INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (XXXX) XXX

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Hydrogen-enriched palm biodiesel as a potential alternative fuel for diesel engines: Investigating performance and emission characteristics and mitigation strategies for air pollutants

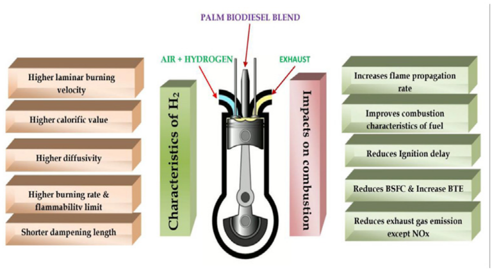
K. Thiruselvam [a], S. Murugapoopathi [b], T. Ramachandran [c], Kassian T.T. Amesho [d,e,f,g,h,*]

[a] *Department of Mechanical Engineering, Panimalar Engineering College, Chennai, India*
[b] *Department of Mechanical Engineering, PSNA College of Engineering and Technology, Dindigul, India*
[c] *Department of Mechanical Engineering, Jain (Deemed-to-be University), Bangalore, India*
[d] *Institute of Environmental Engineering, National Sun Yat-Sen University, Kaohsiung 804, Taiwan*
[e] *Center for Emerging Contaminants Research, National Sun Yat-Sen University, Kaohsiung 804, Taiwan*
[f] *The International University of Management, Centre for Environmental Studies, Main Campus, Dorado Park Ext 1, Windhoek, Namibia*
[g] *Destinies Biomass Energy and Farming Pty Ltd, P.O. Box 7387, Swakopmund, Namibia*
[h] *Regent Business School, Durban, South Africa*

HIGHLIGHTS

- The CO, HC and HC emissions were considerably reduced.
- Utilization of 30% neat palm biodiesel in the engine was achieved.
- Hydrogen enriched palm biodiesel for CI engines can be used as alternative fuels.
- The proposed systemcan be used as a scientific foundation for emission control measures.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 18 November 2022
Received in revised form
9 April 2023
Accepted 22 April 2023
Available online xxx

ABSTRACT

Palm biodiesel is one of the most suitable alternative fuels due to its capability to replace traditional fossil fuel usage in IC engines. Even as palm biodiesel (POBD) reduces harmful pollutant gases, the engine performance is not on an equal scale with neat diesel. To address this shortcoming, an investigation was carried out to examine the application of palm biodiesel (PBD) and hydrogen induction through the intake air at the flow rates of 6 and 8LPM (Litre Per Minute) in the compression ignition (CI) engine. The experimental study shows that POBD has poor engine performance and moderate pollution reduction compared with neat diesel. When compared to POBD and neat diesel, the higher calorific

---

[*] *Corresponding author*. Institute of Environmental Engineering, National Sun Yat-Sen University, Kaohsiung 804, Taiwan.
E-mail address: kassian.amesho@gmail.com (K.T.T. Amesho).

https://doi.org/10.1016/j.ijhydene.2023.04.256

Please cite this article as: Thiruselvam K et al., Hydrogen-enriched palm biodiesel as a potential alternative fuel for diesel engines: Investigating performance and emission characteristics and mitigation strategies for air pollutants, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.256

Keywords:
Hydrogen enrichment
Alternate fuel
Palm biodiesel
CI engine
Exhaust emission
Environmental pollution

value and other H_2 characteristics improve combustion properties, resulting in higher engine performance and lower pollutant gases (except NOx). When compared to the palm biodiesel blend (BD 30), the results of BD30+8LPM reduced the Specific fuel consumption (SFC) by 0.0885kg/kWh and improved the brake thermal efficiency (BTE) by 6.67%. The Carbon monoxide (CO), hydro carbon (HC), and smoke opacity were reduced by 0.047% volume, 29.2 ppm, and 6.52% respectively. A marginal increase in NOx was seen as 297.6 ppm.

