

## Influence of antioxidants and nanoparticles with *Ceiba pentandra* biodiesel/diesel blends on performance and emission characteristics of diesel engine

M. D. Mohan Gift<sup>1\*</sup>, P. Booma Devi<sup>2</sup>, P. Suresh Kumar<sup>3</sup> & T. Loganathan<sup>4</sup>

<sup>1</sup>Department of Mechanical Engineering, Grace College of Engineering, Thoothukudi 628005, Tamil Nadu, India

<sup>2</sup>Department of Aeronautical Engineering, Rajadhani Institute of Engineering and Technology, Rajadhani Hills 641032, Kerala, India

<sup>3</sup>Department of Mechanical Engineering, R. V. R & J. C. College of Engineering, Guntur 522019, Andhra Pradesh, India

<sup>4</sup>Department of Mathematics, S. A. Engineering College, Chennai 600077, Tamil Nadu, India

\*E-mail: mohangift.mech@gmail.com

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The demand for renewable fuel sources has increased as a result of declining fossil fuel supplies and declining air quality. Plant-based biodiesel appears to be a desirable alternative to fossil diesel; however, the usage of biodiesel is restricted due to its low heating value, poor atomization, lower thermal efficiency, and higher nitrogen oxides (NO<sub>x</sub>) emissions. In particular, reducing NO<sub>x</sub> emissions from engines is crucial for environmental protection and public health. The addition of nanoparticles and antioxidant additives to biodiesel plays a crucial role in overcoming its limitations. Antioxidants help reduce NO<sub>x</sub> emissions by removing decomposing peroxides and free radicals, as well as by disrupting the chain reactions of free radicals. This study looks at the influence of incorporating butylated hydroxytoluene (BH) antioxidant and aluminium oxide (Al<sub>2</sub>O<sub>3</sub>) nanoparticles into a *Ceiba pentandra* biodiesel blend (CPB) on engine performance and emission characteristics. The experimental work has been carried out on a direct injection (DI) diesel engine by blending 250, 500, 750, and 1000 ppm of BH and 25, 50, and 75 ppm of Al<sub>2</sub>O<sub>3</sub> with 20% CPB. A total of eight different test blends were prepared and utilized for engine operation, and the results were compared with baseline diesel fuel. The experimental results expose that adding BH and Al<sub>2</sub>O<sub>3</sub> significantly reduced NO<sub>x</sub> emissions. Compared to diesel, the addition of 1000 ppm BH and 50 ppm Al<sub>2</sub>O<sub>3</sub> reduced the emission of NO<sub>x</sub> by 16.1%, carbon monoxide (CO) by 52.38%, and unburned hydrocarbon (HC) by 25.93%. However, there was a slight increase of 2.27 % in brake thermal efficiency (BTE) and a decrease of 7.14% in brake specific fuel consumption (BSFC).

**Keywords:** Diesel engine, antioxidant and nanoparticles, combined effect, performance analysis, NO<sub>x</sub> emission

### Introduction

Today, gasoline and diesel engines are the foundation of the automotive segment. Although both engines use reciprocating pistons, they differ in terms of emissions and performance<sup>1</sup>. Diesel engines, in particular, have demonstrated superior thermal efficiency and reduced throttling losses compared to their gasoline engines. The usage of fossil diesel for transportation and power production contributes not only to environmental degradation but also to fuel scarcity. In addition to that, fossil fuels are the backbone of our global economy, reliance on them has grown significantly across all industries during the past three decades. However, the rapid usage of fossil-based fuels has directed to irreversible ecological deterioration, environmental change, and the release of harmful gasses<sup>2</sup>. British Petroleum estimates that the supply of coal can only survive for another 115 years at its current rate of development,

while combined oil and gas could run out within the span of 50 years<sup>3</sup>. The release of harmful gases from the conventional engine significantly affects the quality of the environment and public health. Additionally, it is essential to integrate concerns from the fuel energy sector, as well as the electricity and thermal energy sectors, in order to improve the regional energy system<sup>4</sup>. Therefore, in order to solve these problems and support renewable energy solutions, it is vital to develop and deploy cleaner, sustainable fuels. With a number of operational and environmental advantages, biodiesel offers a possible substitute for conventional diesel in IC engines<sup>5</sup>. Biodiesel has higher oxygenated molecules and lower sulfur, which significantly decreases the formation of CO, HC, and particulate matter (PM) when burned in IC engines. However, it tends to increase NO<sub>x</sub> emissions<sup>6</sup>. Therefore advanced research on reducing NO<sub>x</sub> emissions from engines without affecting the

effectiveness of biodiesel blended fuel is essential since NO<sub>x</sub> is a key contributor to acid rain, which has detrimental impacts on the environment.

