of a lack of oxygen enrichment, whereas B30 indicates slightly decreased BTE likely because of increased viscosity and decreased volatility that results in incomplete combustion.

Therefore, B20 is the most effective blend out of the biodiesel samples that were subjected to this phase of testing.

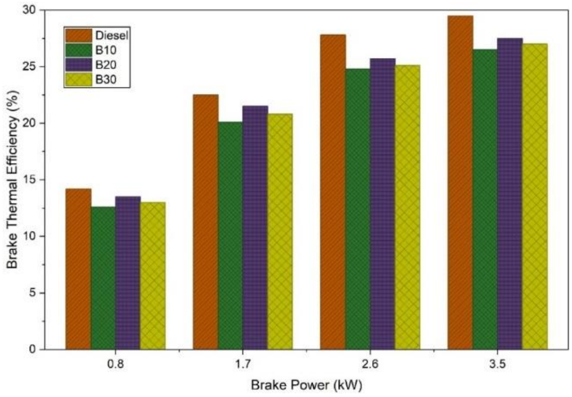


**Fig. 3. Brake Power vs. BTE.**

*Brake Specific Fuel Consumption (BSFC)*

As illustrated in Figure 4, the BSFC tends to decrease with rising BP. The BSFC was seen to be 0.42 kg/kWh when the load was set at the lowest level of 0.9 kW. When the load was raised to 1.8 kW, 2.7 kW, and 3.5 kW, the BSFC levels decreased step by step to 0.32 kg/kWh, 0.29 kg/kWh, and 0.26 kg/kWh, respectively. This reduction in BSFC with rising BP is largely due to enhanced combustion efficiency and improved thermal utilization with higher engine loads. At low loads, more fuel energy is lost by virtue of incomplete combustion, wall heat losses, and work for pumping. With the increase in load, the engine draws closer to its design point, with improved air–fuel mixing and combustion stability, minimizing the fuel burned per unit of brake power delivered [12].

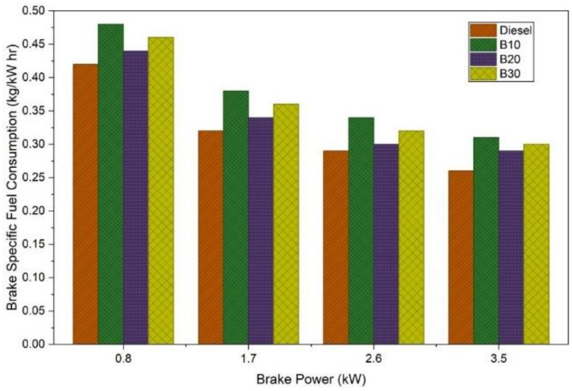


**Fig. 4. Brake Power Vs BSFC.**

*Hydrocarbon (HC) Emissions*

The variation of HC emissions with brake power for Diesel, B10, B20, and B30 is depicted in Figure 5. HCs decrease by increasing the load. This is because of the improvement in the combustion efficiency.

Diesel has the greatest HC emissions at 58 ppm without load to 35 ppm fully loaded. B10 lowers these to 52 ppm without load and 31 ppm fully loaded. B20 and B30 lower the emissions further to 28 ppm and 26 ppm fully loaded, respectively.

The decrease is attributed to the oxygen present in biodiesel, which increases the oxidation of unburned fuel [13]. More cetane number and decreased aromatic content of biodiesel also lead to improved combustion and reduced HC levels.

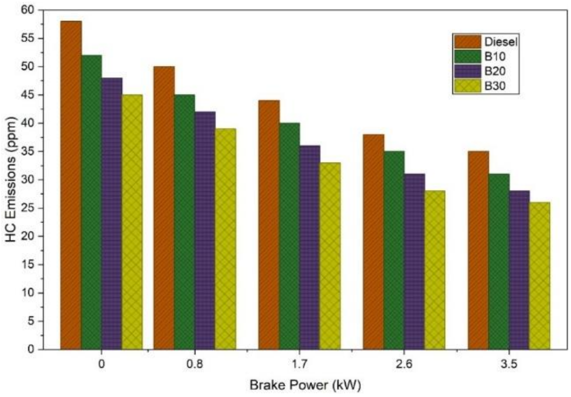


**Fig. 5. Brake Power Vs HC Emissions.**

*CO Emissions*

Figure 6 illustrates the CO emission (% by volume) variation with increasing brake power. CO emission is mainly caused by partial combustion due to a lack of oxygen or inadequate fuel–air mixing. With respect to diesel, the B30 biodiesel blend demonstrates a noticeable decrease in CO emissions under all loads. Diesel produced 0.14% CO at full load, while B30 produced only 0.09%, representing a 35.7% decrease.

