



## PERFORMANCE AND EMISSION OPTIMIZATION OF A DIESEL ENGINE USING KARANJA BIODIESEL–HYDROGEN DUAL-FUEL WITH AZADIRACHTA INDICA ANTIOXIDANT

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### ABSTRACT

Renewable fuels are critically required for internal combustion engines because of environmental degradation and the exhaustion of fossil fuels. Hydrogen, possessing a higher auto-ignition temperature and zero emissions has recently surfaced as a feasible alternative to biodiesel and other renewable fuels. Integrating hydrogen with an alternative liquid fuel and operating the engine in dual-fuel mode reduces the self-ignition temperature of the compression ignition engine. This study aims to investigate the impact of including a natural antioxidant on the performance of a diesel engine operating on biodiesel with an elevated hydrogen concentration. During the testing method, hydrogen is injected into the system by the intake manifold, while a B15 mixture of Karanja biodiesel is delivered into the combustion chamber. The experimental fuel samples comprised Diesel, B15, and B15 augmented with hydrogen at flow rates of 6, 9, 12, 15, and 18 lpm. The combination of B15 with hydrogen results in an enhancement of brake thermal efficiency (BTE). Blends of B15 with 15 liters of gasoline and B15 with 18 liters of gasoline demonstrated superior performance compared to the traditional engine at full load CO, achieving BTE improvements of 28.60% and 27.62%, respectively. HC emissions from B15 at 15 lpm and B15 at 18 lpm are reduced in comparison to other mixtures, however NOx emissions from diesel are elevated by 25 and 27 %, respectively. The combination of B15 + 15 lpm with 1000 ppm of Azadirachta indica (AI), a natural antioxidant, diminished NOx emissions to 1074 ppm, reflecting a reduction of 21.9% relative to B15 + 15 lpm without AI. The outcome was a 2.17% enhancement in BTE relative to B15 + 15 lpm without AI. Consequently, numerous test mixes are inferior than B15 + 15lpm with additive.



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### 1. INTRODUCTION

Growing environmental concerns and the depletion of fossil fuels have accelerated the search for cleaner and more sustainable alternatives for compression ignition engines. Dual-fuel operation, combining biodiesel with hydrogen, offers the potential to enhance combustion efficiency while reducing harmful emissions. The addition of natural antioxidant additives further improves fuel stability and performance characteristics. Optimization of such blends enables a balanced approach to achieving higher efficiency with lower environmental impact. L-ascorbic acid (LA) antioxidant effects were explored in a lanthanum oxide-coated low heat rejection engine using AME, WCOME, and JME biodiesel blends.

AME20 recorded the highest BTE (30.3%) with lower HC, CO, and smoke emissions than diesel, though NO<sub>x</sub> slightly increased (2.1%). Adding LA200 mg further reduced HC by 15.8%, CO by 10.4%, and smoke by 9.3%, indicating antioxidant-assisted blends can reduce oxidation-induced NO<sub>x</sub> without major efficiency losses [1]. Natural antioxidants (NA) explored from *Albizia lebbek* leaves in an LHR engine (zirconia-coated piston and head) using SBME20 (80% diesel + 20% sesame biodiesel). NA addition reduced BSFC to 0.38 kg/kW-hr (from 0.42 in CE), CO to 0.2 g/kWh, and NO<sub>x</sub> to 0.5 g/kWh at higher loads. Smoke opacity fell by 10%, showing NA's role in stabilizing biodiesel and improving combustion in high-temperature LHR conditions [2]. This study examined the addition of diphenylamine (DPA) and ceria nanoparticles (CeO<sub>2</sub>) to a B30 *Jatropha* biodiesel blend. The optimal B30+DPA50+CeO<sub>2</sub>50 blend achieved a 6.35% reduction in brake-specific fuel consumption (BSFC) and an 8.68% decrease in NO<sub>x</sub> emissions, with a 5.74% increase in brake thermal efficiency (BTE). Machine learning modelling showed that the K-nearest neighbors algorithm provided the most accurate predictions compared to multilayer perceptron and random forest regression [3]. ANN and Taguchi-based optimization confirmed improved stress transfer and eco-friendly applicability for packaging and building materials [4]. This study evaluated N-isopropyl-N'-phenyl-1,4-phenylenediamine (IPPD) as an antioxidant in *Jatropha* methyl ester (JME) for thermal barrier coated (TBC) diesel engines. The piston crown was coated with YSZ-CeO<sub>2</sub> (0.3 mm) to improve thermal efficiency. The optimal 1000 ppm IPPD-doped JME reduced NO emissions by 8.9% while increasing BTE by 18.8% and reducing BSFC by 11.7%. HC, CO, and smoke emissions were also reduced by over 22% at maximum load compared to the JME-fueled conventional engine [5]. Palm biodiesel blends with 10% dimethyl carbonate (DMC) were prepared and tested in a CI engine across speeds from 1100 to 2100 rpm.

DMC addition improved brake power (up to +1.70%) and BTE (up to +4.90%), while reducing BSFC (up to -2.93%) and EGT (up to -4.54%). Emissions decreased significantly, with CO reduced by up to 26.47% and HC by up to 33.33% compared to biodiesel blends without antioxidant [6]. Lemongrass oil (5–20 mL/L) was used as an antioxidant in B20 *Calophyllum inophyllum* methyl ester (CIME) blends to improve oxidation and thermal stability. The best blend (B20LG20) extended the induction period to 9.6 h, reduced peroxide value by 51%, and limited acid number growth by 42%. Engine tests showed BTE of 31.2%, with CO and smoke emissions reduced by 15% and 25%, and NO reduced by 6% compared to B20 [7]. Hybrid composites of *Holoptelea integrifolia* bark fiber and *Ziziphus jujuba* seed particles were developed using a tannic acid-based bio-epoxy resin (BBER). Mechanical testing data were modeled using fuzzy logic, achieving an 87% prediction accuracy for tensile, flexural, and impact strengths. The composites demonstrated strong mechanical performance potential with renewable resin systems for sustainable structural applications [8]. Four antioxidants—BHT, BHA (phenols), and DPPD, PPD (aromatic amines)—were tested in neat sunflower biodiesel and B20 blends. PPD showed the greatest NO<sub>x</sub> reduction (52%) compared to other antioxidants. Adding 1000 ppm antioxidants to B20 reduced NO<sub>x</sub> more effectively than in neat biodiesel. CO and HC emissions dropped slightly, while smoke number increased with antioxidant concentration and load [9]. Biodiesel was extracted from *Scenedesmus obliquus* (S1) and *Scenedesmus dimorphus* (S2) using Ni/H<sub>2</sub> transesterification with a Ni(II)-Schiff base promoter. Blends (S1B10–S1B50, S2B10–S2B50) showed slightly higher SFC and lower brake power but reduced greenhouse gas emissions, except for NO<sub>x</sub>. The fuels also exhibited antimicrobial, antioxidant activity, and improved thermal and corrosion resistance [10]. Waste cooking oil biodiesel (B20) was enriched with hydrogen (10 L/min) and synthetic antioxidant TBHQ (1000–2500 ppm).