Introduction

The rising cost of diminishing fossil fuels, as well as GHG concerns, has fuelled the search for alternative sources of energy consumption in IC engines. Biofuels have piqued the interest of authorities, researchers, and companies as a regenerative and recyclable way of expanding energy supply diversity and lowering CO_2 levels from IC engines [1,2]. Biodiesel has many benefits over diesel, including its recyclable nature, non-toxicity, and devoid of sulphur and aromatics. It can also be obtained from a variety of sustainable sources, such as pure or recycled vegetable and livestock lipids [3–5]. Among the many sustainable HCs, vegetable oils are considered an excellent alternative to diesel since they have fuel attributes suitable for consumption in a diesel engine [6–9]. Palm oil contributes to 33% of all vegetable oil production globally [52]. In terms of mechanical and molecular properties, biodiesel from palm oil outperforms petroleum-based diesel. It produces low sulphur levels when compared to petro-diesel [53].

A newly discovered palm biodiesel variant has a significantly reduced pour point, making it a suitable option for usage in cold regions of the world. Palm biodiesel also has a higher cetane number, which ensures clean burning in a diesel engine compared to petroleum diesel. Palm biodiesel has a greater fluidity, a greater flashpoint, and a reduced overall ignition temperature, among other mechanical and molecular drawbacks [10].

By adding nanofluids and nanoparticles, the PBD overcomes the poor physical properties of high viscosity, flash point, and lower calorific value. The addition of 5 and 10 ppm silver oxide NPs to the POBD resulted in the elevation of combustion parameters. This was because of the improved exterior area/volume proportion that resulted in elevated BTE, and minimization of BSFC. Also, the HC, CO, smoke and NOx discharges were reduced [11]. The usage of acetone blended with palm biodiesel reduced CO emission levels by 0.03%. The HC and NOx levels were seen as 2 ppm and 400 ppm respectively [12].

The addition of 0.1% TiO_2 nanoparticles lessened the kinematic viscosity but elevated the cetane number. The heating value and the flash point of palm biodiesel were lowered. The B100 palm biodiesel and 0.1% TiO_2 blend produced 2.43% higher brake power [13]. Palm kernel biodiesel with octanol additions of 10%, 20%, and 30% volume in a CI engine resulted in higher oxygen concentration and atomization. This further contributed to the improvement of combustion characteristics and the reduction of pollutant gases [14]. The efficient removal of nanoparticles from engine exhaust is of utmost importance due to the harmful impact of their environmental exposure on human health and soil quality, which makes the use of nano-optical tweezers for trapping micron-sized particles a critical consideration [15]. The use of hydrogen-enriched biodiesel was analyzed in the current research to combat the environmental risks due to the addition of nanoparticles. Increasing the volume of H_2 reduced the burning time and increased the pressure. It also saved 5.4% on fuel and reduced carbon dioxide emissions [16]. A 30% hydrogen addition could be used as a reserve to preserve diesel while eliminating CO and HC [17]. The usage of H_2 resulted in a reduced density of 0.08 kg/m^3 at 300 K and 1 atm. The extra flammability ranged between 4 and 75 vol% of H_2. While using H_2, the lower ignition threshold of 0.02 mJ required specific consideration [18]. The most serious issues with using hydrogen as a primary fuel include premature burning and knocking. Despite the small amount of hydrogen retained, the mass of the retention apparatus was substantial [19,20]. This increased the vehicle's adaptations and additional expenditures [21]. The utilization of pure vegetable fuel in CI engines reduced the thermal efficiency and increased the smoke levels. At maximum load, the hydrogen fuel enhanced the engine's braking thermal efficiency by 2% and lowered smoke emissions by 20%. The HC and CO levels were also significantly reduced [8,22]. One significant advantage of a hydrogen-powered IC engine is that it can be quickly brought to market, resulting in a steady decrease in diesel car usage in the coming years [23–25]. The primary benefits of hydrogen enrichment are increased mass fraction of high-temperature regions, and increased turbulent intensity during the combustion process [40]. The hydrogen enrichment is not only appropriate for reciprocating engines, but it may also be beneficial for rotary engines by providing turbulence-induced blades (TIB) [41].

