Influence of hydrogen enhancement on diesel engine fueled with Simarouba Glauca DC biodiesel with-Aqueous Al_2O_3 blends

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Abstract

In this study, hydrogen enrichment with nano-fuel was employed as a novel approach to address emissions control in diesel engines. Al2O3 nanoparticles were blended with Simarouba Gluca DC biodiesel at a concentration of 100 ppm. The blend was then ultrasonicated, and hydrogen (H_2) was introduced into the air inlet at low flow rates (2-3 LPM) to maintain safety. The study focused on blending hydrogen (H_2) with Nano fuels at a ratio of 15% hydrogen and 85% Nano fuels by volume and examined their impact on various engine performance metrics. These metrics included brake thermal efficiency (BTE), combustion chamber wall temperature, and emissions of NOx, CO, and HC. To assess the effects of different parameters, a simplified model was employed to calculate associated uncertainties. During the experimental setup, data acquisition was facilitated by a Supervisory Computer Aided Data Acquisition system with an integrated program. Notably, the research findings revealed that engine performance was enhanced when utilizing blends containing 100 ppm Al_2O_3 nanoparticles and hydrogen flow rates of 2 LPM and 3 LPM, resulting in improved BTE values. These blends also exhibited lower emissions of CO, NOx, and HC compared to pure diesel fuel. Among the tested samples, BNP100-2-LPM demonstrated the best performance with a BTE of 34.5, while BNP100-3-LPM achieved a BTE of 29. Regarding emissions, BNP100-2-LPM demonstrated the least amount of CO (0.45 g/kWh), HC (8 g/kWh), and NOx (230 ppm) in contrast to diesel fuel, which released CO, HC, and NOx at levels of 0.6 g/kWh, 27 g/kWh, and 286 ppm, respectively.

Keywords: *Biodiesel, emission, hydrogen, performance, Brake thermal Efficiency*

1. Introduction

Amidst the challenges posed by dwindling fossil fuel reserves, soaring fuel prices, and stringent pollution regulations on a global scale, the search for alternative energy sources has become paramount. As a result, experts have been fervently investigating various options, and one promising contender that has emerged is biodiesel. In recent years, biodiesel has garnered significant attention as a viable and sustainable alternative fuel for internal combustion engines. [1, 2, 3].

The widespread adoption of biodiesel faces substantial issues related to engine performance and its long-term resilience. These concerns include challenges related to engine power, fuel efficiency, cold weather operation, stability, and the risk of clogging, all of which hinder the broad acceptance of biodiesel as a viable fuel source. Additionally, the use of pure biodiesel can exacerbate NOx emissions, thereby presenting a similar environmental risk as other harmful pollutants. Addressing these issues requires comprehensive research efforts. Researchers suggest that potential solutions may involve alterations to engine design or the inclusion of fuel additives, offering the promise of enhancing the combustion characteristics and overall efficiency of pure biodiesel when employed in internal combustion engines [4]. Extensive research efforts are imperative to tackle the challenges linked to biodiesel. Researchers propose potential remedies, such as adapting engine designs and incorporating fuel additives, to improve the combustion properties and fuel efficiency of pure biodiesel in internal combustion engines. [5, 6, 7]
Reformulating biofuels is a more cost-effective approach compared to modifying existing engines to achieve compatibility. By applying principles of fuel reformulation, it becomes possible to reduce emissions, ultimately resulting in enhanced combustion, performance, and fuel efficiency in direct injection (DI) engines. Nevertheless, making modifications to a diesel engine comes with increased maintenance and manufacturing expenses, making it a less favored choice due to the challenges and difficulties associated with these changes [8].
In response to the hurdles associated with pure biodiesel, the incorporation of suitable nano-additives into biodiesel emerges as a viable solution with the potential to markedly enhance fuel efficiency while concurrently mitigating emissions. Nanoparticles (NPs) possess the capacity to curtail the creation of detrimental compounds. The significant surface-area to volume ratio exhibited by NPs assumes a pivotal function in diminishing emissions within diesel engines. Elevating this ratio accentuates the interplay between fuel and oxidizer during combustion, thereby ameliorating ignition delay and fuel evaporation rates, ultimately leading to reduced emissions.
Recent investigations have focused on NPs such as MgO, TiO2, Fe_2O_3, CuO, and CeO_2 as promising options for enhancing combustion and reducing emissions. Introducing nanoparticles (NPs) into liquid fuels enhances combustion by several mechanisms. Firstly, NPs act as catalysts, promoting more efficient fuel oxidation reactions at lower temperatures, thereby reducing ignition delay and enhancing overall combustion efficiency. Additionally, their high surface area-to-volume ratio facilitates better fuel-air mixing, promoting more homogeneous combustion and reducing emissions of incomplete

combustion byproducts. Furthermore, NPs can modify the fuel's physical properties, such as viscosity and surface tension, optimizing spray formation and atomization, which further enhances combustion stability and completeness. [9]. The effectiveness of the NPs is influenced by the stability and preparation techniques of the materials, with pH being a key variable determining their stability. Despite the potential for nanoparticles (NPs) to enhance combustion and reduce emissions, the viscosity of biodiesel-NP mixtures often remains low, limiting the extent to which NOx emissions can be reduced. The low viscosity of biodiesel-NP mixtures can lead to shorter residence times in the combustion chamber, resulting in incomplete combustion and higher NOx (nitrogen oxides) emissions. Additionally, reduced viscosity can promote faster diffusion of oxygen into the combustion zone, leading to higher combustion temperatures, which in turn increases NOx formation via the thermal pathway. Moreover, the enhanced fuel-air mixing facilitated by low viscosity can exacerbate the availability of oxygen for NOx formation reactions, further contributing to elevated NOx emissions despite the potential benefits of nanoparticles on combustion efficiency. However, the introduction of hydrogen into a diesel engine can enhance the air/fuel (A/F) mixing time, resulting in improved combustion and reduced soot formation.