The B20 + 2000 ppm + H<sub>2</sub> blend achieved the highest oxidation stability, 7.39% higher BTE, and 11% lower BSFC than diesel, while reducing NO<sub>x</sub> by 3.63%. Hydrogen-antioxidant synergy improved performance but lowered ICP and HRR [11]. Diphenylamine (DPA, 100 ppm) was added to B30 *Jatropha* biodiesel, with performance modeled using RSM and ANFIS. B30 + DPA100 reduced NO<sub>x</sub> by up to 15.53% compared to B30, with minor changes in BTE and BSFC. BMEP increased by 1.3% over B30, indicating feasibility for use without engine modification [12]. AA2024 metal matrix composites reinforced with nano-ZrO<sub>2</sub> were produced by squeeze casting, with process parameters (melt/die temperatures, pressure) optimized for mechanical and wear performance. The study applied TOPSIS-EWM to identify ideal electrical discharge machining (EDM) settings, ensuring minimal nanoparticle damage and consistent dimensional accuracy. Findings support precise process control for high-quality MMC fabrication [13]. Orange peel methyl ester (OPME) biodiesel was doped with butylated hydroxytoluene (250–1000 ppm) and tested in both conventional and YSZ-coated low-heat rejection engines. At 750 ppm BH, BTE increased by 3.04%, BSFC dropped by 15.3%, and CO and HC fell by 36.6% and 39.1%. Antioxidant addition improved efficiency and lowered emissions [14]. *Pongamia* methyl ester (PME20) biodiesel was combined with natural antioxidant from *Mangifera indica* leaves (1000 ppm) and hydrogen enrichment (16 L/min). PME20 + 16lpm + NA1000 achieved 29.17% BTE and 13.5% lower NO<sub>x</sub> than PME20 + 16lpm. Hydrogen improved efficiency but increased NO<sub>x</sub>, which was mitigated by the antioxidant [15]. This review highlights the role of additives, especially antioxidants in improving biodiesel stability, combustion, and emission characteristics. Antioxidants enhance storage life, reduce corrosion, and maintain engine cleanliness.

Metal-based additives also aid emission control, making biodiesel more viable for CI engine applications [16]. A low heat rejection (LHR) diesel engine with a TBC piston coated in YSZ and CeO<sub>2</sub> (0.3 mm) was fueled with *Jatropha* Methyl Ester (JME20) doped with 500–2000 ppm N,N'-diphenyl-p-phenylenediamine (DPPD). The coated engine (CE) running on JME20B4 reduced NO by 6.5%, HC by 17.4%, and CO by 34.6% at full load. Smoke opacity also dropped by 15.3%, though peak HRR and cylinder pressure decreased by 5–6% [17]. Clove (CEO), thyme essential oils (TEO), and synthetic BHT (3000 ppm) were added to B20 colza biodiesel–diesel blends. While antioxidants slightly raised SFC (0.9–2.4%) and reduced thermal efficiency (1.1–2.2%), BHT cut NO emissions by 21% but increased CO by 3.68%. CEO improved overall performance and emissions more than TEO, while all antioxidants reduced smoke and CO<sub>2</sub> [18]. *Karanja* oil biodiesel B20 was blended with carbon nanotubes (CNTs) using QPAN80 surfactant (1:4 NP:surfactant ratio). The B20CNT50 blend boosted BTE by 9.8% and reduced BSFC by 18.7%. Emissions reduced significantly—CO by 7.7%, CO<sub>2</sub> by 11.2%, HC by 10.2%, smoke by 5.7%, and NO<sub>x</sub> by 10.9%—while machine learning models (SVR, RF) accurately predicted performance and emissions [19]. *Karanja* oil biodiesel was produced using cobalt-doped zinc oxide (CZO) nanoparticles (~75 nm) by a dual-step esterification–transesterification process. At optimal conditions (1:25 oil:methanol, 0.3 wt% catalyst, 70°C, 180 min), biodiesel yield reached 98.5%. CZO provided high purity, easy glycerol separation, and reusability, making it a commercially viable catalyst for biodiesel production [20]. A single-zone, zero-dimensional progressive combustion model was developed in Python to predict CI engine performance, combustion, and emissions. Validated against experimental data for diesel, *Pongamia* biodiesel, and blends, the model accurately estimated in-cylinder pressure and HRR.

Results showed blending up to 30% biodiesel had minimal performance impact, though exhaust oxygen concentration increased with blend ratio [21]. Pongamia biodiesel blends (20BD, 50BD, 100BD) were tested in a CI engine with and without thermal barrier coatings (TBC) of NiCrAl (1 mm) and TiO<sub>2</sub> (4 mm). With 20BD in the coated engine, fuel consumption dropped by 10.6% and BTE increased by 4.7% compared to the uncoated engine. Enhanced heat retention improved fuel vaporization, shortened ignition delay, and increased mechanical efficiency [22]. B20 biodiesel blends from Pongamia, Juliflora, and Calophyllum were evaluated in a low heat rejection engine with zirconia-coated components. Adding 2.5% neem leaf extract improved BTE and reduced NO<sub>x</sub> compared to blends without additives. Biodiesel blends lowered CO, HC, and PM emissions, while increasing cylinder pressure and HRR. Neem extract further minimized ignition delay and enhanced combustion stability [23]. This study presents the findings of a CI engine utilizing Karanja B15 biodiesel-hydrogen in dual fuel mode, enhanced with a natural antioxidant additive, focusing on performance and emission characteristics. The incorporation of the additive into the biodiesel-enhanced hydrogen blend resulted in an elevation of BTE and a reduction in NO<sub>x</sub> emissions. In addition to diesel engines, this study evaluates the performance and emission parameters of CI engines that use other fuels. This study does not require engine modifications; instead, it necessitates a specialized fuel system for hydrogen fuel, enabling the gas to reach the intake manifold in conjunction with air.

II. MATERIALS AND METHODS

II.1 PREPARATION OF PRIMARY FUEL

The present study utilizes a mechanical crusher to extract Karanja oil, which functions as a feedstock. Prior to the addition of the methoxide solution, 500 cc of Karanja oil is heated to 105 °C. The catalyst in a 150 ml methoxide solution comprises 1.5 wt% potassium hydroxide (KOH). The solution mixture is constantly stirred at 700 rpm using a mechanical stirrer, and the reaction temperature is kept at 60 °C. Subsequent to transferring the liquid to the conical beaker, allow it to settle for a duration of 15 to 24 hours. Subsequently, biodiesel will be observed floating atop, while glycerol will settle at the bottom. The resulting solution is rinsed to remove any excess water, alcohol, or catalyst. Table 3 presents the fuel characteristics of the B100 and B15 Karanja biodiesel blends. The B15 mix resembles diesel fuel more closely and has superior performance compared to the B100 blend.