This decrease is due to the oxygen-rich composition of biodiesel, which favors the oxidation of carbonaceous intermediates during combustion, resulting in more complete fuel burning. The increased cetane number in biodiesel also helps in better ignition quality and more efficient burning, thus reducing the formation of CO further. The lower carbon-to-hydrogen ratio in biodiesel than in diesel also reduces carbon-based emissions [14]. Thus, the trend observed here verifies that combustion using B30 yields cleaner combustion with much reduced emissions of CO.

*NOx Emission Analysis*

Variation of NOx emissions with BP is plotted in Figure 7. The NOx emissions were found to rise with an increase in the brake power because of the rise in the temperature of combustion at higher loads. Among all samples, B30 had the highest NOx emissions of 990 ppm at 3.5 kW and diesel had 880 ppm at the same brake power—an increase of 12.5%. B20 and B10 had 950 ppm and 910 ppm, demonstrating 7.9% and 3.4% increases, respectively.

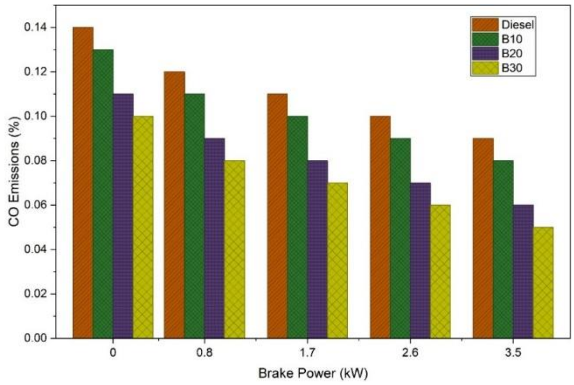


**Fig. 6. Brake Power Vs. CO emissions.**

The rise in NOx with all loads can be explained by the greater oxygen content of the biodiesel blends, which leads to more complete combustion and higher peak temperatures, thus increasing thermal NOx formation [15]. As observed in Figure 7, the NOx emission of biodiesel blends—particularly B30—is much greater, reflecting a trade-off between better combustion and greater NOx formation at higher in-cylinder temperatures.

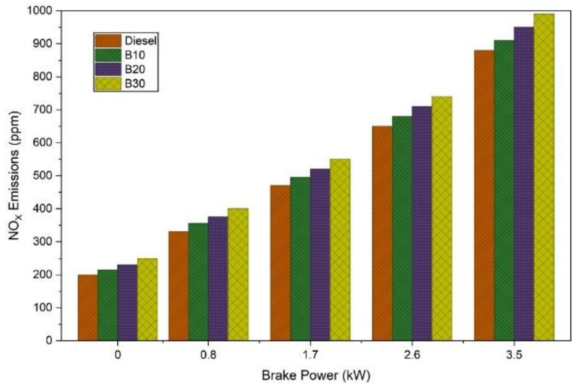


**Fig. 7. Brake Power Vs. NOx emissions.**

*Smoke Opacity Analysis*

Figure 8 shows the smoke opacity variation in terms of FSN (Filter Smoke Number) with respect to various blends of biodiesel for different BP. The neat diesel fuel smoke opacity grew progressively with load, from 1.1 FSN at zero load to 3.6 FSN at full load (3.5 kW). The B10, B20, and B30 fuels consistently had FSN values that were lower than diesel, showing decreasing smoke emissions with higher biodiesel content. The B30 blend showed the minimum smoke opacity levels across the load range, ranging from 0.8 FSN at no load to 2.7 FSN at full load. This trend agrees that an increased concentration of biodiesel convincingly reduces the formation of smoke because its oxygenated molecular structure enhances improved oxidation of soot precursors during combustion [16]. In total, the operation of biodiesel blends, particularly B30, is a considerable contributor to smoke emission reduction without sacrificing load operating characteristics.