Dimitriou and Tsujimura conducted an extensive investigation centered on the application of hydrogen (H_2) in a direct injection (DI) engine. Introducing H_2 into DI engines leads to a significant decrease in emissions of carbon dioxide (CO_2), hydrocarbons (HC), and carbon monoxide (CO). However, as the H_2 proportion in the diesel engine increases, it also raises the heat release rate (HRR) and cylinder pressure, resulting in a concurrent increase in NOx emissions. Nevertheless, utilizing a moderate H_2 flow rate tends to alleviate NOx emissions. [10]. In light of the dwindling fossil fuel reserves and the adverse environmental impacts of elevated NOx emissions, it is imperative to investigate alternative fuels that provide superior quality, enhanced performance, improved combustion, and reduced emissions in comparison to traditional fossil fuels. One such approach is the admixture of hydrogen (H_2) with Simarouba Glauca DC biodiesel, in combination with an aqueous Al_2O_3 fuel blend, for use in diesel engines. This combination aims to achieve a fuel with better properties and environmental benefits.

Reports indicate that specific hydrogen-enriched Nano fuels have been observed to generate elevated levels of nitrogen oxides (NO_x) emissions. Several studies have demonstrated that the use of hydrogen-blended biodiesel as a diesel engine fuel resulted in increases NOx emissions without significant improvements in combustion rates [11, 12, 13]. The observed phenomena can be attributed to alterations in the physicochemical properties of biodiesel, potentially causing extended ignition delays and changes in fuel characteristics. Careful management of hydrogen flow rates is crucial; as excessive flow rates have been associated with elevated NOx emissions. Additionally, to prevent blockage of engine tubes, nanoparticle sizes should be kept below 10 nm [14].

This study employed a blend of aqueous Al_2O_3 nanoparticles and hydrogen (H_2) at a moderate flow rate to reduce NOx emissions during the combustion of Simarouba Glauca DC biodiesel in a diesel engine. This approach aimed to address the challenges associated with the fuel's quality in diesel engines. Increasing the proportion of H_2 in the blend during higher engine loads resulted in an advanced combustion phase, leading to improved thermal efficiency but increased unburned hydrocarbon (HC) emissions. However, NOx emissions also increased as the H_2 proportion grew. To improve the physicochemical and combustion properties of the fuel while reducing emissions, aqueous Al_2O_3 nanoparticles were used due to their high surface area. To optimize engine performance under various parameter variations, determining the optimal conditions for hydrogen and nanoparticle inclusion in biofuels is crucial [15, 16]. This study is primarily aimed at addressing a research gap by investigating the use of a blend composed of H2-enriched Al_2O_3-Simarouba Glauca DC biodiesel as a potential fuel alternative for diesel engines. This particular area has received limited scrutiny thus far. The primary objective of this research is to evaluate the combustion, performance, and emissions attributes of an unmodified diesel engine operating on a combination of hydrogen-enriched Simarouba Glauca DC biodiesel and Al2O3 nanoparticles.

2. MATERIAL METHOD

2.1 Production of Simarouba Glauca DC biodiesel

The Simarouba Glauca DC seeds were sourced from Karnataka, India. The Simarouba Glauca DC oil was extracted from the seeds using a Mechanical Press [17]. The raw seed oil underwent transesterification, a process that transformed it into biodiesel fuel. Here are the steps involved:

1. Heating the Simarouba Glauca DC seed oil to 60 °C.
2. Mixing methanol and KOH (potassium hydroxide) in a distinct conical flask until the KOH is completely dissolved in the methanol.
3. Transferring the homogeneous blend into the flask filled with hot oil.
4. Stirring the mixture for 1.5 hours.
5. Moving the mixture to a separation funnel following the transesterification procedure to distinguish the biodiesel from glycerin.
6. Gathering the obtained biodiesel.

These steps outline the process of obtaining biodiesel from Simarouba Glauca DC seed oil [18].

2.2 Aqueous Al_2O_3 Nanoparticle

Aqueous aluminum oxide nanoparticles with a size of 50nm were purchased from Sigma Aldrich in Bangalore.

2.3 Characterization of Al_2O_3 Nanoparticle

The biodiesel was mixed with nanoparticles using a probe-type ultra-sonication method, enabling the homogeneous distribution of nanoparticles in both deionized water and oil phases. This process facilitated the formation of emulsions. The stability of the Al_2O_3 nanoparticles is crucial in preventing nozzle blockage in the diesel engine, so longer sonication duration was employed to minimize particle agglomeration [19]. In order to improve surface modifications and enhance stability, Sodium Dodecyl Sulfate (SDS) was introduced into the nonfuel component in different proportions. This addition served to decrease the likelihood of coagulation, minimize surface tension, and prevent coalescence. The experiment was replicated three times (triplicates), and the findings were displayed as mean values. Sonication was performed at a rate of 150 revolutions per minute (rpm) for a duration of 60 minutes, with a corresponding frequency of 50 Hz. Scanning Electron Microscopy (SEM) was utilized to investigate the surface morphology and structures of the Al_2O_3 nanoparticles. This imaging technique allows for high-resolution visualization of the particle surfaces, enabling researchers to observe their size, shape, and distribution. SEM provides valuable insights into the physical characteristics of the nanoparticles, which are crucial for understanding their behavior and interactions in various applications, ranging from catalysis to materials science.