Adding antioxidants to biodiesel notably improves the performance of the engines by enhancing fuel stability and combustion efficiency. To preserve the value of biodiesel throughout storage and consumption, antioxidants reduce oxidative degradation. According to Rashedul *et al.* incorporating antioxidants such as Baynox Plus into palm biodiesel blends improved oxidation stability and enhanced engine performance, resulting in a 3.10% increased brake power and a 2.40% decrement in BSFC<sup>7</sup>. Additionally, it contributes to lower formation of NO<sub>x</sub>, CO, and HC. Velmurugan and Sathiyagnanam investigated the impact of various antioxidant mixed with mango seed biodiesel for engine operation. The study found that the BTE remained unchanged with the addition of different antioxidant. However, the emission analysis revealed a reduction in NO<sub>x</sub> with the antioxidants, while CO, HC, and smoke were more compared to those from conventional biodiesel<sup>8</sup>. The performance of CI engines was enhanced by adding butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT), to a 20% sunflower oil biodiesel blend. Compared to BHT, BHA significantly decreased NO<sub>x</sub> emissions, suggesting that it could be an excellent additive to enhance biodiesel properties in conventional engines<sup>9</sup>. Saikia *et al.* examined the role of tert-butyl hydroquinone (TBHQ) as an antioxidant in enhancing the storage stability of yellow oleander biodiesel<sup>10</sup>. While BP remained largely unchanged, emissions showed minimal variation. But the higher concentrations of TBHQ led to increased BSFC and decreased BTE. The use of TBHQ for IC engines was also tested by Krupakaran *et al.*, whereas the authors blended TBHQ with *Ricinus communis* biodiesel and tested engine operating parameters along with selective catalytic reduction (SCR)<sup>11</sup>. The study showed an 86% reduction in NO<sub>x</sub> emissions without changing BSFC and BTE. By combining SCR with TBHQ, there was a minor rise in CO, and HC were recorded. Silambarasan *et al.* investigated the effects of adding L-ascorbic acid (LA) to 10% and 20% Annona biodiesel–diesel blends<sup>12</sup>. The study demonstrated that incorporating LA as an antioxidant improved engine performance by reducing NO<sub>x</sub> emissions by 6.03%, CO by 15.38%, and HC by 21.42% under standard

operating conditions. In order to meet international requirements and lower emissions, Nambiraj and Kumar assessed the effects of essential oils derived from agricultural leftover as antioxidants on the stability of biodiesel storage and engine performance<sup>13</sup>. The study showed that natural antioxidants avert the development of free radicals and reserve biodiesel quality. In comparison to aged biodiesel blends, adding natural antioxidants, such as 4% *Citrus aurantifolia* to biodiesel improved engine performance by extending storage stability, boosting BTE by 9.4%, and lowering CO, HC, and NO<sub>x</sub> formation.

The increased NO<sub>x</sub> production with the use of biodiesel can be controlled by using metal oxide nanoparticles<sup>14</sup>. However, the results differ according to different nanoparticles, fuel blend composition, and the engine conditions. The addition of CuO and MnO nanoparticles to diesel significantly lowers the ignition delay, which promotes efficient combustion<sup>15</sup>. Adding CeO<sub>2</sub> nanomaterials in jatropha biodiesel showed a 1.5% increase in BTE, along with significant reductions in HC and NO<sub>x</sub> by 40% and 30%, respectively<sup>16</sup>. Raj *et al.* achieved a reduction in NO<sub>x</sub> emissions by incorporating CuO nanoparticles into a fuel blend consisting of 20% biodiesel derived from waste cooking oil (WCO) and pumpkin oil and 80% conventional diesel<sup>17</sup>. The study reported a 13.02% improved BTE with decreased NO<sub>x</sub> emissions. Kumar *et al.* investigated the outcome of injection pressure (IP) by utilizing WCO biodiesel and CeO<sub>2</sub> nanoparticles, observing a positive impact on energy conversion at higher IP<sup>18</sup>. Enhanced combustion, indicated by increased cylinder pressure and a faster HRR, led to improved BTE and reduced BSFC when higher IP was combined with nanoparticles. According to Sabet Sarvestany *et al.*, a 1% volume addition of magnetite ferrofluid to mustard oil biodiesel increases BTE by 5.12% and decreases BSFC by 4.72%<sup>19</sup>. Incorporating CeO<sub>2</sub> nanoparticles into orange peel oil biodiesel notably enhanced engine performance, leading to a 12% improvement in BTE. When compared to regular diesel, this blend achieved reductions in NO<sub>x</sub>, CO, and smoke by 27%, 6.5%, and 7%, respectively<sup>20</sup>. Like other metal nano-oxide nanoparticles, the utilization of graphene oxide (GO) nanoparticles with simarouba biodiesel was tested by Paramashivaiah *et al.*<sup>21</sup>. Compared to diesel operation, the study reported that the inclusion of GO enhanced

engine performance by increasing BTE by 9.14% and decreasing emissions of NO<sub>x</sub>, CO, and unburned HC by 15.38%, 42.85%, and 12.71%, respectively<sup>21</sup>. Çilgin *et al.* explored the usage of nano magnesium oxides combined with acetone, which led to drops in CO, HC, and NO<sub>x</sub> emissions by 1.10%, 1.48%, and 10.62%, respectively, demonstrating a beneficial impact on emission characteristics<sup>22</sup>.

Like before, numerous studies have examined the impact of carbon-based additives and antioxidants independently in addressing the biggest obstacle for utilizing biodiesel in conventional engine. However, only a limited number of studies are available that clearly address both aspects. Krishnakumar *et al.* deliberated the impact of graphene nanoparticles combined with various antioxidants including BHT, BHA, and TBHQ on the engine performance when blended with WCO biodiesel<sup>23</sup>. The outcome of the study specified that, in comparison to 20% biodiesel blend alone, the addition of 30 ppm graphene along with three types of antioxidants led to increases in BP by approximately 0.29%, 0.58%, and 0.58%, and in BTE by 6.22%, 3.11%, and 3.31%, respectively. Furthermore, the modified fuel blend showed significant reductions in HC and NO<sub>x</sub>. Kumar and Choudhary examined the result of adding diphenylamine (DPA) and CeO<sub>2</sub> nanoparticles to a 30% jatropha biodiesel blend. The results of the experimental study on conventional engine showed that treating B30 with 50 ppm of both DPA and CeO<sub>2</sub> significantly reduces NO<sub>x</sub> by 8.68% and BSFC by 6.35%, in comparison to untreated 30% biodiesel blend and additionally, the BTE of the engine increased by about 5.74%. However, the maximum cylinder pressure for the B30+DPA50+CeO<sub>2</sub>50 blend was 2.54% lower than that of the 30% blended fuel<sup>24</sup>. Reddy and Wani explored the combination of fuel containing of 20% palm biodiesel, 1500 ppm N-phenyl-1,4-phenylenediamine, and 60 ppm of TiO<sub>2</sub> nanoparticles<sup>25</sup>. The results demonstrated a higher BTE and a decreased BSFC, HC, and NO<sub>x</sub> emissions. From the above literature study, it came to be known that the engine operating characteristics were benefitted by the combination of antioxidants and nanomaterials when mixed with various biodiesels under various proportions.