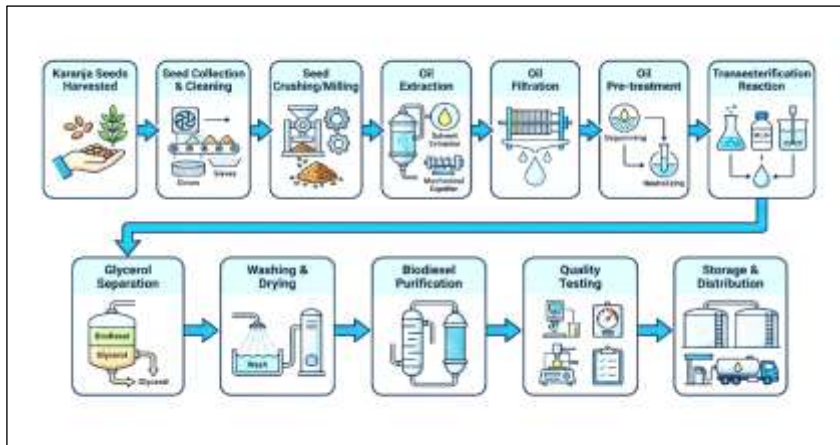


Figure 1: Procedure for making biodiesel.

Source: Authors, (2026).

Table 1: Properties of Test fuel.

Property	Diesel	Karanja Methyl ester	
		B15	B100
Viscosity	2.85	3.27	4.58
Density	832	842	890
Heating Value (kJ/kg)	43,500	42,050	37,050
Cetane index	47	49	53
Flash Point ( ° C )	57	63	92
Fire point ( ° C )	66	73	100

Source: Authors, (2026).

II.2 PILOT FUEL PREPARATION

Table 2: Properties of hydrogen and diesel.

Parameter	Hydrogen	Diesel
Formula	H <sub>2</sub>	C <sub>n</sub> H <sub>1.8*n-c8-c20</sub>
Heating value (MJ/kg)	141.9	44.8
Self-ignition temperature (K)	773–858	483–573
Viscosity at 300 K ( mm <sup>2</sup> /s )	95–120	0.4–1.0
Cetane number	-	45–52
Specific Gravity	0.069–0.073	0.82–0.86
Flame Velocity (cm/s)	250–330	25–40

Source: Authors, (2026).

Table 2 enumerates the attributes of diesel and hydrogen. The data in the table indicates that hydrogen possesses a higher self-ignition temperature compared to diesel. This indicates that for optimal combustion, hydrogen fuel ought to be combined with diesel, biodiesel, or ethanol, all of which possess lower ignition temperatures. Using 99.9 % pure hydrogen, experiments are carried out using a modified CI engine that has a flame arrester and other devices. The section on experiments delineates the specific steps.

### II.3 ANTIOXIDANT ADDITIVE PREPARATION

The foliage of *Azadirachta indica* (neem), a tree typically reaching 20–30 m in height (occasionally up to 40 m) was selected for antioxidant extraction owing to its high carotenoid and chlorophyll content, proven radical-scavenging properties, low cost, and wide availability. Neem leaves are pinnate (20–40 cm long) with serrated leaflets, exhibiting lighter green on the lower leaflets and deeper green on the upper ones; the tree produces oval drupes that ripen to a yellowish-green color. Freshly harvested leaves were shade-dried for 10 days to minimize photooxidative degradation, followed by oven-drying at 50–70 °C for 10–15 min to remove residual moisture. To inactivate oxidative enzymes such as polyphenol oxidase, the dried leaves were immersed in water at 50 °C for 10 min. The material was then cut into 1–2 mm fragments to increase surface area and pulverized into a fine powder using a mechanical crusher. For solvent extraction, 100 g of powder was combined with 20 mL of an acetone–ethanol mixture (v/v) and agitated at ambient temperature for 1 h, producing a pale green opalescent suspension. The mixture was allowed to rest for 1 h to facilitate sedimentation, and the supernatant was collected and concentrated under reduced pressure using a rotary evaporator at 40 °C. The concentrate was dried at the same temperature for 72 h to obtain the crude antioxidant extract. This extract was incorporated into a B15 Karanja biodiesel blend at a concentration of 1000 ppm for subsequent oxidative stability and performance evaluations.

### II.4 EXPERIMENTATION

This research utilizes a water-cooled, single-cylinder direct injection engine together with all necessary loading and measuring apparatus. Operating conditions can be regulated by sustaining specific ranges for exhaust gas temperature, cylinder pressure, air flow, and fuel flow,. A piezoelectric transducer is utilized to monitor the engine cylinder pressure. The engine possesses a rated power of 3.7 kW, a compression ratio of 16.5:1, and operates at a speed of 1500 rpm. All potential loads, ranging from 0% to 100%, including 25%, 50%, 75%, and full load, are evaluated during the trials. An eddy current dynamometer is employed to modify the load during experiments. A gas analyzer, an AVL smoke meter, and thermocouples are employed to measure emissions including hydrocarbons, smoke, and nitrogen oxides, in addition to the exhaust temperature and fuel flow rate. A flow meter and flame arrester are used to feed more hydrogen into the CI engine's air and hydrogen intake systems. Flame arrestors are a group of devices used in hydrogen systems that are intended to stop explosions. Flame traps have proven effective in lowering backfire and other unfavorable combustion events in a hydrogen engine system.

A non-return valve (NRV) in the fuel line prevents gases from returning to the cylinder. Hydrogen is supplied by a 140-bar high-pressure cylinder with an outlet pressure of 2 bar. Upon traversing the flame arrester and trapper, the hydrogen proceeds to the non-return control valve. The digital flow meter quantifies the flow rate. As additional hydrogen gas reaches the non-return valve, it inhibits reverse flow, directing the gas to the engine. The flame arrester is then filled with hydrogen. A flame arrester can prevent an explosion in the fuel encasing system. The fundamental concept of the flame arrester is that the gas must provide sufficient heat to sustain the flame. The enrichment of hydrogen transpires when air and hydrogen are amalgamated post-collection at the flame trap unit and subsequently discharged into the input manifold. A variety of hydrogen flow rates—8 lpm, 10 lpm, 12 lpm, 15 lpm, and 18 lpm—were supplied into the input manifold. The findings make it possible to compare the performance and emission characteristics of the CSI engine using a hydrogen and B15 combination with and without the antioxidant AI. Figure 2 illustrates the configuration of the CI engine employed in the trials.