Several studies have been conducted to investigate the performance and emission characteristics of hydrogen-enriched diesel engines. Kumar et al. [54] reported that the thermal efficiency was increased by up to 10.7%, and the fuel consumption was lower as compared to diesel fuel, while the emission of CO and HC was decreased by 16% and 7%, respectively. Other studies have also shown that the addition of hydrogen to diesel fuel can result in higher percentage of efficiency and reduction in exhaust emissions. However, the

Please cite this article as: Thiruselvam K et al., Hydrogen-enriched palm biodiesel as a potential alternative fuel for diesel engines: Investigating performance and emission characteristics and mitigation strategies for air pollutants, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.256

impact of hydrogen on engine stability, performance, and emissions varies depending on the specific engine type and operating conditions.

The introduction of hydrogen into diesel engines has been considered a suitable alternative option in recent years due to its advantages such as absence of carbon structure, nonharmful nature, and high calorific value [55]. While hydrogen has limitations such as higher oxides of nitrogen, explosion, and hazardous practices [56], research has shown promising results in terms of performance and emission characteristics. Gnanamoorthi and Vimalananth [57] investigated the effect of hydrogen fuel on a CRDI diesel engine and reported that the addition of 30 lpm of hydrogen resulted in higher efficiency and reduced exhaust emissions. Castro et al. [58] used a turbocharged four-cylinder DI engine to investigate the performance and emission parameters under different loading conditions and found that while the backfire limited the hydrogen substitution by 70% and 45% at medium and full load operating conditions, the emission parameters exhibited a positive impact with dual fuel compared to baseline operation. Other studies have also shown improvements in thermal efficiency, reduction in emissions of CO and HC, and lower specific fuel consumption when hydrogen was used as a fuel in diesel engines [59,60]. In this paper, we investigate the use of hydrogen-enriched palm biodiesel as a potential alternative fuel for diesel engines and explore its performance and emission characteristics, as well as mitigation strategies for air pollutants.

Haut du formulaire

Several studies have investigated the effect of hydrogen addition on diesel engine performance and emissions. Jamrozik et al. [61] found that up to 25% hydrogen share had no significant impact on engine stability in a CI engine. Saravanan et al. [62] reported an increase in brake thermal efficiency (BTE) of up to 17% and lower exhaust emissions of UHC, CO, and carbon oxides with hydrogen addition in an IC engine. Karagoz et al. [63] demonstrated a decrease in BTE by 8.5% but significant reductions in CO, CO2, and smoke emissions by up to 68%, 29.5%, and 51.3%, respectively, with 30% hydrogen enrichment in a CI engine. Finally, Zhou et al. [64] found that hydrogen enrichment of up to 40% improved thermal efficiency by 12.5% and decreased specific fuel consumption by 10.1% compared to diesel fuel in a naturally aspirated diesel engine.

Several studies have investigated the effects of hydrogen-enrichment in combination with different types of fuels on the performance and emissions of diesel engines. Kumar et al. [65] found that the addition of a moderate amount of hydrogen to jatropha oil and diesel as pilot fuels resulted in an 8.15% increase in brake thermal efficiency (BTE) and significant reductions in emissions of HC, CO, and smoke opacity, though with a slight increase in nitrogen oxide emissions. Verma et al. [66] investigated mitigation strategies for air pollutants using a combination of Jatropha Curcas and hydrogen in dual fuel mode, resulting in reductions in emission parameters. Loganathan et al. [67] used blends of diesel and cashew nut shell liquid with hydrogen and observed improved performance characteristics, with reduced emissions of CO and HC, but an increase in nitrogen oxide emissions. Serin and Yıldızhan [68] studied the effects of hydrogen in tea seed oil biodiesel blends and found promising results for both performance and emissions. These studies highlight the potential of hydrogen-enriched biodiesel as a viable alternative fuel for diesel engines, and the importance of investigating mitigation strategies for air pollutants.