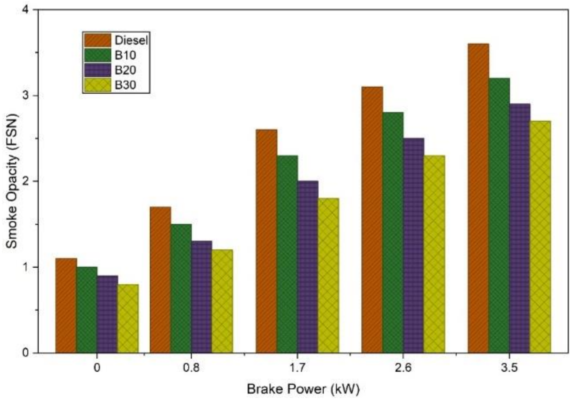


**Fig. 8. Brake Power Vs. Smoke Opacity.**

*Phase 2: Emulsified Biodiesel Results Analysis*

*Brake Thermal Efficiency (BTE)*

Figure 9 illustrates the trend of BTE Vs. BP. Under all the loading conditions, Diesel had the maximum BTE throughout, due to its better calorific value and better combustion properties [17]. In the emulsified blends of biodiesel, B20W10 was the most effective among all of them, even performing better than B20W5 and B20W15 at medium and higher loads. The BTE of B20W10 remained between 3.0–3.3% that of Diesel for the entire load range. Comparatively, B20W5 recorded a drop of around 4.7–4.8% with respect to Diesel, while B20W15 had the maximum drop in BTE with a fluctuation of about 5.8–6.5% with respect to Diesel at different loads. In comparison to B20W10, the BTE of B20W5 was lower constantly by 1.7–2.1%, while that of B20W15 decreased by 2.7–2.8%, reaffirming that a 10% water addition is an optimal between micro-explosion effect and delay in combustion.

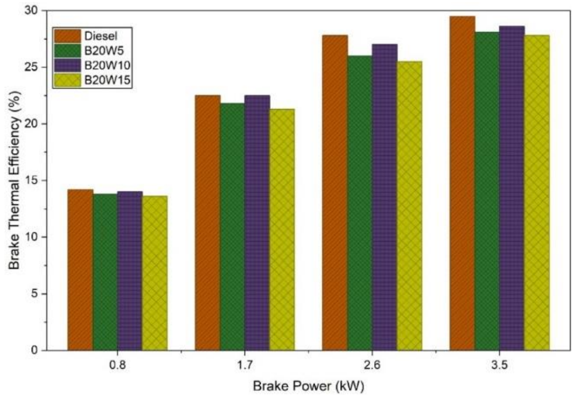


**Fig. 9. Variation of Brake Power Vs BTE.**

*Brake Specific Fuel Consumption (BSFC)*

Figure 10 illustrates the variation of BSFC and BP. BSFC consistently decreases with increasing brake power for all fuel samples due to enhanced combustion efficiency at higher loads. Diesel exhibits the lowest BSFC across all operating conditions because of its higher calorific value and better combustion characteristics. At maximum load, B20W5 recorded a BSFC of 0.28 kg/kWh, reflecting a 7.7% increase over Diesel (0.26 kg/kWh), while B20W10 showed a BSFC of 0.27 kg/kWh with a 3.8% rise. B20W15 exhibited the highest BSFC at 0.29 kg/kWh, representing an 11.5% increase compared to Diesel. When compared to B20W10, BSFC of B20W5 and B20W15 was higher by 3.7% and 7.4% respectively. The increase in BSFC for emulsified blends is attributed to the lower heating value and longer ignition delay; however, the relatively lower BSFC of B20W10 suggests improved combustion behavior due to a balanced micro-explosion effect of water in the fuel [18].

The HC emission variation with BP is shown in Figure 11. HC emissions, expressed in ppm, fall with rising brake power in all fuel samples owing to higher combustion temperatures and enhanced oxidation at high loads. Under no load, Diesel gave 58 ppm, whereas B20W5, B20W10, and B20W15 gave 46 ppm, 44 ppm, and 42 ppm respectively indicating reductions of 20.7%, 24.1%, and 27.6% from Diesel. Under full load (3.5 kW), HC emissions of Diesel, B20W5, B20W10, and B20W15 were 35 ppm, 27 ppm, 25 ppm, and 24 ppm, reflecting reductions of 22.9%, 28.6%, and 31.4% from Diesel. The reduced HC emissions of emulsified blends are due to the micro-explosion effect promoted by water content, which increases secondary atomization and ensures complete combustion [19]. Of the blends, B20W15 presents the least HC emissions in all loads.