The current study emphasizes on evaluating an engine performance and emission characteristics engine using *Ceiba pentandra* biodiesel blends enhanced with a combination of butylated

hydroxytoluene (BH) antioxidants and Al<sub>2</sub>O<sub>3</sub> nanomaterials. According to earlier research, the usage of oxygenated nanoparticles as a fuel-borne catalyst could enhance engine performance parameters and emission characteristics. The objective of this work is to experimentally test the combined effect of Al<sub>2</sub>O<sub>3</sub> nanoparticles and antioxidants in reducing exhaust emissions while maintaining engine performance. This work is novel in terms of the combined use of BH and Al<sub>2</sub>O<sub>3</sub> with *Ceiba pentandra* biodiesel, since no work was identified with these combinations. Nanoparticles are added with the blended fuel to improve thermophysical properties due to their higher surface area to volume ratio, while, antioxidants are added to extend induction duration and delay the initiation of oxidation.

## Experimental Section

### Extraction of bio-oil

The bio-oil used for this work was extracted from *Ceiba pentandra* seeds using the physical pressing method. The seeds were purchased from a local seed vendor in Coimbatore, India. Blending biodiesel produced from *Ceiba pentandra* oil with regular diesel is a cost-effective option, particularly in the southern regions of India, where these trees are widely cultivated due to favorable tropical climatic conditions. In addition to that, seed collection and oil extraction are economically viable due to the availability of labour and low-cost transesterification methods.

### Transesterification process

Crude *Ceiba pentandra* oil is transformed into *Ceiba pentandra* biodiesel (CPB) through a two-step transesterification process. Therefore, an esterification reaction by sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) is employed to control the free fatty acid (FFA) level to below 2 wt.%. For this process, a warmed reactor was initially filled with 500 mL of crude bio-oil, which was at 60°C. A mixture of 165 mL of methanol and 1% H<sub>2</sub>SO<sub>4</sub> catalyst was prepared and added into the reactor at a methanol-to-oil molar ratio of 8:1. After this process, the mixture was continuously agitated using an overhead stirrer set to 1200 rpm. Throughout the process, the mixture was kept at 50°C temperature. Following this procedure, the entire sample was transformed to a separation funnel for 5 h to isolate surplus methanol and water. After 5 h, the

excess methanol and water had settled in the lower layer, while the esterified oil was gathered in upper layer. Subsequently, the esterified oil was washed with cleaned water. To eliminate further methanol and water, it was then subjected to an evaporation process. The esterified oil has been measured and put into a reactor for the transesterifications. For the transesterification process, 1% of NaOH and an 8:1 methanol-to-oil ratio are blended. Throughout the transesterification reaction, the blend was continuously agitated at 1200 rpm using a magnetic stirrer. To eliminate contaminants, the biodiesel was then filtered and gently cleaned at 40°C using distilled water. In a separating funnel, the mixture was kept to settle for three hours. To eliminate any remaining methanol and water, the product was lastly evaporated at 65°C.

#### Selection of antioxidant

Despite having crucial characteristics, the oxidation stability of the biodiesel is weak when related to fossil diesel<sup>26</sup>. Antioxidant chemicals are utilized with biodiesel as a highly effective way to stop fuel oxidation. BH was previously used as an addition by Reddy *et al.*<sup>27</sup> and Ashok *et al.*<sup>28</sup> to evaluate the use of orange peel and CPB in a diesel engine. The reason BH was selected from the other antioxidants was because of its outstanding oxidation stability. BH is employed as an antioxidant in this investigation at different doses with CPB blends.

#### Preparation of blended fuel

In order to prepare the test fuels, the antioxidant, the selected BH antioxidant at the concentration of 250, 500, 750, and 1000 ppm, is mixed with fuel containing 20% CPB. The Al<sub>2</sub>O<sub>3</sub> nanoparticles were blended into antioxidant-doped biodiesel blend at the dosage levels of 25, 50, 75, and 100 ppm. An ultrasonicator is employed to blend the antioxidant

and nanoparticles with the fuels. To ensure thorough and uniform mixing, the fuel sample is sonicated for a minimum of 3 h. Table 1 shows the experimental program, and Table 2 displays the details of the nanoparticles.

#### Test engine set up

An engine test bed installed for testing different biodiesels was used for the evaluation of engine operating performance. In this study, BP, BSFC, and exhaust gas emissions at full and partial load conditions were measured using a single-cylinder, four-stroke diesel engine fitted with automated experimental technologies. Fig. 1 illustrates the arrangement of the test engine bed, and Table 3 displays its technical details. For loading purpose, an eddy current dynamometer was fixed with engine flywheel, and data acquisition system was used to record, and analyzes data from different sensors. Furthermore, the emission of CO, HC and NO<sub>x</sub> was measured using a DiGas analyzer (AVL DiGas 444).

#### Error analysis

Apparatus selection, climatic conditions, investigation, calibration, and test planning can all lead to errors and uncertainties related to the study. All physical quantity measurements involve some degree of uncertainty. This analysis is important to validate the correctness and reliability of the experimental results. The percentage uncertainties for load and BTE were determined using the instrument uncertainty values provided in Table 4.

## Results and Discussion

#### Characterization analysis

As displayed in Table 5, the properties of conventional diesel fuel, CPB, CPBF<sub>1</sub>, CPBF<sub>2</sub>, CPBF<sub>3</sub>, CPBF<sub>4</sub>, CPBF<sub>5</sub>, CPBF<sub>6</sub>, CPBF<sub>7</sub>, and CPBF<sub>8</sub> were measured in accordance with ASTM standards.