According to research findings, incorporating 20% waste cooking oil into diesel and introducing hydrogen injection at a rate of 20 L per minute resulted in a decrease in specific fuel consumption (SFC) by 1.66%, an increase in brake thermal efficiency (BTE) by 0.3%, and a decrease in carbon monoxide (CO), hydrocarbon (HC), and smoke emissions, although there was no significant change in nitrogen oxides (NOx) [42]. To reduce NOx emissions, water injection into the intake lowers the engine's volumetric efficiency [43]. A low disturbance combustion chamber, optimized compression ratio, and aftertreatment system are necessary to improve engine performance with hydrogen injection [44]. A neat hydrogen-air mixture can self-ignite at room temperature with a high compression ratio without any additives. An optimal compression ratio of 26–32 and a higher equivalence ratio are needed [45]. The optimum injector duration and flow rate for hydrogen injection were 200 crank angle degrees before top dead center (CA bTDC) and 120 g/h, respectively, resulting in a 10.71% improvement in BTE at 70% maximum load. The abundance of oxygen in the combustion reduces heat transfer efficiency at high hydrogen flow rates. Adding 20% exhaust gas recirculation (EGR) reduces peak pressure and NOx levels [46]. The broad flammability range of hydrogen allows the engine to operate over a wide range of air-fuel ratios, even at an equivalence ratio of 0.1. The lean mixture improves fuel efficiency by promoting complete combustion with fewer residuals, thanks to the high diffusivity and flame speed of hydrogen [47]. Hydrogen-oxygen-enriched biodiesel (HOEBD) outperforms pure hydrogen-enriched biodiesel (HEBD) in terms of engine efficiency and emissions [48]. Hydrogen inclusion in the intake air reduces vibration acceleration and sound pressure levels due to reduced combustion delay and variance in peak pressure increase rate, which decreases engine block vibration [49]. Third-generation algal biofuel in CI engines reduces CO and NOx and increases CO_2, with minimal power and torque due to the inclusion of hydrogen and hydroxyl gas [50]. The pressure increase due to fast combustion occurs at numerous places in the combustion chamber under diesel injection into the hydrogen-air mixture in a four-cylinder, supercharged CI engine. The HRR caused by hydrogen occurs during the premixed combustion phase with a fixed volume of starter diesel. Most of the hydrogen is consumed before the main injection, and a uniform blend of air and hydrogen on the cold cylinder surface leads to prolonged burning [51].

The novelty of the current work is the usage of palm biodiesel blend along with hydrogen as a substitute fuel. The high flow rate of hydrogen enrichment reduced BTE by 1.6% at 70% load due to the lack of oxygen in combustion process [33]. In comparison to diesel, the use of neat palm biodiesel reduced BTE by 1% on average due to its lower calorific value and high viscosity [39]. It observed that oxygenated fuel is required for efficient full-load hydrogen utilization. Furthermore, the poor performance characteristics of the higher productivity oil from palm biodiesel can be overcome by using higher calorific value hydrogen as a substitute fuel. It was also discovered that the high heat energy content of hydrogen resulted in higher NOx emissions and the usage of higher blend of palm biodiesel required the proper designed fuel delivery system. As a result, the hydrogen flow rate was limited to 6 LPM (32.4 g/h) and 8 LPM (43.2 g/h), and the palm biodiesel blend was limited to 30%.

Experimental setup and test procedure

The base engine test fuel (diesel fuel), palm biodiesel blend fuel (BD 30), 6 and 8 LPM hydrogen-air flow rate along with palm biodiesel blend (BD 30+ H_2 6LPM) and (BD 30+ H_2 8LPM) were tested using a 4-stroke mono-cylinder, water cooled direct injection CI engine without any engine modifications. The engine's specified power was 5.2 kW @ 1500 revolutions per minute. The technical details of engine are listed in Table 1. An eddy current dynamometer was used as outlined in Fig. 1. An 'Engine soft' analysis software was used for online performance evaluation and measurement of combustion pressure and crank angle. The exhaust gas discharges were estimated with an AVL Digas 444 analyzer. The smoke opacity was evaluated with an AVL 437C opacity indicator. The investigations were conducted repeatedly for 100 cycles until all the process factors were obtained. Each experiment was done under stable-phase circumstances to establish the values' dependability. Before the measurements, the engine was operated for 15 min to ensure stability.