2.4 The Nano-doped Fluid

In this experiment, a blend comprising 100 mg of Al_2O_3 nanoparticles and 1000 mL of biodiesel fuel was meticulously prepared and then exposed to sonication. The primary objective of this study was to explore the impact of incorporating Al_2O_3 nanoparticles into biodiesel. Through this procedure, researchers aimed to gain insights into how these nanoparticles influenced the properties and characteristics of the biodiesel fuel. This process was conducted with precision and rigor to ensure accurate results. The experimental setup allowed for a comprehensive investigation of the interactions between Al_2O_3 nanoparticles and biodiesel.

2.5 Flow rate of hydrogen in comparison to the flow rate of sonicated biodiesel-Al_2O_3 nanoparticle blend

In the experimental setup, two distinct hydrogen (H_2) mass flow rates were employed to enhance the air intake into the engine: 2 and 3 liters per minute (LPM). A consistent volume of hydrogen, precisely 15 vol/vol, was introduced into the inducted air for all configurations of hydrogen-enriched fuel mixtures. This method ensured a uniform volume of methyl ester (biodiesel) consumption, irrespective of varying flow rates. The detailed volumetric compositions of the Simarouba Glauca DC methyl esters-Al_2O_3 nanoparticle mixed H_2-air combinations at the intake manifold are available in Table 1, providing a comprehensive overview of the experimental conditions and their respective compositions. This meticulous approach aimed to maintain stability in the fuel mixture's composition, allowing for more accurate and reliable data collection. By keeping the hydrogen volume constant, researchers could effectively analyze the effects of different flow rates on the biodiesel-nanoparticle mixture.

Table 1. *Ratios of fuel blending*

Parameter	Description	Shortening
D-100	Diesel Fuel	D-100
B-20	80% Diesel+20% Simarouba Biodiesel	B20
B20+100 ppm Al_2O_3	80% Diesel+20% Simarouba Biodiesel with100 ppm Al_2O_3	BNP100
B20+100 ppm Al_2O_3/ H_2 @ 2 LPM	80% Diesel+20% Simarouba Biodiesel with100 ppm Al_2O_3/ Hydrogen at 2 LPM	BNP100+H_2(2 LPM)
B20+100 ppm Al_2O_3 / H_2 @ 3 LPM	80% Diesel+20% Simarouba Biodiesel with100 ppm Al_2O_3 / Hydrogen at 3LPM	BNP100+H_2(3LPM)

Table 1a. Engine Specifications

Engine parameters	**Specifications**
No. of cylinders	1
No. of strokes	4
Fuel	High Speed Diesel
Rated power	3.5 kW @1500 RPM
Cylinder diameter	87.5 mm
Stroke length	110 mm
Connecting rod length	234 mm
Compression ratio	12 to 18:1
Orifice diameter	20 mm
Dynamometer arm length	185 mm

2.6 Experimental Procedure

Figure 1 provides a visual representation of the experimental flow process within the biofuel-Al_2O_3-hydrogen fuel system. The hydrogen (H_2) flow pathway is composed of various essential components, which include a pressure regulator, a cylinder, a flame arrestor, a flame trapper, and a flowmeter. The hydrogen source is a high-pressure cylinder operating at 200 bar, with its pressure being regulated down to an exit pressure of 2 bar by the regulator. To precisely control the air-to-H_2 ratio, the H_2 flow line incorporates both air and H_2 flowmeters. Additionally, for safety considerations, a flame arrestor and flame trapper have been incorporated into the setup.

Air-hydrogen flow rates of 2 and 3 liters per minute (LPM) are delivered at elevated pressure levels to ensure a consistent 15% volume/volume ratio of hydrogen to air. The 85% blend of Simarouba Glauca DC methyl esters and Al2O3 nanoparticles was likely achieved by combining 85 parts by volume of the Simarouba Glauca DC methyl esters and Al2O3 nanoparticles mixture with 15 parts by volume of the hydrogen-air mixture. This calculation is based on the assumption that BNP 100, which contains 20% biodiesel, is used as the base fuel. Therefore, by adding the hydrogen-air mixture to the BNP 100, the resulting blend would consist of 85% Simarouba Glauca DC methyl esters and Al2O3 nanoparticles and 15% hydrogen-air mixture.. Prior to introduction into the test engine, the Nano fuels produced with the aid of hydrogen undergo a process of homogenization and agitation at 1500 revolutions per minute (rpm). The measured physicochemical properties of the test fuels are comprehensively presented in Table 2, offering valuable insights into the characteristics of the experimental fuels used in the study.