Table 1 — Experimental program

Notation	Fuel type	Abbreviation	Load percentage
D	Diesel	D	No load, 20%, 40%, 60%, 80% and 100%
CPB	<i>Ceiba pentandra</i> biodiesel	CPB	
CPBF <sub>1</sub>	20%CPB + 80%D	CPB20	
CPBF <sub>2</sub>	20%CPB + 80%D + 250 ppm BH	CPB20+BH250	
CPBF <sub>3</sub>	20%CPB + 80%D + 500 ppm BH	CPB20+BH500	
CPBF <sub>4</sub>	20%CPB + 80%D + 750 ppm BH	CPB20+BH750	
CPBF <sub>5</sub>	20%CPB + 80%D + 1000 ppm BH	CPB20+BH1000	
CPBF <sub>6</sub>	20%CPB + 80%D + 1000 ppm BH + 25 ppm Al <sub>2</sub> O <sub>3</sub>	CPB20+BH1000+A25	
CPBF <sub>7</sub>	20%CPB + 80%D + 1000 ppm BH + 50 ppm Al <sub>2</sub> O <sub>3</sub>	CPB20+BH1000+A50	
CPBF <sub>8</sub>	20%CPB + 80%D + 1000 ppm BH + 75 ppm Al <sub>2</sub> O <sub>3</sub>	CPB20+BH1000+A75	

Table 2 — Specifications of the nanoparticles

Item	Specification
Chemical name	Aluminum Oxide
Formula	Al <sub>2</sub> O <sub>3</sub>
Purity	99.9%
Supplier	Ultra nanotech Pvt Ltd, Bengaluru, India
Molar mass	101.96 g/mol
Average particle size	20–50 nm
Surface area (SSA)	>150 m <sup>2</sup> /g
Appearance	White
Density	3.8 g/cm <sup>3</sup>
Thermal Conductivity	~35 W/mK
Melting point	2050 °C
Boiling point	3000 °C

Table 3 — Technical specification of the engine

Make and Model	Kirloskar TV1
Number of stroke	Four stroke
Number of cylinder	1
Ignition type	Compression
Cooling type	Water
Compression ratio	17.5:1
Rated power	5.2 kW
Engine capacity	661 cc
Rated speed	1500 rpm
Bore and stroke	87.5 and 110 mm
Injection pressure	210 bar
Loading type	Eddy current dynamometer

Table 4 — Uncertainty analysis of the devices

Instruments	Range	Accuracy	Percentage uncertainty
Gas analyzer	CO – 0 to 10%	± 0.1%	± 0.5
	HC – 0 to 20000 ppm	± 10 ppm	± 0.5
	NOx – 0 to 5000 ppm	± 25 ppm	± 0.2
Engine speed	0 to 2000 rpm	± 10 rpm	± 0.2
Load indicator	0 to 15 kg	± 0.1 kg	± 0.2
Fuel measurement	0 to 30 cc	± 0.1 cc	± 1.0
Pressure pickup	0 to 100 bar	± 0.1	± 0.3
Crank angle encoder	–	± 1°	± 0.3

Table 5 — Physicochemical properties of the test fuel

Fuel type	Density kg/m <sup>3</sup>	Kinematic viscosity cSt	Flash point °C	Cetane number	Calorific value MJ/kg
CPB	890	4.6	142	55.5	39.82
CPBF <sub>1</sub>	858	3.9	75	51.3	42.43
CPBF <sub>2</sub>	860	3.9	74	51.2	42.61
CPBF <sub>3</sub>	861	4.0	72	51.1	42.72
CPBF <sub>4</sub>	865	4.1	71	51.0	42.80
CPBF <sub>5</sub>	869	4.1	69	51.0	43.05
CPBF <sub>6</sub>	870	4.2	70	51.5	43.07
CPBF <sub>7</sub>	872	4.3	70	51.9	43.08
CPBF <sub>8</sub>	875	4.4	71	52.8	43.10
D	850	3.7	58	50.0	43.25

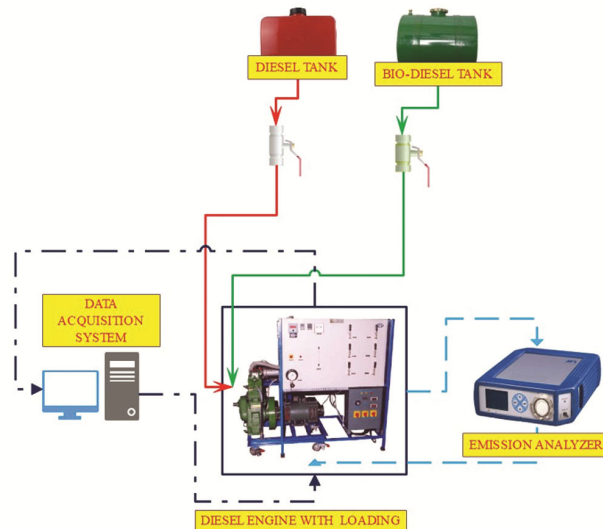


Fig. 1 — Schematic of the test bench

Generally, viscosity, cetane index, and energy of the fuel primarily influence the engine performance characteristics. Viscosity is a crucial one since it directly influences the injection system and fuel atomization behaviour. Density is a critical property for fuels used in engines, as variations in density can influence both power output and in-cylinder combustion<sup>29</sup>. The table displays that the CPB is denser than diesel; however, the density of the fuels blended with antioxidant and nanomaterial is closer to diesel fuel. In general, the density of blended fuel has generally been identified to be about 5% more than that of diesel and also the CPB and CPBF<sub>8</sub> blend is approximately 24.3% and 18.9% more viscous than diesel fuel. The viscosity is increased with the addition of a concentration of BH and Al<sub>2</sub>O<sub>3</sub>. Compared to CPBF<sub>1</sub>, adding BH enhanced the kinematic viscosity by about 5.1%, whereas the

accumulation of Al<sub>2</sub>O<sub>3</sub> improved the viscosity by about 12.8%. In comparison to diesel, the energy value of the blended fuel is marginally low; however, when BH and Al<sub>2</sub>O<sub>3</sub> nanoparticles are added, the energy value is increased to nearly diesel. The cetane index is an important measuring parameter for fuel since it affects the ignition delay period during combustion. In this study, the cetane index is reduced by adding higher concentration of BH antioxidants. But the cetane index was increased with increased dosage of nanoparticles. Therefore

the test results demonstrated improved combustion characteristics.