Transesterification of palm biodiesel

Palm oil was altered into palm biodiesel utilizing a simple transesterification method including KOH (catalyst) and CH_3OH. Palm oil, 15% CH_3OH, and 5% KOH were mixed for 75 min at 60 °C. Table 2 lists the key molecular parameters of palm biodiesel (BD30) and diesel as determined by ASTM standards.

Table 1 – Technical specification of engine.

Serial number	Parameters	Values
1	Engine make	Kirloskar
2	Model	TV 1
3	No.of Cylinder	1
4	No.of strokes	4
5	Fuel	Diesel
6	Rated Power	5.2 kW @ 1500 rpm
7	Cylinder diameter	87.5 mm
8	Stroke length	110 mm
9	Compression ratio	17.5:1
10	Ignition type	Compression ignition
11	Cooling	Water cooled
12	Loading type	Eddy current dynamometer
13	Combustion chamber injector nozzle	Three holes with 0.3 mm diameter each
14	Combustion chamber shape	Hemi spherical shape
15	Injection timing	23^0 bTDC
16	Injection pressure	200 bar

Uncertainty analysis

During the experiments, the equipment selection, calibration, ambient influence, data, and appropriate views are likely to cause mistakes. Hence, the precision of the engine performance measurements were established using the uncertainty and error assessments.

The assessments were obtained through experimentation to get the mean ($\overline{X}_i$) and the standard deviation (σ_i) of the estimated variables. The uncertainty of the estimated variables are considered as $X_1 \pm \Delta x_1, X_2 \pm \Delta x_2, X_3 \pm \Delta x_3, ----$ $X_n \pm \Delta x_n$ and the uncertainty of calculated estimation as $R = \Delta R$. The root-sum square approach is utilized to gain higher precise fault boundaries for the computed numbers, and the extent of the fault is indicated by the expression (1).

$$\Delta R = \sqrt{\left(\frac{\partial R_1}{\partial x_1}\Delta x_1\right)^2 + \left(\frac{\partial R_2}{\partial x_2}\Delta x_2\right)^2 + \left(\frac{\partial R_3}{\partial x_3}\Delta x_3\right)^2 + ----- \left(\frac{\partial R_n}{\partial x_n}\Delta x_n\right)^2} \tag{1}$$

The uncertainties were computed for the measured quantities using the above equation for the established operating conditions which are given below Table 3.

The proportion of experimental uncertainty is estimated utilizing equation (2), as shown in the subsequent stages.

$$Y = \sqrt{\left[BP^2 + SFC^2 + BTE^2 + EGT^2 + CO^2 + HC^2 + NO^2 + S^2 + {CO_2}^2 + P^2 + N^2 + L^2\right]} \tag{2}$$

$$= \sqrt{\left[0.2^2 + 1^2 + 1^2 + 0.15^2 + 0.2^2 + 0.2^2 + 0.2^2 + 1^2 + 1^2 + 1^2 + 0.5^2 + 0.2^2\right]}$$

$$= \pm 2.38\%.$$

Results and discussion

Brake specific fuel consumption (BSFC)

Higher viscosity characteristics of palm biodiesel resulted in high specific fuel consumption in all load conditions as shown in Fig. 2. The average SFC rate of BD 30 is 0.016kg/kWh higher than diesel since the elevated fluidity of BD minimized the mixing of A/F levels in the combustion chamber [26,27]. The addition of hydrogen at 6 and 8LPM reduced brake-specific fuel consumption by 0.0635kg/kWh and 0.0885kg/kWh, respectively, compared to BD30, while it was 0.0475kg/kWh and 0.0725kg/kWh lower than neat diesel. The reason is that the increase in the volume of the hydrogen-air mixture raised the laminar burning velocities and the flammability limit [28]. This improved ignition throughout the cylinder enabled easy ignition of the high-viscosity palm biodiesel blend. The higher flow rate of enriched hydrogen usage is limited in the combustion chamber due to the limited compression ratio.