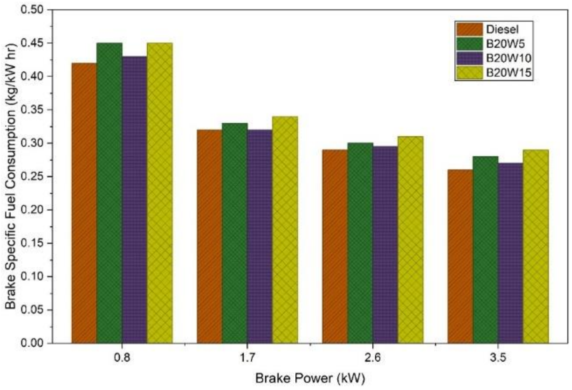


**Fig. 10. Variation of Brake Power with BSFC.**

*Hydrocarbon (HC) Emissions*

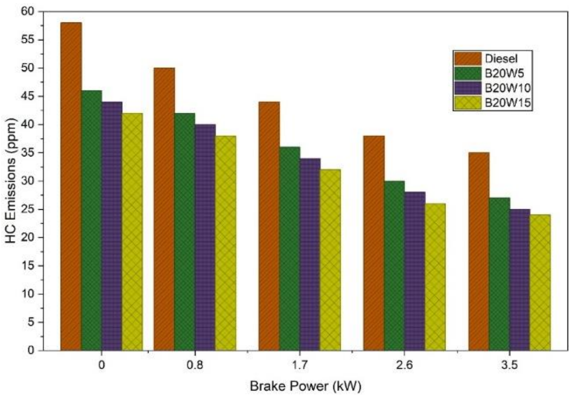


**Fig. 11. Variation of Brake Power with HC emissions.**

*Carbon Monoxide (CO) Emissions*

The CO emission variation with BP is presented in Figure 12. The CO emissions in % demonstrate a smooth decrease with an increase in brake power for all the fuel samples, owing to better combustion at elevated loads. At no load, Diesel showed a CO emission of 0.14%, while B20W5, B20W10, and B20W15 showed 0.10%, 0.09%, and 0.08% respectively, corresponding to reductions of 28.6%, 35.7%, and 42.9% over Diesel. At full load (3.5 kW), Diesel released 0.09% CO, while B20W5, B20W10, and B20W15 released 0.06%, 0.05%, and 0.04% respectively, showing reductions of 33.3%, 44.4%, and 55.6% concerning Diesel. The reduced CO emissions from the emulsified blends are due to the water content, which enhances complete combustion by secondary atomization and in-cylinder temperature control [20]. All of them show, among which B20W15 shows the largest reduction in CO emissions at all the load conditions.

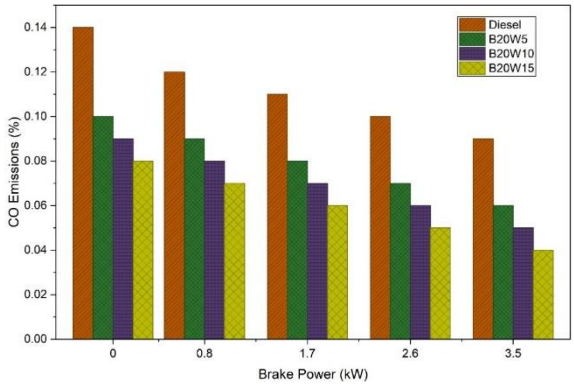


**Fig. 12. Variation of BP with CO emissions.**

### 4.11 NOx Emissions

Figure 13 presents NOX emissions at a different BP. A uniform increase in the NOx emissions with an increase of load is evident due to the increase in combustion temperature and in-cylinder pressure. Under full load (3.5 kW), diesel emitted the greatest NOx emissions of 880 ppm, with B20W5 coming in at 860 ppm, B20W10 at 840 ppm, and B20W15 at 800 ppm. Against diesel, the B20W15 blend reported a decrease of 9.09% in NOx emissions, while B20W10 and B20W5 reported decreases of 4.54% and 2.27%, respectively. The reduction in NOx emissions for the emulsified biodiesel blends is due to the micro-explosion mechanism and water latent heat of vaporization, which reduces peak combustion temperatures [21]. The outcome supports the success of water-in-diesel emulsification in preventing thermal NOx formation.