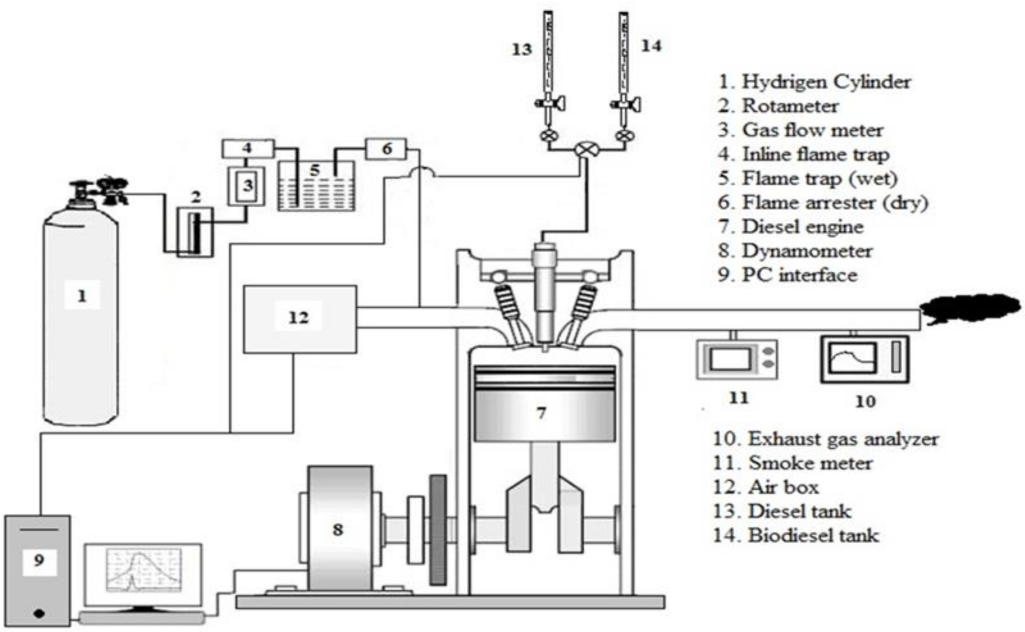

Figure 1. *Experimental set up for Hydrogen-Biodiesel-Aqueous aluminum oxide flow*

Table 2. *Physiochemical Properties of test fuels*

Parameter	D100	B20	BNP100	BNP100+H_2 (2 LPM)	BNP100+H_2 (3 LPM)	Testing Method
Kinematic Viscosity @ 40^0C	3.2	3.5	3.52	2.98	3.1	ASTM D-445
Cetane Number	49	50	50	51	51	ASTM D-976
Density (kg/m^3)	870	875	875	860	864	ASTM D-1298
Calorific Value (kJ/kg)	45,000	43800	43900	44800	44900	ASTM D-240
Flash Point ^{0}C	63	70	71	67	70	ASTM D-93-2A

2.7 Uncertainty measurement

In the measurement process, inaccuracies may arise from various factors, including improper calibration of measurement devices. The magnitude of these errors can be determined by assessing the repeatability of measurements, which is typically obtained by conducting five measurements and calculating the standard deviation with a low level of variation. Table 3 displays the percentage of measurement uncertainty attributed to the recorded data.

Table 3. *Uncertainty analysis*

Parameter measured	Uncertainty in %
Speed	±0.1
Load	±0.3
BTE	±1.1
Pressure	±0.9
HC	±0.25
CO	±0.2
NO_x	±0.1
Temperature	±0.2

3. THE RESEARCH FINDINGS AND DISCUSSION

3.1 Properties of Crude Simarouba Gluca DC Oil And Simarouba Gluca DC Biodiesel.

Table 2 presents the physicochemical characteristics of both crude Simarouba Gluca DC oil and biodiesel. In comparison to the crude Simarouba Gluca DC oil, biodiesel exhibits higher density and kinematic viscosity, mainly due to the inclusion of methyl esters in its composition. Table 2 also provides additional properties of the oil, including the Cetane number, calorific value, and flash point.

3.2 Characteristics of The Al_2O_3 Nanoparticles

In the Supplementary file, Fig. S1 displays the SEM image of the prepared nanoparticles. The image provides a visual representation of the surface morphologies of the nanoparticles, allowing for the observation of pore sizes and textural outlooks. This information helps in determining the porous architectures of the nanoparticles.

3.3 The stability of the nanoparticles

Weekly stability assessments were carried out on mixtures of Aluminum oxide nanoparticles with a surfactant (Al_2O_3: SDS) to evaluate their propensity for coagulation, surface tension changes, and coalescence. According to the UV-vis spectroscopy data, the absorbance levels for all nanoparticle-SDS blends showed a gradual decline over the evaluation period. It is important to highlight that the Nano fluids remained in a stationary state throughout the duration of this assessment. To assess the stability of these blends, absorbance measurements were conducted at the conclusion of each week. By the end of the 9th week, the results clearly indicated that the absorbance curves for the nanoparticle-sodium dodecyl sulfate (SDS) blends had stabilized, suggesting a state of relative equilibrium.

To prevent any further agglomeration, the prepared nanoparticles were promptly put to use as planned. This immediate utilization played a crucial role in maintaining the stability of the blends, effectively minimizing the risk of agglomeration or alterations in their properties. The consistent absorbance measurements over time demonstrated the sustained stability of the nanoparticle-SDS blends, further affirming their suitability for the intended applications. This approach ensured that the blends were in a condition conducive to their anticipated use without any undesirable changes in their characteristics. The meticulous monitoring and timely utilization of the nanoparticles contributed to their stability and reliability in the experimental context [20].