Please cite this article as: Thiruselvam K et al., Hydrogen-enriched palm biodiesel as a potential alternative fuel for diesel engines: Investigating performance and emission characteristics and mitigation strategies for air pollutants, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.256

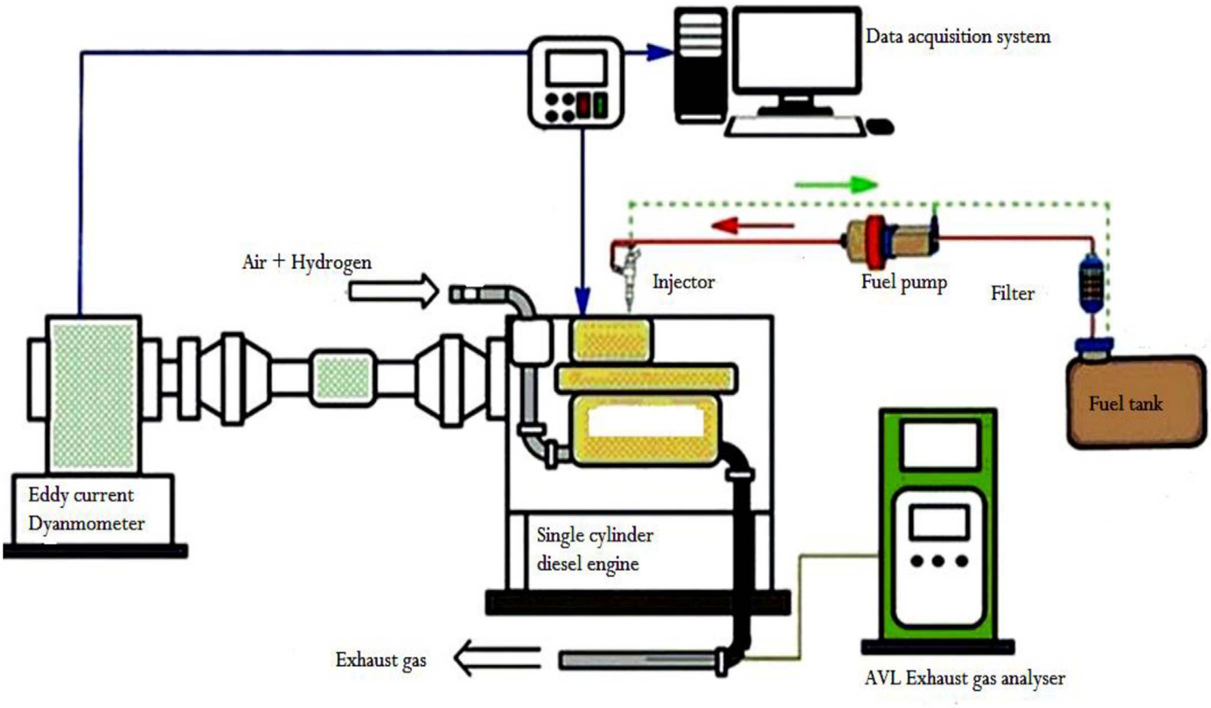


Fig. 1 – Engine dynamometer setup.

Table 2 – Properties of tested fuel.

Properties	Palm biodiesel (BD 30)	Diesel	Method
Water content (%)	0.03	0.001	ASTM D2709
Density @18 °C (g/m^3)	0.8833	0.8210	ASTM D4052
Kinematic viscosity @35 °C (mm^2/s)	4.30	2.5	ASTM D455
Calorific value (KJ/Kg)	38,108	42,950	ASTM D240
Cetane Index (CI)	52	46	ASTM D976
Flashpoint in ^{0}C	140	50	ASTM D93
Iodine value (g/100 g oil sample)	65	–	ASTM D1510
C (%)	77.2	–	ASTM D5291
H (%)	11.4	–	ASTM D5291
O (%)	11.4	–	

Table 3 – Uncertainties of measured quantities.