Figure 14 displays the smoke opacity values in terms of Filter Smoke Number (FSN) for diesel and water-emulsified biodiesel blends (B20W5, B20W10, and B20W15) across different brake powers. Smoke opacity grows with growing load for all fuel samples because of higher fuel injection as well as incomplete combustion at higher pressures [22]. But the emulsified blends show consistently lower smoke content than diesel. At full load (3.5 kW), diesel had the maximum smoke opacity at 3.6 FSN, while B20W5, B20W10, and B20W15 indicated 2.7, 2.5, and 2.3 FSN, respectively. This corresponds to a 36.11% decrease in smoke opacity for B20W15 compared to diesel. The decrease is because of improved atomization, increased availability of oxygen from the biodiesel component, and the disruptive micro-explosion effect due to water, which aids in fuller combustion and restricts soot formation [23].

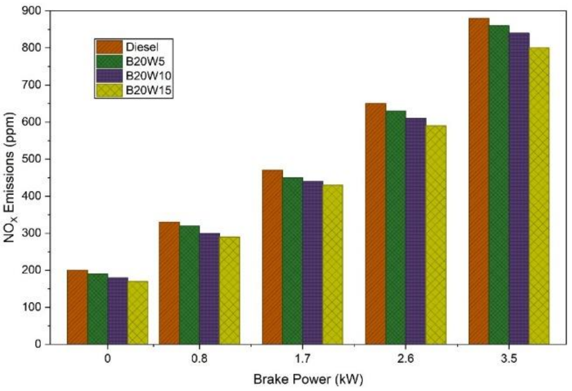


**Fig. 13. Brake Power Vs. $N_{OX}$ emissions.**

*Smoke Opacity*

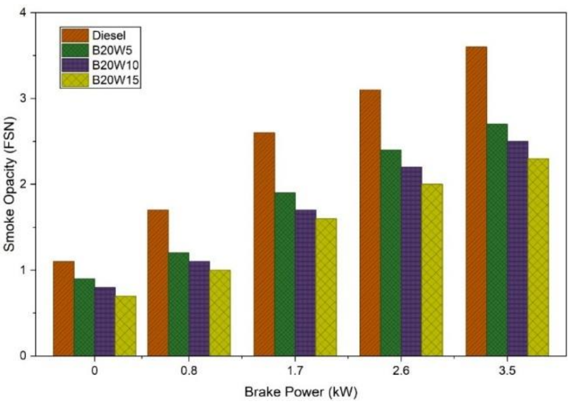


**Fig. 14. Brake power Vs. Smoke opacity.**

*Performance–Emission Trade-offs in Water-Emulsified Biodiesel Blends*

Performance evaluation and emissions analysis reveal that higher water content in the emulsified biodiesel blends represents a trade-off. While increase in water content (e.g., up to 15%) brings significant drops in NOx, CO, HC, and smoke opacity, it also results in a considerable reduction in brake thermal efficiency, which is a negative result for real-world applications [24]. In contrast, smaller water content (5%) preserves slightly higher efficiency but offers relatively lower emission drop. In light of this equilibrium, the B20W10 blend was discovered to be the most appropriate compromise because it ensured relatively high efficiency while still providing impressive emission reductions in all studied parameters [25]. In this context, B20W10 can thus be seen as the best blend for real-world application, with optimal integration of performance and environmental advantages.

## CONCLUSION

The experimental analysis of the B20 biodiesel emulsified with different water contents (5%, 10%, and 15%) in a single-cylinder diesel engine revealed significant improvements in performance as well as emission characteristics. Brake Thermal Efficiency (BTE) followed an increasing trend with load for all test fuels, with B20W5 attaining a maximum BTE of 34.5% at full load, higher than neat diesel (32.6%). Hydrocarbon (HC) and Carbon Monoxide (CO) emissions clearly decreased with a rise in load, with B20W15 indicating minimum HC (24 ppm) and CO (0.04%) emissions at full load, respectively. There was a significant reduction in Smoke Opacity for emulsified fuels, and the lowest smoke value of 2.3 FSN was recorded by B20W15 at full load. But Nitrogen Oxide (NOx) emissions increased marginally with diesel but reduced considerably with increasing water content. B20W15 had a maximum NOx reduction by 80 ppm from diesel. The findings verify that water-in-diesel emulsified biodiesel blends, especially B20W15, are efficient in lowering harmful emissions without impacting engine performance considerably. Therefore, the employment of emulsified biodiesel can be a promising means toward cleaner combustion and lower environmental footprint, particularly in low-heat rejection or newer diesel engines modified for alternative fuel blends.

***Data availability statement***

The authors confirm that the data supporting the findings of this study are available within the article.

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