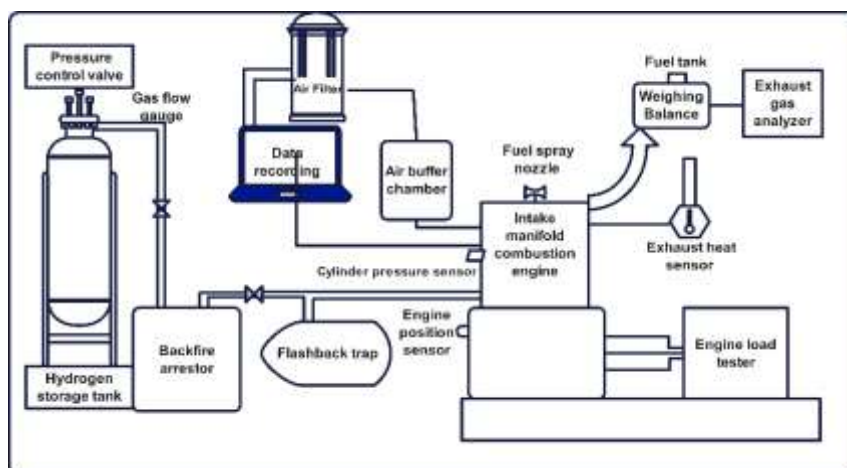


Figure 2: Configuration of CI engine test setup.

Source: Authors, (2026).

The Kirloskar AV-1 is a water-cooled, four-stroke, single-cylinder diesel engine operating continuously at 1500 rpm in the experimental configuration. The engine parameters comprise a 560-cc displacement, 80 mm bore, 110 mm stroke, and a compression ratio of 16.5:1. The injection pressure is maintained at 20 Pa, with the injection duration for both diesel and biodiesel set at 23° CA before top dead center (bTDC). The engine, connected to an eddy current dynamometer for load assessment, can deliver a maximum power output of 3.7 kW.

## II.5 UNCERTAINTY ANALYSIS.

The standard deviations and uncertainties of the experimental measurements were subjected to statistical analysis. The fuel volume flow rate, defined as the duration required to consume 10 cc of gasoline, exhibited an absolute error of  $\pm 0.1$  s and a relative uncertainty of  $\pm 0.5\%$ , with a standard deviation of 0.18 s. The overall fuel consumption exhibited a relative uncertainty of  $\pm 0.5\%$  and an absolute error of  $\pm 0.005$  kg/h, with a standard deviation of 0.01 kg/h. The peak pressure exhibited a relative error of  $\pm 1\%$ , an absolute uncertainty of  $\pm 1$  bar, and a standard deviation of 1.58 bar. The exhaust gas temperature fluctuated by  $7.97$  °C, with absolute uncertainties of  $\pm 3.6$  °C and relative uncertainties of  $\pm 1.1\%$ . The standard deviation for nitrogen oxides (NOx) was 8.72 ppm, accompanied by a relative uncertainty of  $\pm 0.5\%$  and an absolute inaccuracy of  $\pm 4$  ppm. The hydrocarbon emissions exhibited a relative uncertainty of  $\pm 1.5\%$ , an absolute error of  $\pm 2.5$  ppm, and a standard deviation of 5.4 ppm. The carbon monoxide values exhibit a relative inaccuracy of  $\pm 5\%$ , an absolute uncertainty of  $\pm 0.008\%$ , and a standard deviation of 0.02%.

## II.6 ERROR ANALYSIS

It is infeasible to entirely eradicate the potential for errors or unforeseen circumstances during testing procedures. The selection of equipment, environmental conditions, calibration, observation, evaluation, analytical methods, testing protocols, and preparation can all mitigate these errors and uncertainties. It is essential to verify the dependability, probability and accuracy, of the experimental results. Consequently, an unforeseen analysis is conducted using the methodology outlined by Holman. The overall percentage of the experiment's uncertainty is calculated by taking the square root of the sum of the squares of the uncertainties for, HC, EGT BTE, CO, BSFC, NOx, BP and Pressure. Total experiment uncertainty =  $\sqrt{((\text{pressure transducer uncertainty})^2 + (\text{angle encoder uncertainty})^2 + (\text{NOx uncertainty})^2 + (\text{HC uncertainty})^2 + (\text{CO uncertainty})^2 + (\text{EGT uncertainty})^2 + (\text{stop watch uncertainty})^2 + (\text{manometer uncertainty})^2)}$ .

$$\text{Total percentage of uncertainties} = \sqrt{\{(0.1)^2 + (0.2)^2 + (0.1)^2 + (1)^2 + (0.2)^2 + (1.0)^2 + (0.15)^2 + (1.0)^2\}} = \pm 2.3\%$$

## III. RESULT AND DISCUSSION

### III.1 COMPARISON OF VARIOUS HYDROGEN FLOW RATES WITH BIODIESEL

This text discusses the performance and emission characteristics of B15 Karanja biodiesel, which was initially utilized as fuel in CI engines with hydrogen flow rates of 6, 9, 12, 15, and 18 lpm. Graphs of emissions for HC, CO, and NOx are plotted versus load, while efficiency and BSFC are utilized to create performance graphs.

### III.2 EFFECT ON BRAKE THERMAL EFFICIENCY (BTE)

Figure 3 illustrates the correlation between BP and BTE for B15 as a function of hydrogen flow rate. The optimal brake thermal efficiency, in comparison to diesel fuel, is attained with hydrogen flow rates of 15 lpm and 18 lpm combined with B15. Consequently, it may be inferred that hydrogen actively participates in combustion and is responsible for enhancing thermal efficiency. The enhancement of brake thermal efficiency results from hydrogen's numerous advantageous properties, such as its elevated calorific value, swift combustion characteristics, and its ease of amalgamation with air. Blends of B15 with 15 lpm and 18 lpm exhibited improved brake thermal efficiency compared to diesel, at 28.60% and 27.62%, respectively.

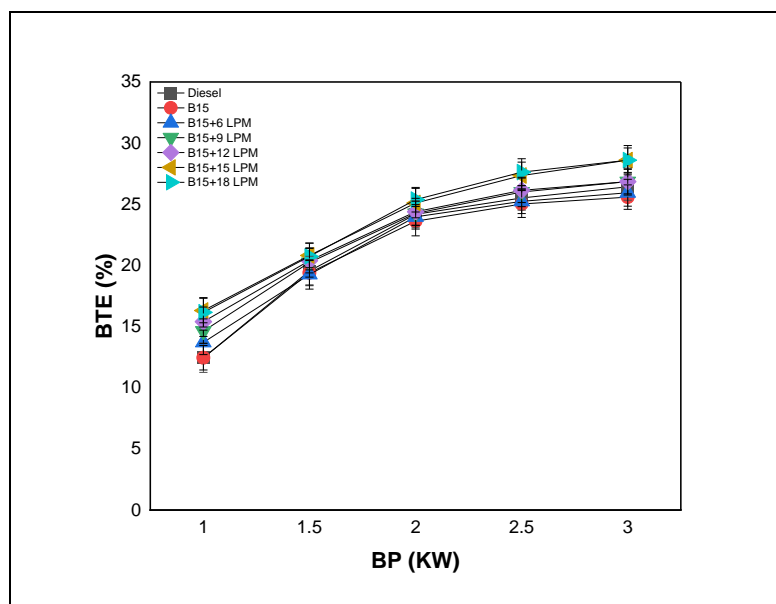


Figure 3: The B15 blend's BP and BTE at varying hydrogen mass flow rates.