Sl.No.	Measured quantities	Uncertainties (%)
1.	BP (Brake Power)	0.2%
2.	SFC (Specific Fuel Consumption)	1%
3.	BTE (Brake Thermal Efficiency)	1%
4.	EGT (Exhaust Gas Temperature)	0.15%
5.	CO (Carbon monoxide)	0.2%
6.	HC (Hydrocarbon)	0.2%
7.	NO (Nitrogen oxide)	0.2%
8.	S (Smoke opacity)	1%
9.	CO_2 (Carbon dioxide)	1%,
10.	P (Cylinder pressure)	1%
11.	N (Speed)	0.5%
12.	L (Load)	0.5%

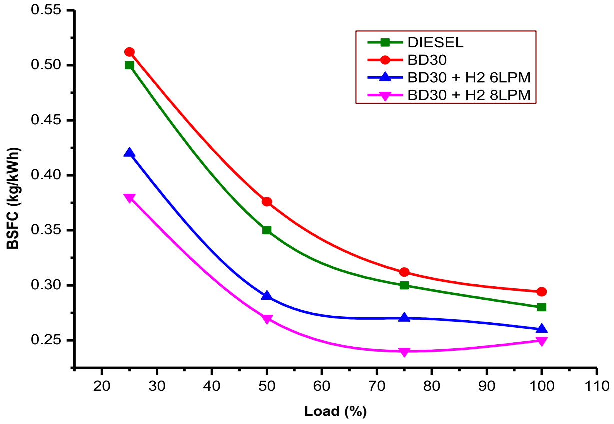


Fig. 2 – BSFC variation with load.

However the usage of 8 LPM of enriched hydrogen reduced the average SFC by 0.025 kg/kWh when compared to 6 LPM.

Brake thermal efficiency

The brake thermal efficiency of various evaluation fuels is plotted in Fig. 3. Because of its higher viscosity, the palm biodiesel blend (BD30) consumed more SFC per kW power output than all other tested fuels. The poor engine performance of biodiesel was improved by the inclusion of H_2 induction in the inlet manifold. The results show that adding hydrogen fuel at 6 and 8LPM increased BTE by 4.98% and 6.67%, respectively when compared to biodiesel (BD30), and by 3.88% and 5.97% when compared to neat diesel. Hydrogen's increased diffusivity, flame propagation, and lower dampening length allow for thorough combustion, eliminating the

Please cite this article as: Thiruselvam K et al., Hydrogen-enriched palm biodiesel as a potential alternative fuel for diesel engines: Investigating performance and emission characteristics and mitigation strategies for air pollutants, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.256

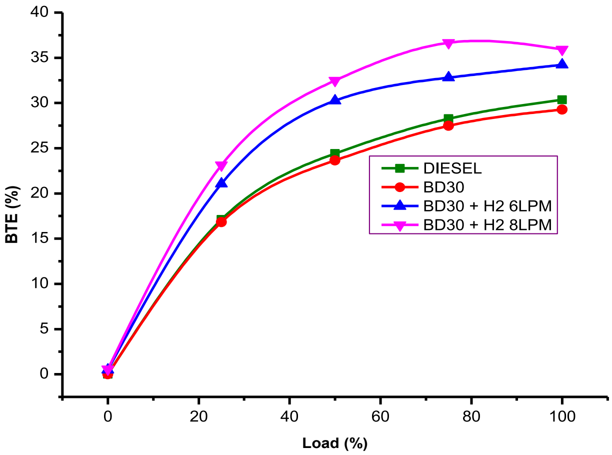


Fig. 3 – BTE variation with load.

disadvantages of biodiesel's poor atomization and longer ignition latency [29]. When compared to 6 LPM of hydrogen, 8 LPM of hydrogen increased BTE by 1.69% on average. This suggests that hydrogen enhancement is required because it allows for leaner combination operation due to full ignition within the cylinder compartments and less fuel regression.

Variation in-cylinder pressure

The peak pressure differences of different fuel conditions are plotted in Fig. 4. The lower calorific value of POBD produced a maximum pressure of 65.43 bar which was 5.16 bar lower than neat diesel fuel. The addition of 6 and 8LPM of hydrogen fuel with blended biodiesel produced maximum pressure was 72.06 bar and 73.44 bar, respectively which were 1.16 bar and 2.54 bar higher than neat diesel. The increased rate of oxy-hydrogen supply into the input stream reduced the burning time while increasing the rate of pressure increase and the rate of combustion. As a result, the scheduling may be delayed, reducing harmful activity during combustion and increasing fuel efficiency [16] (see Fig. 5).