### Engine performance evaluation

#### Brake thermal efficiency

The capability of the engine to proficiently transform chemical energy in fuel into usable mechanical power is measured by its BTE. The BTE of the engine may vary when biodiesel replaced traditional diesel for a number of reasons, such as incomplete combustion, increased viscosity and density, and decreased energy content. Fig. 2 illustrates the changes in BTE when operated with different fuels. The BTE of the engine decreases when 20% *Ceiba pentandra* biodiesel is blended with regular diesel. Under all load conditions, BTE is consistently lower for CPBF1 than diesel. At higher load, diesel has a BTE of 35.3%, while CPBF<sub>1</sub> has a BTE of roughly 33.1%. Antioxidants greatly improve the efficiency of the engine when added to biodiesel. By reducing oxidative degradation, antioxidants enhance engine performance and combustion characteristics. Slight variations in BTE were observed when different fuels were used. The minor differences between the fuels can be attributed to variations in their energy content, density, and kinematic viscosity. At all loads, petroleum-based diesel (D) produced higher power output, which is consistent with other research findings<sup>30,31</sup>. The maximum BTE at 100% load conditions for antioxidant-doped biofuels such as CPBF<sub>2</sub>, CPBF<sub>3</sub>, CPBF<sub>4</sub>, and CPBF<sub>5</sub> are 33.9%, 34.5%, 35.0%, and 35.2%, respectively. It also can be understood that the addition of BH increased the BTE of the engine. Among the antioxidant blends, 1000 ppm BH-dosed CPBF<sub>5</sub> fuel shows higher BTE due to its higher heating value<sup>32</sup>. The higher density of the fuel dosed

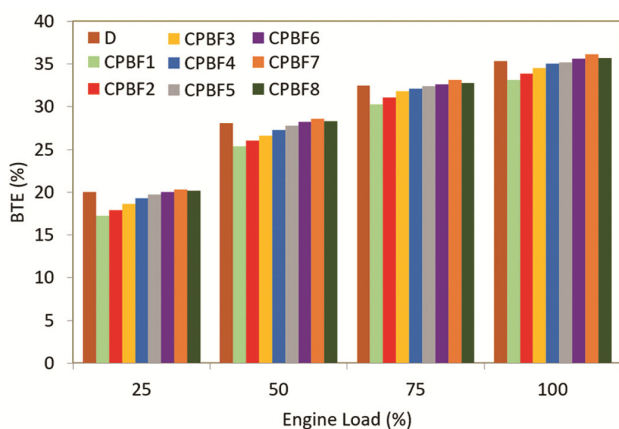


Fig. 2 — Variation of BTE versus engine loads

with antioxidant led to a higher BP since a more quantity of fuel was fed into the engine for the same fuel volume<sup>33,34</sup>. In addition to that, the leakage in the fuel supply system also decreases with increasing fuel viscosity. Moreover, compared to CPBF<sub>1</sub>, antioxidants dosed biofuel may have reduced the cetane number, leading to improved combustion and consequently higher power output<sup>35</sup>. Similar findings were reported by Hirkude, where the author showed 4.78% more BTE when the biodiesel was dosed with BHA and BHT antioxidants compared to untreated B40 fuel<sup>36</sup>. By incorporating nanoparticles into biodiesel, the BTE of blends was marginally increased up to 36.1%. The improved combustion is endorsed by adding nanoparticles, which retain higher heating value and large surface area-to-volume ratio. Additionally, adding nano compounds progresses thermal stability, which serves as an oxidation agent to promote better combustion and raise BTE<sup>25</sup>. In this study, adding 50 ppm Al<sub>2</sub>O<sub>3</sub> with fuel showed 2.27% higher BTE than diesel fuel. Further, 75 ppm Al<sub>2</sub>O<sub>3</sub> with fuel, reduced the efficiency to 35.7%. The diminishing efficiency with larger dosages may be due to the increased viscosity<sup>37</sup>.

#### Brake specific fuel consumption (BSFC)

BSFC is a crucial indicator that evaluates the performance of the engine. It calculates the fuel consumption per unit of power generated. The difference in BSFC for varying engine loads is displayed in Fig. 3. Regardless of operating conditions, usage of CPBF<sub>1</sub> blends enhanced the BSFC by roughly 12% compared baseline fuel. The lower energy density of CPBF<sub>1</sub> caused the increase in the BSFC for CPBF<sub>1</sub> (see Table 5). This outcome is consistent with earlier research<sup>38,39</sup>. In general, the