Source: Authors, (2026).

In another study, A preheater was fabricated to raise intake air temperatures ( $30$ – $60$ °C) for B20 Pongamia biodiesel. Higher intake air temperature improved BTE by 1% and reduced BSFC by 9%, while lowering HC by 36% and smoke by 16%. However, NOx emissions increased by 10.1%. [24].

### III.3 EFFECT ON BSFC

Figure 4 depicts the correlation between BP and BSFC for the B15 blend at varying H<sub>2</sub> flow rates. For B15 + 15 lpm and B15 + 18 lpm blends, it is seen that brake specific fuel consumption decreases with an increase in hydrogen flow rate. The minimum BSFC for B15 at 15 lpm is 0.23 kg/kW-hr, and for B15 at 18 lpm, it is also 0.20 kg/kW-hr. B15 BSFC demonstrates superior performance under maximum load circumstances compared to traditional fuel, with varying hydrogen flow rates. When hydrogen and air are properly combined, the flame velocity can be enhanced, resulting in more efficient combustion. The B15 blend surpasses other blends with a BSFC of 15 lpm and 18 lpm. The optimal mixture for all loads is B15, containing a hydrogen concentration of 15 liters per minute.

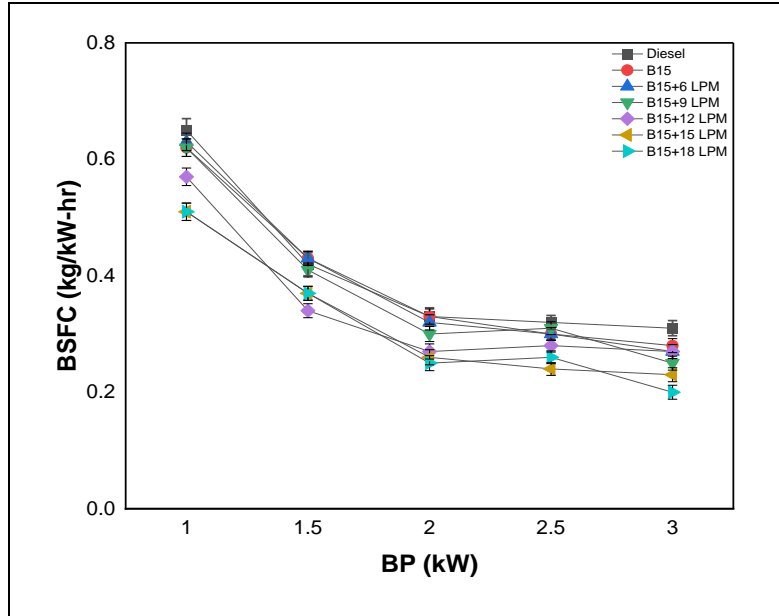


Figure 4: Comparison of BP and BSFC for the B15 blend at various hydrogen mass flow rates.

Source: Authors, (2026).

### III.4 EFFECT ON HC

Figure 5 illustrates the hydrocarbon (HC) levels in relation to boiling point (BP) for B15 at various H<sub>2</sub> flow rates. HC emissions were reduced in the B15 + 15 lpm and B15 + 18 lpm blends relative to standard diesel. The cylinder holds a blend of hydrogen and Karanja biodiesel oil, ensuring adequate mixing in the engine, elevating temperature, and facilitating the post-flame oxidation process. The hydrocarbon emission levels for diesel are 115 ppm, 75 ppm, and 80 ppm for B15 + 15 lpm and B15 + 18 lpm, respectively. B15 combined with 15 lpm decreases HC by 32.17%, whereas B15 combined with 18 lpm reduces it by 26.96%, respectively. In another study, Pongamia Pinnata methyl ester B20 was enhanced with 40–100 mg/L graphene oxide (GO) nanoparticles and 3% diethyl ether. At 100 mg/L GO + 5% ether, BTE rise by 19.7% and BSFC fell by 10.71% at maximum load. CO, HC, and smoke dropped by up to 70%, while combustion improved with higher peak pressure and shorter ignition delay [25].

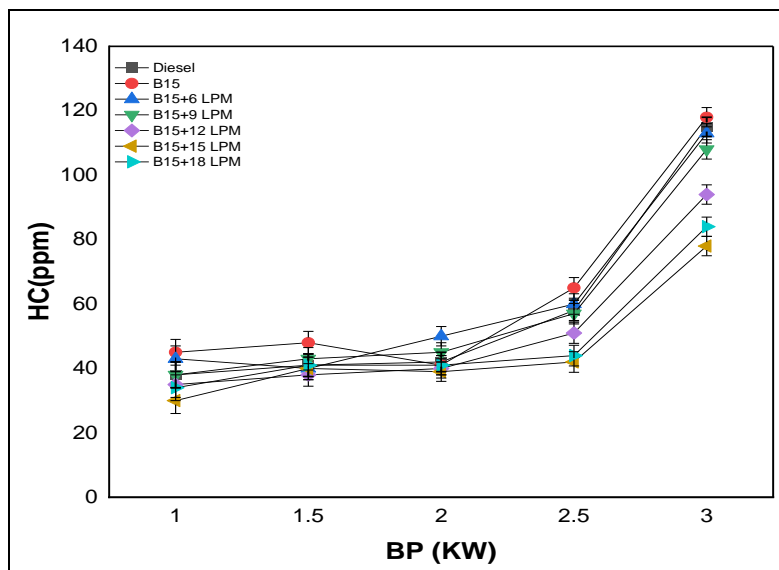


Figure 5: Variation of HC emissions with BP for the B15 blend at various hydrogen mass flow rates.

Source: Authors, (2026).