3.4 The physicochemical characteristics of the experimental fuels.

Table 2 offers a comprehensive summary of the key physicochemical properties of both the test fuels and conventional diesel, highlighting their critical attributes. The blended fuels share fundamental fuel properties closely with conventional diesel fuel. However, they do display slightly higher values for both density and kinematic viscosity when compared to diesel fuel. These marginal variations in density and kinematic viscosity distinguish the blended fuels from the conventional diesel, although they remain within the acceptable range for diesel fuel. This disparity signifies the effective blending of the fuels, promoting better mixing and atomization of the blended counterparts. Moreover, the blended fuels boast a higher Cetane number and a favorable calorific value compared to conventional diesel. These attributes suggest a shorter ignition delay period and improved combustion characteristics, particularly in relation to the heat release rate (HRR). These qualities make a substantial contribution to heightened combustion efficiency and overall fuel performance

3.5 Brake Thermal Efficiency

Figure 2 offers a visual representation of the alterations in brake thermal efficiency (BTE) under 100% engine load for all the fuels tested. It is evident that as BTE rises, so does the engine load, indicating a correlation between these variables. Among the fuels examined, the highest Brake Thermal Efficiency (BTE) recorded was 34.5%, attained when utilizing a fuel blend comprising biodiesel and hydrogen combined with 100 ppm of Al_2O_3 nanoparticles. (2 liters per minute). In contrast, biodiesel and diesel fuels produced BTE values of 20% and 27%, respectively. One of the primary factors contributing to the lower BTEs is the suboptimal atomization and spray characteristics of the fuel. The hydrogen-enriched fuels, especially those incorporating 25 ppm Al_2O_3 nanoparticles + H_2 at 2 liters per minute and 100 ppm Al_2O_3 nanoparticles + H_2 at 3 liters per minute, displayed exceptional performance due to their higher heating value and reduced fuel consumption. The decreased BTE observed with pure biodiesel is attributed to its tendency for extensive premixing. The introduction of hydrogen into the Nano fuel resulted in an increased brake thermal efficiency (BTE), which can be attributed to the term "synergistic effects" refers to the combined or cooperative action of different elements or components that results in an effect greater than the sum of their individual effects. In the context of fuel blends, synergistic effects indicate that the combination of various fuel components, such as biodiesel, hydrogen, and nanoparticles, leads to enhanced performance or efficiency beyond what would be achieved by each component alone. This could include improvements in combustion properties, emissions reduction, or fuel efficiency due to the complementary interactions among the blend constituents. Furthermore, increasing the engine load intensified this effect, further enhancing BTE.

In summary, Figure 2 underscores the relationship between BTE and engine load, with the fuel blend containing 100 ppm of Al_2O_3 nanoparticles, biodiesel, and hydrogen delivering the highest BTE among the tested fuels. This superior performance can be attributed to several factors, including improved fuel characteristics and reduced fuel consumption, all of which contribute to elevated BTE levels, making it a notable highlight of the study. [21, 22].

The introduction of hydrogen had the notable effect of increasing the hydrogen-to-carbon ratio in the fuel, which, in turn, led to a marked improvement in brake thermal efficiency (BTE). Additionally, the incorporation of hydrogen had a significant impact on elevating the Cetane number of the fuel blends, particularly notable in the case of the 100 ppm Al_2O_3 nanoparticles + H_2 at 2 LPM and 100 ppm Al_2O_3 nanoparticles + H_2 at 3 LPM blends. This elevation in Cetane number contributed to improved overall performance and fuel efficiency. The Cetane number is a vital factor in determining fuel ignition and ignition delay. As depicted in Figure 2, a positive correlation emerged between increasing load at 5 kW and its influence on the Cetane number. This correlation is rooted in the reduction of viscosity and specific fuel consumption. To further enhance BTE at higher engine speeds, it is feasible to reduce the mass of fuel entering the combustion chamber. Achieving this can be accomplished by reducing viscosity and optimizing specific fuel consumption, demonstrating the intricate relationship between various fuel properties and engine performance.