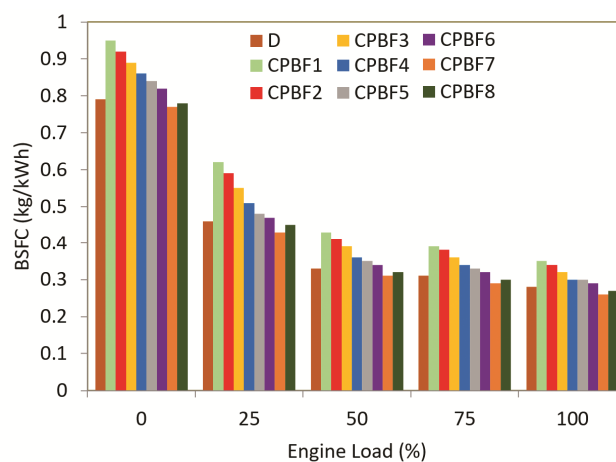


Fig. 3 — Variation of BSFC versus engine loads

energy content of the testing fuel and combustion quality are the primary elements influencing the BSFC<sup>40</sup>. As seen in Fig. 3, when BH was added to blended fuel, the BSFC dropped at all concentrations. Overall, it was found that a larger concentration of antioxidants caused greater decrease in BSFC. The value of BSFC for CPBF<sub>2</sub>, CPBF<sub>3</sub>, CPBF<sub>4</sub>, and CPBF<sub>5</sub> is 0.34, 0.32, 0.3, and 0.3 kg/kWh, respectively. Varying the BH dosage from 750 ppm to 1000 ppm had no substantial impact on BSFC value. The outcomes of this study align with previous research<sup>41,42</sup>. According to Alagu *et al.* the addition of BHA and BHT at 1000 ppm to a 20% ricebran biodiesel blend reduced BSFC by 2.1% and 1.2%, respectively, in comparison with raw blended fuel, indicating enhanced fuel efficiency<sup>41</sup>. Likewise, incorporating antioxidant additives specifically 5% diethyl ether and 10% *Moringa oleifera*—into the biodiesel-diesel blend resulted in a 5.14% reduction in BSFC<sup>42</sup>. Based on the findings, BSFC significantly reduced when Al<sub>2</sub>O<sub>3</sub> nanoparticles were utilized with the blends. Since BP and combustion efficiency are closely correlated with BSFC, adding oxygen to the blend using nanoparticles improves combustion efficiency<sup>43</sup>. Additionally, nanoparticles can speed up combustion by performing as a catalyst and providing oxygen. Due to higher surface-to-volume ratio, these additives significantly improve combustion characteristics, which improves BSFC. Here, the addition of 25 ppm, 50 ppm, and 75 ppm of Al<sub>2</sub>O<sub>3</sub> to the blend resulted in BSFC values of 0.29, 0.26, and 0.27 kg/kWh, respectively. It is also evident from earlier research that the fuel with metal nanoparticles burned more efficiently in the cylinders than the fuel without additives. At full load conditions, the biofuel blend containing 50 ppm Al<sub>2</sub>O<sub>3</sub> and 1000 ppm BH exhibited a 7.14% reduction in BSFC. The reduced fuel consumption may also be due to a reduced rate of evaporation and increased physical delay. After the initial micro-explosion, oxygenated nanomaterials such as Al<sub>2</sub>O<sub>3</sub> facilitate secondary atomization<sup>44</sup>.

### Engine emission analysis

#### CO emission

The main reason for CO emission in IC engines is incomplete combustion process. Fig. 4 indicates the variations in engine load and its effect on CO emissions. CO emissions decreased according to increased engine load. Amid all the selected fuels, diesel had higher CO content across all operating

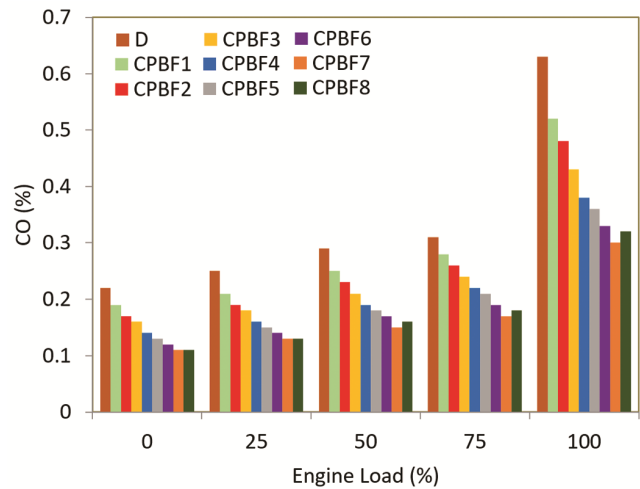


Fig. 4 — Variation of CO versus engine loads

conditions. The blended fuels displayed reduced CO emissions than diesel. The emission of CO from diesel, CPBF<sub>1</sub>, CPBF<sub>2</sub>, CPBF<sub>3</sub>, CPBF<sub>4</sub>, and CPBF<sub>5</sub> was 0.52%, 0.48%, 0.43%, 0.38%, and 0.36%, respectively. Compared to baseline fuel, the reductions in CO emissions for CPBF<sub>1</sub>, CPBF<sub>2</sub>, CPBF<sub>3</sub>, CPBF<sub>4</sub>, and CPBF<sub>5</sub> were 17.46%, 23.81%, 31.75%, 39.68%, and 42.86%, respectively. In antioxidant-doped biodiesel blends, their greater CN content and oxygen concentration work together to reduce CO emissions<sup>45</sup>. A greater CN of the fuel permits longer combustion duration and demonstrates shorter ignition delay. This development is ascribed to the oxygenated molecules in biodiesel, which helps efficient combustion. Compared to diesel, the oxygen concentration offers a higher combustion temperature, which encourages thorough combustion and converts a greater amount of CO into CO<sub>2</sub><sup>(46)</sup>. These findings are in line with those reported by Fattah *et al.* who showed CO reductions of 29.8% with 20% palm biodiesel and 21.2% with the addition of a BHA antioxidant<sup>47</sup>. When different dosages of Al<sub>2</sub>O<sub>3</sub> nanoparticles were blended with antioxidant-dosed biodiesel blends, the emission of CO was further reduced. The emission of CO at higher engine loads for CPBF<sub>6</sub>, CPBF<sub>7</sub> and CPBF<sub>8</sub> is 0.33%, 0.3%, and 0.32%, respectively. Use of CPBF<sub>7</sub> showed the lowest CO production at low and higher loads. The air-fuel ratio, or stoichiometric percentage, is the primary factor influencing CO emissions. The blended fuels containing nanoparticles have substantially higher oxygen content, which lowers more CO production. The reduction in CO emissions with Al<sub>2</sub>O<sub>3</sub> may be due to the disruption of fuel homogeneity upon