### III.5 EFFECT ON CO

Variations in the H2 flow rate result in alterations to the CO/BP deviation for the B15 blend (refer to Figure. 6). Karanja biodiesel B15 lowers CO emissions with an increase in hydrogen flow rate. Reduced CO emissions were seen with the B15 + 15lpm and B15 + 18lpm blends in comparison to the others. This decreases CO emissions as the B15 + H2 mixture contains no carbon molecules. As a result, a substantial decrease in CO emissions is attained at all H2 flow rates. Diesel, B15 + 15 lpm, and B15 + 18 lpm exhibited CO emissions of 0.18%, 0.06%, and 0.17%, respectively. B15 combined with 15 lpm decreases CO emissions by 30% relative to diesel, while B15 with 18 lpm results in a 39% reduction. Prolonging combustion beyond the combustion stroke and subsequent extended injection results in a significant rise in CO levels at maximum load. As a result, when the exhaust valve was opened, the carbon monoxide emissions from the intermittent combustion products would solidify.

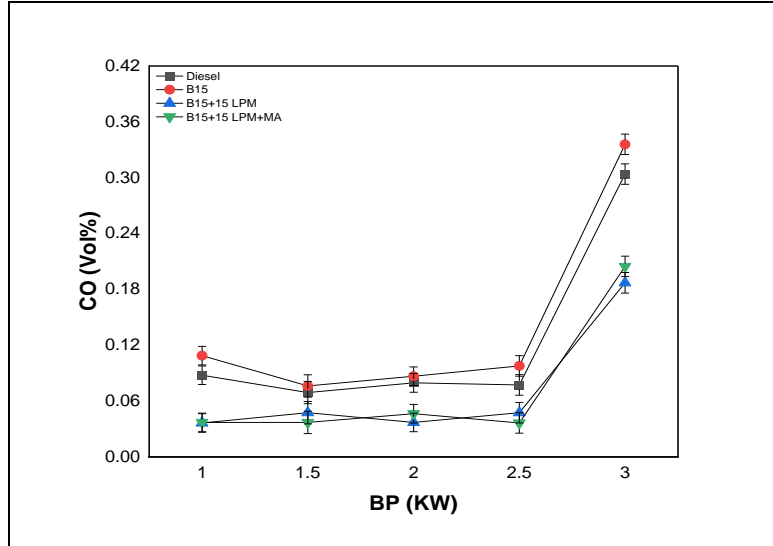


Figure 6: Variation of BSFC with BP the B15 blend at different hydrogen mass flow rates. Source: Authors, (2026).

### III.6 EFFECT ON NOX

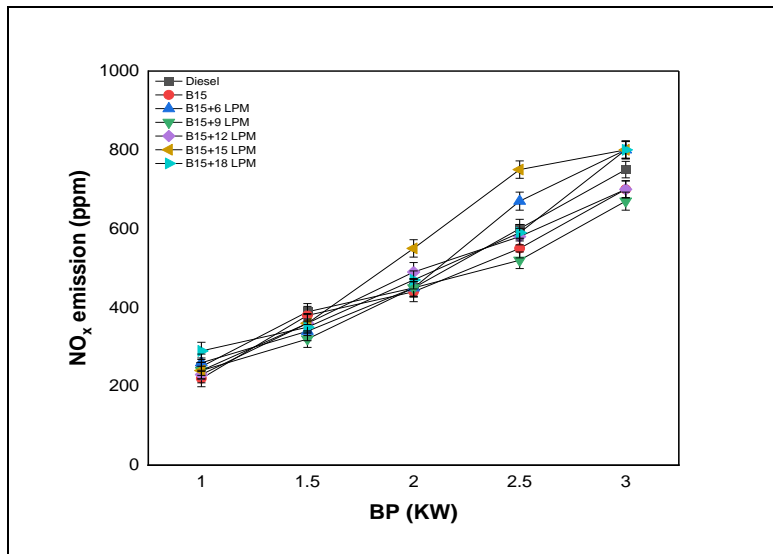


Figure 7: Emission of B15 blend with varying H2 flow rates as a function of BP and NOX. Source: Authors, (2026).

Figure 7 illustrates the NOx levels in relation to BP for various H2 flow rates in the B15 mix. The complete response of an alternate fuel in the engine is governed by NOx, the most pivotal factor among these elements. As hydrogen flow rates increase, NOx levels also escalate. The production of nitrogen oxides (NOx) is primarily influenced by the temperature of the combustion chamber and the internal oxygen composition. Moreover, the presence of additional oxygen in the B15 blend exacerbates the production of NOx emissions. The combustion residence time is reduced due to the diesel engine's exceptionally narrow flame response zone. Diesel with B15 at 15 lpm exhibits NOx levels of 967.26 ppm, whereas B15 at 18 lpm shows values of 1307.72 ppm and 1340.58 ppm, respectively. The blends B15 + 15 lpm and B15 + 18 lpm exhibit increases of 25.2% and 27.6%, respectively, in comparison to diesel fuel. In earlier study, the use of TiO<sub>2</sub> nanoparticles (25–100 mg/L) in a B30 blend of Pongamia Pinnata biodiesel was studied. The B30T75 sample delivered the best performance. NOx emissions increased slightly (2.91%), and HRR rise by 5.4% compared to B30, indicating improved combustion efficiency [26].

### III.7 INVESTIGATION ON NATURAL ANTIOXIDANT ADDITIVE

The optimal test fuel was identified as B15 + 15 lpm in the previous investigation. Nonetheless, irrespective of the load, this fuel generates a higher volume of NOx. Consequently, diesel, B15, and B15 + 15 lpm are evaluated using an antioxidant component inherently found in the B15 mixture. After using a natural additive, we can notice changes in performance and emissions. Following the same procedure as before, graphs of performance and emissions are produced.

### III.8 EFFECT ON BTE

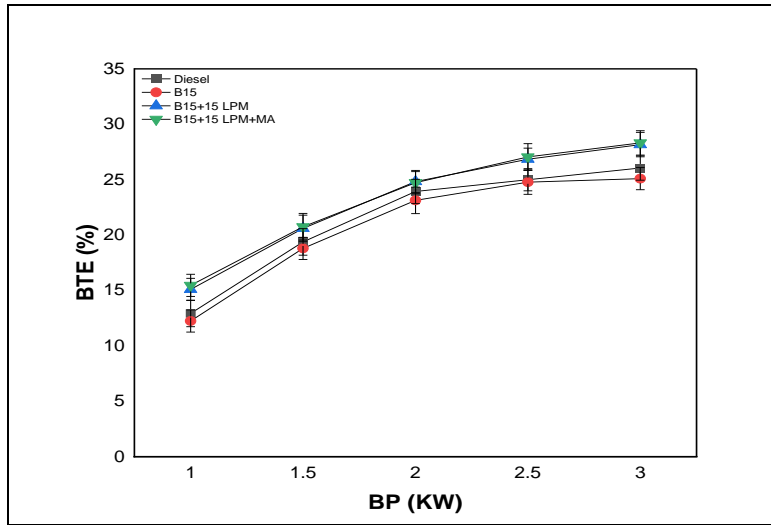


Figure 8: Comparison of B15 + 15 lpm BP against BTE with and without MA.  
Source: Authors, (2026).