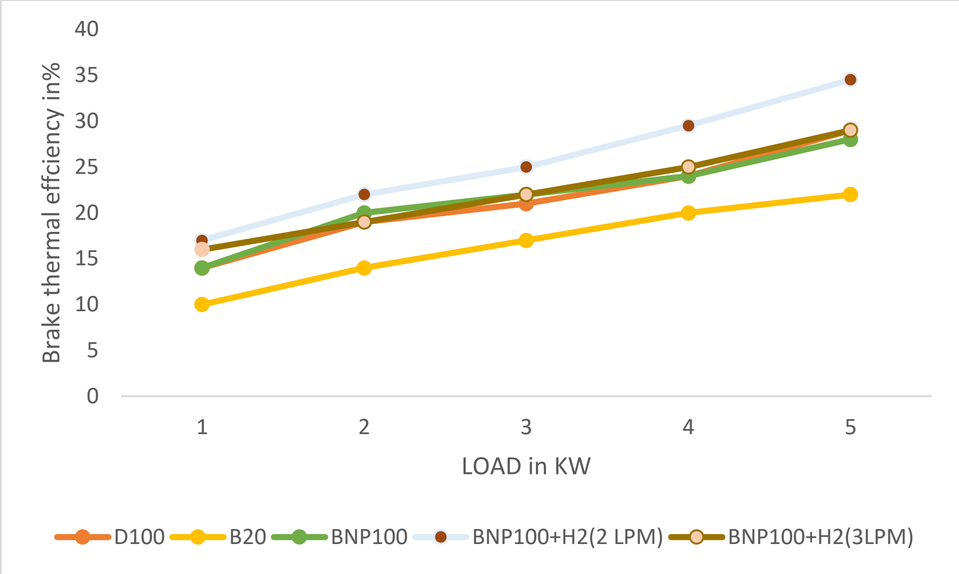

Figure 2. *Variation of brake thermal efficiency with change in load*

3.6 Exhaust Emissions

Figure 3 illustrates the variations in carbon monoxide (CO) emissions were observed during tests conducted under 100% load conditions using different fuels. Adding hydrogen to the fuel blend increases the available oxygen content of biodiesel through a process called oxygenation (R.A. Bakar, 2024). Hydrogen, with its high affinity for oxygen, reacts with oxygen in the air during combustion to form water vapor (H_2O). This reaction liberates oxygen atoms, effectively increasing the oxygen content available for combustion of the biodiesel component. The increased oxygen availability enhances combustion efficiency and promotes more complete combustion of the fuel blend, leading to reduced emissions of carbon monoxide (CO) and unburned hydrocarbons (HC). The inherent oxygen concentration within the nanoparticles within the biofuel accelerates the combustion rate (Soohoon Choi, 2017), leading to reduced NOx emissions. This effect is particularly pronounced during demanding full-load operational conditions, underscoring the environmental benefits of incorporating nanoparticles in the fuel blend (Wang, 2019). The inherent oxygen concentration within the nanoparticles within the biofuel accelerates the combustion rate, leading to reduced NOx emissions. This effect is particularly pronounced during demanding full-load operational conditions, underscoring the environmental benefits of incorporating nanoparticles in the fuel blend. The nanoparticles act as catalysts, promoting more efficient fuel oxidation reactions at lower temperatures, thereby reducing ignition delay and enhancing overall combustion efficiency. Additionally, their high surface area-to-volume ratio facilitates better fuel-air mixing, promoting more homogeneous combustion and reducing emissions of incomplete combustion byproducts (Chuanhao Jin, 2023). . As a result, there was a significant decrease in CO emissions. In contrast, diesel fuel demonstrated higher CO emissions attributed to incomplete combustion and suboptimal mixing processes. The incorporation of hydrogen into Nano fuels played a crucial role in elevating oxygen levels within the fuel mixture. This, in turn, promoted more thorough combustion of the fuel, thereby mitigating CO emissions. Moreover, higher proportions of hydrogen within biodiesel demonstrated a direct correlation with decreased carbon content in the fuel. This reduction further contributed to the diminished generation of carbon monoxide. Moreover, the introduction of nanoparticles had a noticeable impact on the comprehensive attributes of the fuel blend, thereby molding its combustion characteristics.

The introduction of nanoparticles raises the oxygen content within the biofuel, which, in turn, fosters lean combustion. Additional variables, such as pressure and injection timing, also contribute to the decline in CO emissions. The amalgamation of biodiesel with nanoparticles prominently manifests a reduction in CO emissions. As engine load increases, the augmented combustion rate further aids in lowering CO emissions. Notably, the BNP100 + H_2 (2 LPM) and BNP100 + H_2 (3 LPM) fuels exhibit a 25% and 9% reduction in CO emissions, respectively, when compared to pure diesel fuel. The incorporation of Al_2O_3 nanoparticles into the biodiesel-hydrogen blend produces a substantial decrease in CO emissions, as highlighted by the study's findings [23].