injection, prominent to better air-fuel mixing and more efficient burning. The nanoparticles can improve several physical properties of the fuel and influence combustion propagation within the chamber, potentially affecting CO formation<sup>48</sup>. In this study, the maximum reduction of 52.58% of CO was achieved by blending 50 ppm of Al<sub>2</sub>O<sub>3</sub>. At a concentration of 50 ppm, more CO is reduced as a result of the increased production of OH radicals. A similar pattern was observed with biodiesel derived from pumpkin and rapeseed oil<sup>17,49</sup>.

### HC emission

The performance of the engine suffered from incomplete fuel combustion, which led to increased HC emissions. The emission of HC is generally exaggerated by various operating parameters, including fuel spray characteristics. Two primary reasons for HC emissions are (1) fuel-air mixtures becoming too lean during the ignition delay period, exceeding the lean combustion limit, and (2) poor fuel mixing, where fuel is injected late during combustion at low velocity, leading to incomplete combustion. Fig. 5 indicates the variations in HC emissions for different fuels under different operating conditions. In this work, diesel produced more HC than other tested fuels. At 100% load, the emission of HC from diesel is 135 ppm. Blending oxygenated biodiesel with conventional fuel reduces the emission of HC at all operating conditions. Notably, in the fuel-rich areas, the oxygen molecules present in biofuel may have created favorable conditions (post-flame oxidation, increased flame velocity, etc.) in air-fuel relations, which boosted the oxidation of unburned HC and consequently reduced HC considerably<sup>50</sup>. Adding BH antioxidant with biodiesel blends reduced the

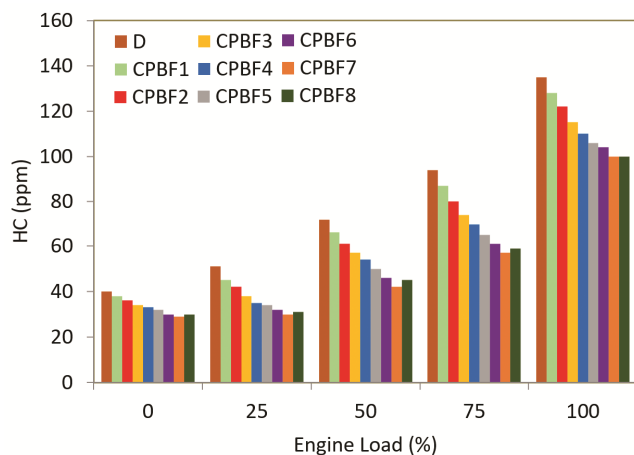


Fig. 5 — Variation of HC versus engine loads

emission of HC at all concentrations. The HC emissions from diesel, CPBF<sub>1</sub>, CPBF<sub>2</sub>, CPBF<sub>3</sub>, CPBF<sub>4</sub>, and CPBF<sub>5</sub> were recorded at 135, 128, 122, 115, 110, and 106 ppm, respectively. BH acts as a sinking agent, decreasing the quantity of different functional elements in diesel, which results in a notable reduction in HC emissions across all BH blend ratios. Comparing diesel, the usage of CPBF<sub>1</sub>, CPBF<sub>2</sub>, CPBF<sub>3</sub>, CPBF<sub>4</sub>, and CPBF<sub>5</sub>, the HC emission was minimized by about 5.19%, 9.63%, 14.81%, 18.52%, and 21.48%, respectively. The results are also in line with the findings of Balaji and Cheralathan, where the authors demonstrated that adding ethylenediamine antioxidant to the neem oil biodiesel greatly lowers the production of HC by 33.07% compared to neat biodiesel<sup>51</sup>. Similarly, Silambarasan *et al.* reported a reduction of approximately 21.42% in HC emissions at rated load when using biodiesel blended with L-ascorbic acid compared to diesel, indicating enhanced emission performance<sup>12</sup>. In addition to improving the air-fuel mixture, the use of Al<sub>2</sub>O<sub>3</sub> causes complete combustion, which lowers the amount of HC released at the exhaust. Under full load conditions, the addition of 25 ppm Al<sub>2</sub>O<sub>3</sub> resulted in a drop of 22.96% and 50 ppm in 25.93% of HC emissions than diesel. The enhanced oxidation of Al<sub>2</sub>O<sub>3</sub> and improved conversion efficiency are responsible for the decrement. In order to reduce the quantity of HC in the exhaust, nanoparticles aid in more thorough combustion. The same pattern was noted in earlier studies that verified the efficiency of different nanoparticles in controlling HC emissions. According to Sarma *et al.* the adding TiO<sub>2</sub> to mahua biodiesel blends ensued in a 22.5% decrease in HC<sup>52</sup>. The addition of TiO<sub>2</sub> to a palm and soybean biodiesel led to approximately a 21.5% reduction in HC attributed to improved combustion characteristics<sup>53</sup>.