Both with and without the inclusion of a natural antioxidant component, Figure 8 shows BP with BTE for B15 and H2. The B15 + 15 lpm combination exhibits a Brake Thermal Efficiency (BTE) of 28.96%, which increases to 29.58% when an antioxidant ingredient (AI) is used. When operating at full load, the BTE efficiency of B15+ hydrogen with AI surpasses that of diesel by 5.2%. In previous study, Jojoba (JME), polanga (PME), and mixed methyl ester (MME) biodiesels tested enhanced with diglyme (cetane improver) and cumene (antioxidant) in a single-cylinder DI diesel engine at 1500 rpm. MME15+DG5 achieved the highest BTE improvement of 15.78%. Cumene also improved efficiency, with MME15+CU5 showing an 8.77% BTE increase and reduced exhaust gas temperature [27].

### III.9 EFFECT ON BSFC

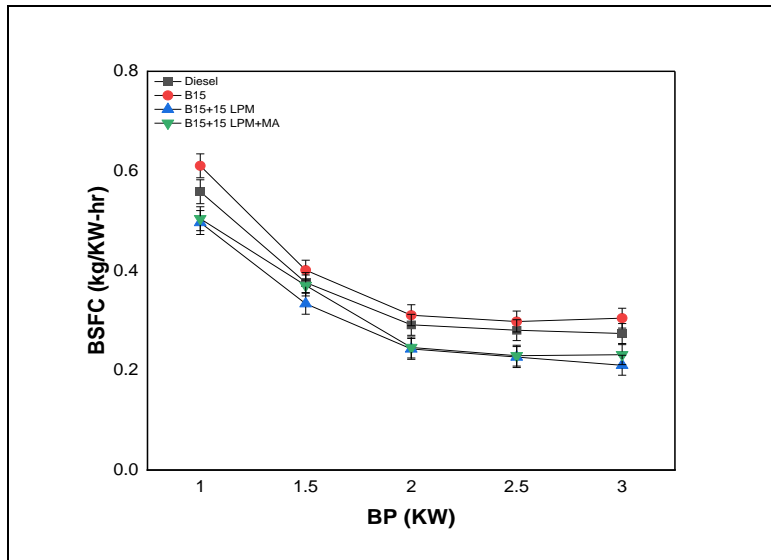


Figure 9 Comparison of BP and BSFC for B15 + 15 lpm with and without MA.  
Source: Authors, (2026).

Both with and without the addition of the natural antioxidant MA, Figure 9 shows BP with BSFC for B15 and H2. Incorporating a natural antioxidant into a B15 blend with hydrogen in dual fuel mode in compression ignition engines enhances the brake specific fuel consumption (BSFC). The brake specific fuel consumption (BSFC) for B15 at 15 liters per minute with AI is 0.23152 kg/kW-hr, but without AI it is 0.21023 kg/kW-hr. The presence of chlorophyll and carotenoids results in a greater BSFC for B15 + 15 lpm compared to the additive blend.

In another study, Diphenylamine (DPA) antioxidant with ceria nanoparticles in a B30 Jatropha blend to address biodiesel’s NOx emissions. Using hybrid RSM–MCDM (entropy, TOPSIS, VIKOR), the optimal B30+DPA50+CeO<sub>2</sub>50 blend improved BTE by 1.01%, lowered BSFC by 5.67%, and reduced NOx by 18.87% [28].

### III.10 EFFECT ON CO

Figure 10 illustrates the impact of CO on BP and B15 with H<sub>2</sub>, both with and without the inclusion of MA, a natural antioxidant. The addition of an antioxidant slightly increases CO levels. Incorporating 1000 ppm of additive into B15 + 15 lpm increases CO emissions from 0.187 08% to 0.43%. This happens because the natural antioxidant component takes too long to convert carbon monoxide to carbon dioxide and the combustion process is inadequate. The reduction in CO emissions can be attributed to the absence of carbon molecules in H<sub>2</sub>.

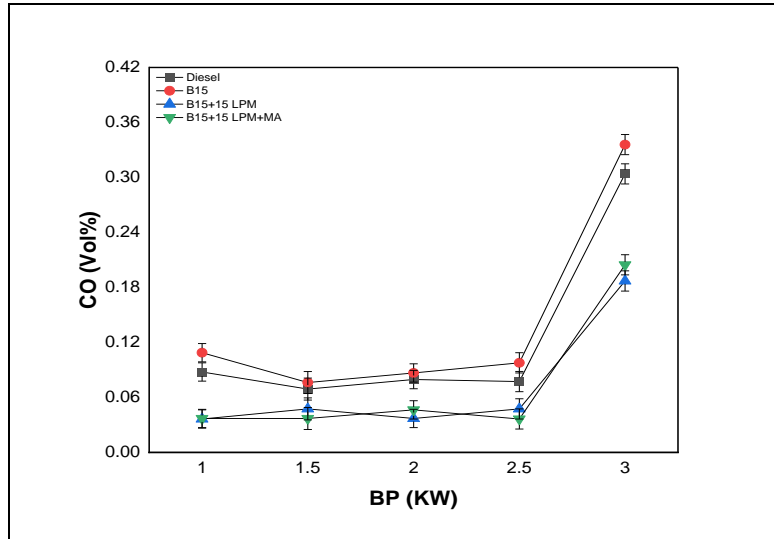


Figure 10: Comparison of B15 + 15 lpm's BP and CO with and without MA. Source: Authors, (2026).

### III.11 EFFECT ON HC

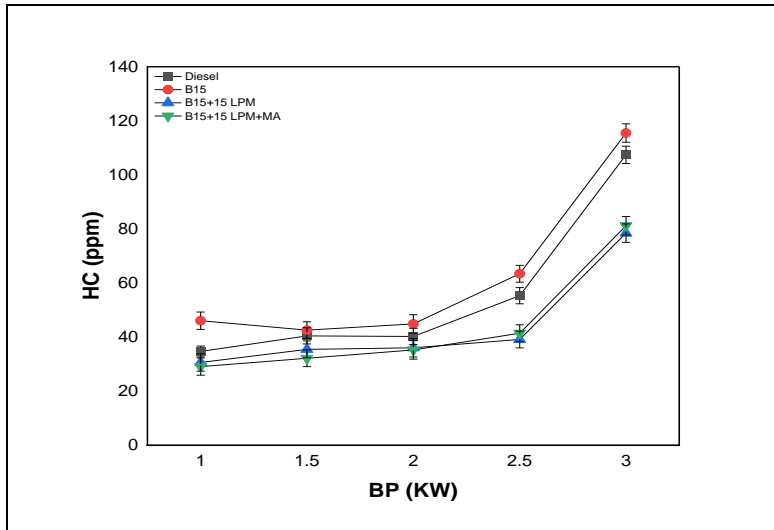


Figure 11: Comparison of B15 + 15 lpm BP and HC with and without MA. Source: Authors, (2026).