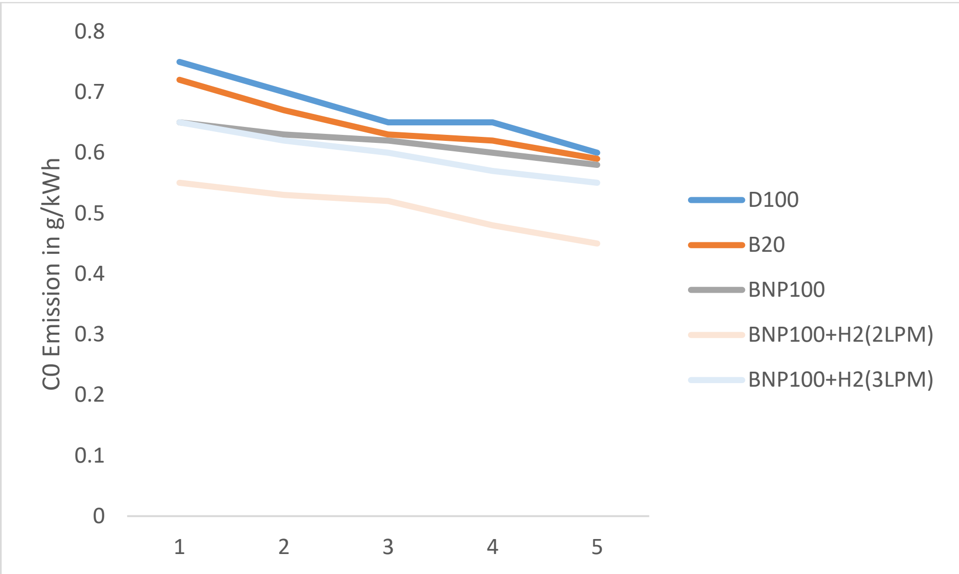

Figure 3. *Variation of CO Emission with respect load*

Figure 4 depicts the alterations observed in hydrocarbon (HC) emissions across various engine loads. Within a diesel engine, HC emissions commonly arise due to incomplete combustion taking place within the confines of the combustion chamber. Remarkably, during lower engine speeds, the presence of an elevated compression ratio plays a pivotal role in curbing HC emissions. However, increased power requirements typically necessitate operating engines at increased speeds. Regrettably, this circumstance results in incomplete combustion, primarily influenced by factors such as wall wetting and flame quenching, which consequently contribute to higher hydrocarbon (HC) emissions. Interestingly, a curious trend becomes apparent, wherein an increase in engine load correlates with a decrease in HC emissions. This phenomenon can be attributed to a reduction in the rate of fuel droplet evaporation, coupled with an improved homogenization of the fuel blend. Additionally, factors like fuel quality, spray pattern, and the prevailing operating conditions exert added influence, ultimately affecting the levels of HC emissions. These interrelated elements collectively shape the complex dynamics of HC emissions in the context of engine operation and fuel composition [24].

The Al_2O_3-biodiesel blend showcases diminished hydrocarbon (HC) emissions in comparison to pure diesel fuel. This decrease can be attributed to the higher oxygen content present in the Nano fuels blended with hydrogen, promoting more efficient and complete combustion. Regardless of the engine load, hydrogen-enriched Nano fuels consistently exhibit reduced HC emissions. At full load, diesel fuel emits 70% more HC emissions in contrast to the BNP100 ppm + H_2 (2 LPM) and BNP100 ppm + H_2 (3 LPM) fuels. The incorporation of Al_2O_3 nanoparticles in biodiesel enhances the fuel's calorific value and combustion characteristics, resembling those of a catalytic reactor.

The addition of hydrogen to the Nano biofuel reduces the latent heat of vaporization, resulting in a richer mixture of air and fuel. Moreover, an increase in the hydrogen ratio reduces the viscosity of the blended fuel. As a result, the BNP100 ppm + H_2 (2 LPM) and BNP100 ppm + H_2 (3 LPM) fuels exhibit slightly reduced HC emissions, as visually depicted in Figure 4. This comprehensive analysis underscores the multifaceted impact of fuel composition, hydrogen enrichment, and the presence of Al_2O_3 nanoparticles on HC emissions, ultimately contributing to a deeper understanding of their interplay in engine performance.

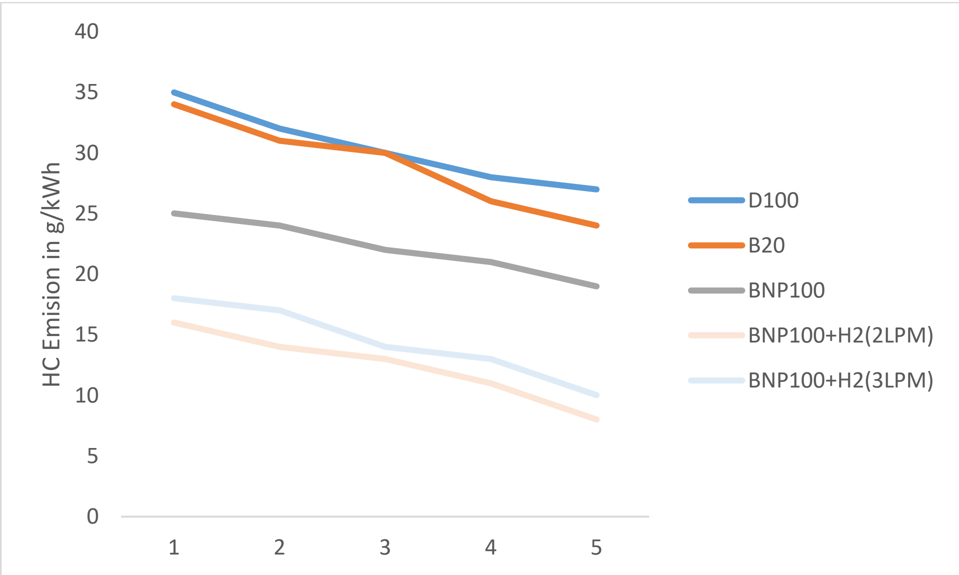

Figure 4. *Variation of HC Emission with respect to load*

Figure 5 presents the NOx emissions data for all the tested fuels. Notably, Simarouba Gluca DC biodiesel records higher NOx emissions in contrast to diesel fuel. This disparity is mainly linked to the increased mass flow rate of biodiesel entering the combustion chamber, contributing to the elevated NOx emissions. Other contributing factors to the increased NOx emissions include elevated oxygen concentrations and the compressibility modulus. Specifically, Simarouba Gluca DC biodiesel emits approximately 13.28% more

NOx compared to regular diesel fuel, as illustrated in Figure 5. However, the inclusion of Al_2O_3 nanoparticles has a favorable impact on reducing NOx emissions.

Furthermore, the incorporation of Al_2O_3 nanoparticles into the biofuel matrix yields significantly better results in terms of NOx emissions when compared to conventional diesel fuel. The composite nano-biofuel demonstrates a remarkable reduction of 19.58% in NOx emissions when compared to regular diesel fuel. While higher oxygen content can theoretically contribute to more complete combustion, reducing certain emissions like CO, it does not directly correlate with lower NOx emissions. In fact, higher combustion rates, often associated with elevated oxygen levels, can lead to higher temperatures in the combustion chamber, which in turn can increase NOx formation. The inherent oxygen concentration within the nanoparticles within the biofuel accelerates the combustion rate, leading to reduced NOx emissions. This effect is particularly pronounced during demanding full-load operational conditions, underscoring the environmental benefits of incorporating nanoparticles in the fuel blend.