### NOx emission

Higher combustion temperature is the main reason for NOx emissions in IC engines. Reducing NOx emissions from engines is a key focus for both engine manufacturers and researchers. Longer combustion time, and the amount of oxygenated molecules increase the production of NOx. Fig. 6 demonstrates the changes in NOx with the load of the engine for various fuels. At 25% load, the value of NOx for diesel is 289 ppm, but the value was changed by up to 293% when the load was changed to 100%. The sharp variations in NOx were ascribed to higher combustion

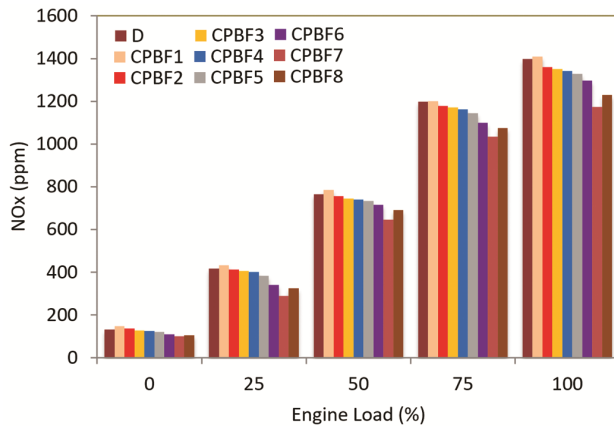


Fig. 6 — Variation of NOx versus engine loads

temperatures. When biodiesel was added to diesel fuel, NOx emissions increased because of increased oxygen concentration. Adding BH to 20% CPB led to a reduction in NOx emissions, with greater decreases observed as the antioxidant concentration in the fuel increased. At maximum load, the NOx emissions from the engine using CPBF<sub>2</sub>, CPBF<sub>3</sub>, CPBF<sub>4</sub>, and CPBF<sub>5</sub> were recorded as 1360, 1350, 1342, and 1329 ppm, respectively. This reduction is credited to the presence of antioxidants, known for their ability to neutralize free radicals. By hindering free radicals from forming NO, they contribute to a decrease in NOx emissions<sup>54</sup>. Similar observations were recorded when different types of antioxidants, including BHA, were blended with 20% biodiesel, where the average NOx reduction was 0.85–4.12%<sup>55</sup>. This is reliable with the outcomes of Fattah *et al.* who found that blended *Calophyllum inophyllum* biodiesel containing BHA, BHT, and 2-tert-butylbenzene-1,4-diol reduced NOx by 1.6–3.6% when compared to 20% *Calophyllum inophyllum* biodiesel without antioxidant<sup>56</sup>. Additionally, Rashed *et al.* discovered that 20% of *Calophyllum inophyllum* biodiesel with N-phenyl-1,4-phenylenediamine and N,N'-diphenyl-1,4-phenylenediamine reduced NOx by 4.75% and 1.46%, respectively<sup>57</sup>. The figure also represents the change in NOx when fuel was blended with different dosages of Al<sub>2</sub>O<sub>3</sub> nanoparticles. Among the various dosage level, blending 50 ppm of nanoparticles lead to an 8.68% reduction in NO<sub>x</sub> emissions than diesel fuel. This result might be endorsed to enhanced convective heat transfer within the chamber, which lowers flame temperature. Furthermore, improved fuel properties such as the higher latent heat and thermal conductivity of water molecules in the nanofluid mixture help reduce the flame temperature,

potentially leading to decreased NOx emissions<sup>58</sup>. Changing the dosage from 50 ppm to 75 ppm, the emission of NOx increased to 1230 ppm. When 1000 ppm of the BH antioxidant and 50 ppm of Al<sub>2</sub>O<sub>3</sub> were added, the NOx was reduced by 16.09% in comparison to baseline fuel. The joined effect of free radical absorption and catalytic activity is responsible for this decline. Antioxidants reduce NO by preventing the production of free radicals and breaking the chain reaction among them and NOx<sup>24</sup>. Furthermore, Al<sub>2</sub>O<sub>3</sub> in the fuel serves as a catalyst during combustion process, producing nitrogen dioxide from nitric oxide radicals<sup>59</sup>.

## Conclusion

Although *Ceiba pentandra* is a viable source of biofuel, the resulting biodiesel and their blends are oxidation-prone and hence need additional processing. Antioxidants and nanoparticles were thought to be a sustainable technique to improve the qualities of biodiesel and its blends so that they would function better when used as transportation fuel. The thorough investigation carried out in this work highlights the significant influence of BH antioxidant and Al<sub>2</sub>O<sub>3</sub> nanoparticles on the emission properties and combustion efficiency of blends of *Ceiba pentandra* biodiesel. The addition of antioxidants greatly improved the efficiency of the engine when added to biodiesel blends. Specifically, blending 1000 ppm BH with CPB increased the BTE of the engine to a level comparable to that of diesel. The combination of BH and Al<sub>2</sub>O<sub>3</sub> with biodiesel improved the efficiency to 36.1%, which is 2.27% more than diesel. Adding BH and Al<sub>2</sub>O<sub>3</sub> had a significant impact on fuel consumption; as a result, the biofuel blend with 50 ppm Al<sub>2</sub>O<sub>3</sub> and 1000 ppm BH showed a 7.14% decrease in BSFC when compared to diesel. The enhanced performance and lower fuel consumption may also result from a decreased evaporation rate, increased physical delay, micro-explosion, and secondary atomization. Compared to diesel, blending 1000 ppm BH and 50 ppm Al<sub>2</sub>O<sub>3</sub> resulted in a reduction of CO emission by 52.38%, HC by 25.93% and NOx by 16.1%. As reducing NO<sub>x</sub> emissions from engines is a major goal for both researchers and manufacturers, the combined effects of free radical absorption by BH and the catalytic activity of Al<sub>2</sub>O<sub>3</sub> in this study led to a decrease in NO<sub>x</sub> formation from the engine. In conclusion, the addition of the BH antioxidant and Al<sub>2</sub>O<sub>3</sub> nanoparticles to CPB biodiesel

resulted in improved combustion characteristics and engine performance. Therefore, future research could focus on a comprehensive analysis of oxidative stability and combustion analysis with CPB blends and other types of biodiesel.

### Conflict of interest

The authors declare no conflict of interest.

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