Figure 11 illustrates the comparative effects of BP and HC on B15 and H<sub>2</sub>, both with and without the incorporation of MA, a natural antioxidant. A reduction in combustion chamber temperature is attributed to inadequate mixture formation, which leads to elevated HC emissions for B15 with 1000 ppm and 15 lpm of hydrogen. In comparing B15 + 15 lpm with and without the AI additive, the rise in HC for the former is 2.36 %. Furthermore, HC is measured at 79 ppm for the B15 + 15 lpm blend and 82 ppm for the B15 + 15 lpm blend with MA. In previous study, Albizia lebbek leaf-derived natural antioxidant (NA) was incorporated into SBME20 (soybean methyl ester) biodiesel for low heat rejection (LHR) engines at 500–2000 ppm concentrations. The 1000 ppm blend delivered the best results, reducing BSFC to 0.38 kg/kWh and increasing BTE to 32%, alongside decreases in CO (–15%), HC (–10%), NOx (–12%), and smoke opacity (–20%) [29].

### III.12 EFFECT ON NOX

Figure 12 illustrates both the NO<sub>x</sub> B15 and H<sub>2</sub> BP samples, with and without the incorporation of the natural antioxidant agent MA. The NO<sub>x</sub> emissions from a B15 + 15 lpm blend are 24.14 % greater than those from conventional diesel, which is already significantly elevated. To reduce NO<sub>x</sub> emissions, add 1000 ppm of a natural ingredient to the B15 mixture. To reduce NO<sub>x</sub> emissions, the temperature and oxygen concentrations in the combustion chamber are diminished. The nitrogen oxides (NO<sub>x</sub>) for B15 + 15 lpm blends at 1000 ppm, with no load, are 1371.27 ppm and 1074.0 ppm, respectively. B15 combined with 15 lpm of additive decreases NO<sub>x</sub> emissions by 21.7 % relative to B15 with 15 lpm without the addition.

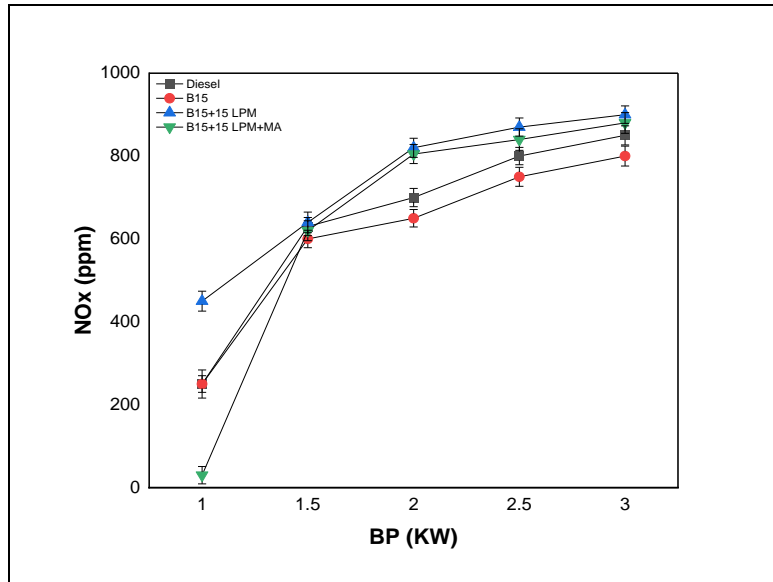


Figure 12: B15 + 15 lpm BP against NO<sub>x</sub> with and without MA.

Source: Authors, (2026).

### IV. CONCLUSION

The subsequent results were obtained from tests performed on hydrogen and B15 in a CI engine, both with and without the use of 1000 ppm of AI additive.

- The B15 with 15 lpm and 18 lpm hydrogen shown an enhancement in brake thermal efficiency (BTE) and a reduction in brake specific fuel consumption (BSFC) compared to diesel. The BTE for B15 + 16 lpm, B15 + 18 lpm blends is 28.96 % and 29.58 %, respectively.
- In comparison to the B15 blend, the Brake Specific Fuel Consumption (BSFC) for the B15 + 15 lpm and B15 + 18 lpm mixtures is reduced to 0.23 kg/kW-hr and 0.20 kg/kW-hr, respectively.
- At maximum capacity, the CO emissions for the B15 + 15 lpm blends are diminished by 26.98%.
- HC emissions are diminished by 32% when B15 is amalgamated with 15 lpm of H<sub>2</sub>.
- As the flow rate of H<sub>2</sub> increases, NO<sub>x</sub> emissions also rise.
- The outcomes for B15 at 15 lpm under maximum load are 1307 ppm, but the outcomes for B15 at 18 lpm are 1340 ppm. All measures enhanced when B15 and 15 lpm H<sub>2</sub> with 1000 ppm MA were utilized.
- When B15 + 15 lpm with additive is compared to B15 + 15 lpm without additive, the BTE is elevated by 2.62 %. Both combinations exceed diesel in terms of brake thermal efficiency (BTE).
- Radioactive symbol B15 + 15 lpm without additive exhibits a BSFC of 0.2315 kg/Kw-hr, which is 8.8% higher than B15 + 15 lpm with additive.
- The B15 + H<sub>2</sub> + MA blend exhibits a little increase in HC and CO emissions.
- The incorporation of antioxidant compounds leads to a substantial reduction in NO<sub>x</sub> emissions. In comparison to B15 + 15 lpm without additive, the mixture B15 + 15 lpm + AI decreases NO<sub>x</sub> emissions by up to 21.7%.

### V. AUTHOR'S CONTRIBUTION

**Conceptualization:** Kumaran P\*, Natarajan S, Sathiyaraj S, Shanmugasundaram K and Subramanian T.

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**Investigation:** Kumaran P\*, Natarajan S, Sathiyaraj S, Shanmugasundaram K and Subramanian T.

**Discussion:** Kumaran P\*, Natarajan S, Sathiyaraj S, Shanmugasundaram K and Subramanian T.

**Writing:** Kumaran P\*, Natarajan S, Sathiyaraj S, Shanmugasundaram K and Subramanian T.

**Writing:** Kumaran P\*, Natarajan S, Sathiyaraj S, Shanmugasundaram K and Subramanian T.

**Resources:** Kumaran P\*, Natarajan S, Sathiyaraj S, Shanmugasundaram K and Subramanian T.

**Supervision:** Kumaran P\*, Natarajan S, Sathiyaraj S, Shanmugasundaram K and Subramanian T.

**Approval of the final text:** Kumaran P\*, Natarajan S, Sathiyaraj S, Shanmugasundaram K and Subramanian T.

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