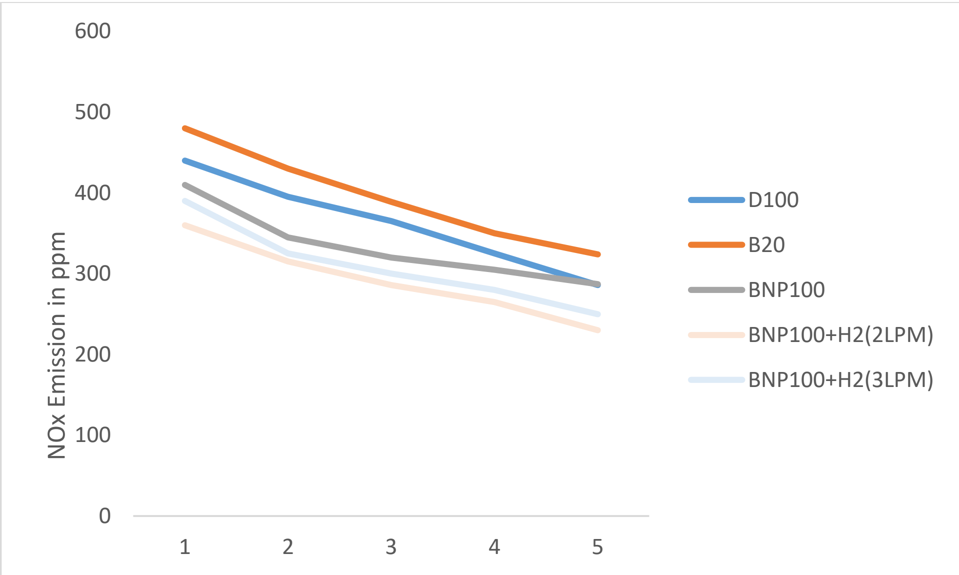

Figure 5. *Variation of NOx emission with respect load*

4. RESULTS AND CONCLUSION

The main objective of this study was to evaluate the effects of introducing hydrogen (H_2) into nano-enhanced biofuels. Specifically, the study investigated the impact of hydrogen-infused biofuels, which included a mixture of Al_2O_3 nanoparticles and Simarouba Glauca DC biodiesel, on the operational efficiency and emission characteristics of a single-cylinder direct injection diesel engine. The viability of these blended Nano-biofuels was assessed through comprehensive fuel quality evaluations, conforming to ASTM specification tests, and compared to the properties of conventional diesel fuel. The main findings from experiments conducted across various engine load conditions are summarized as follows:

a) Under full load conditions, the hydrogen-enriched Nano-biofuel blends exhibited BTE. This enhancement can be attributed to the significant surface area provided by Al_2O_3 nanoparticles, accelerating combustion rates. Furthermore, the catalytic effects of Al_2O_3 nanoparticles improved the reactive surfaces of the biofuel and enhanced heat transfer rates.

b) The blended fuels displayed reduced emissions of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) in comparison to diesel fuel. The introduction of hydrogen (H_2) into the air system lowers emissions through several mechanisms. Firstly, hydrogen has a high flame speed, promoting more complete combustion of the fuel-air mixture and reducing emissions of carbon monoxide (CO) and unburned hydrocarbons (HC). Secondly, hydrogen's presence in the combustion process increases the available oxygen content, facilitating more efficient combustion and further reducing CO and HC emissions. Lastly, hydrogen's high heat of combustion can lower the peak combustion temperature, mitigating the formation of nitrogen oxides (NOx), thus contributing to overall emission reduction.. According to the experimental results, hydrogen-enriched nano-biofuels can be regarded as efficient alternative fuels.

c) The synergistic effects of H_2-enriched Nano-biofuels not only improved performance parameters but also significantly decreased fuel consumption and the resulting emissions. Al_2O_3 nanoparticles played a crucial role in enhancing the emission and performance characteristics of the fuel.

d) In summary, the Nano-fuels demonstrated satisfactory performance as viable fuel sources for diesel engines. In terms of BTE, the ranking of Nano-biofuels' performance was as follows: BNP100 + H_2 (2 LPM) > BNP100 + H_2 (3 LPM) > D-100, BNP25 ppm > B-20. This highlights the superior performance of the BNP100 + H_2 (2 LPM) fuel in comparison to the other tested fuels.

In conclusion, the addition of hydrogen to Nano-biofuels showed promising results in terms of enhancing performance and reducing emissions in the diesel engine. The utilization of Nano-fuels presents a promising option for powering diesel engines, offering a greener and more efficient alternative to traditional diesel fuels.

Future investigations could delve deeper into optimizing the composition and blending ratios of hydrogen-infused biofuels to further enhance engine performance and emissions reduction. Furthermore, exploring the long-term durability and reliability of engines running on such novel fuel blends could provide valuable insights into their practical feasibility and potential for widespread adoption. Additionally, considering the scalability and commercial viability of implementing these technologies on a larger scale would be essential for realizing their broader environmental and economic benefits.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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