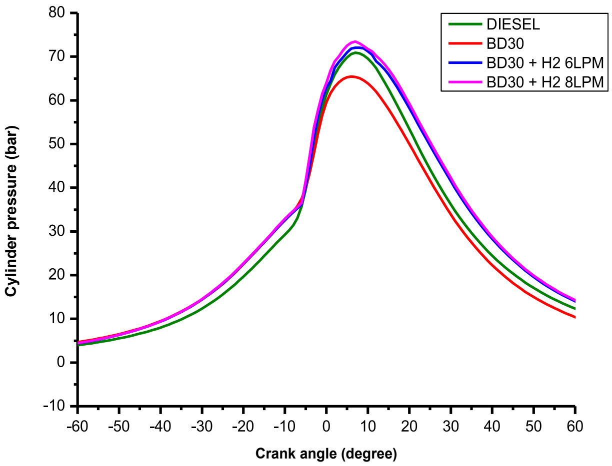


Fig. 4 – Variation of cylinder pressure at 100% load.

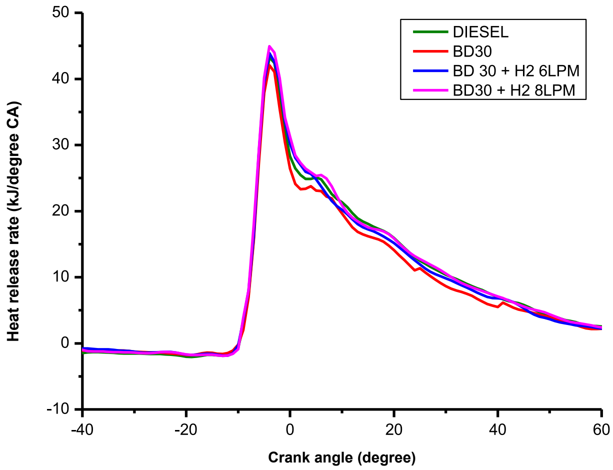


Fig. 5 – Variation of heat release rate at 100% load.

Variation in heat release rate

The difference in HRR of various tested fuels at 100% load conditions is portrayed in Fig. 4. The low viscosity nature of palm biodiesel blend (BD 30) revealed a heat release rate of 42.07 kJ/deg CA which was 1.22kJ/deg CA lower than diesel. Adding 6 and 8LPM of hydrogen-air flow rate reduced ignition delay time and increased the HRR to 43.89 and 44.94kJ/deg CA, respectively which were 1.82 and 2.87kJ/deg CA, higher than the biodiesel blend (BD 30) respectively. The reason was due to decreased intensity, lower energy level per unit volume, broader combustible band, low initiation energy, faster flame duration, and shorter dampening length of H_2 fuel [30]. The available time for the palm biodiesel to mix with air and hydrogen before ignition enabled proper combustion and streamlined HRR. As a result, a lean mixture served as the ignition source throughout the cylinder's entire range.

Carbon monoxide (CO) emission

Carbon monoxide emissions were low up to part load for all tested fuel conditions, as illustrated in Fig. 6. The emission rate went up under complete load owing to a lack of oxygen in the burning regions and an elevated fuel-to-air proportionality factor [31]. The considerable abundance of O_2 levels in palm biodiesel was effectively used to transform CO as CO_2 throughout the combustion phase. Another explanation is that palm biodiesel has a greater cetane number, which minimized the likelihood of a fuel-rich region [14,26]. The utilization of blended palm biodiesel (BD 30) reduced CO emissions by an average of 0.022% volume when compared to neat diesel because biodiesel contains more oxygen [32].

The addition of hydrogen-air volume flow rates of 6 and 8 LPM reduced CO emission levels by an average of 0.033% and 0.044% volume compared to neat diesel, and by 0.011% and 0.0218% volume compared to palm biodiesel (BD30). Partial and complete combustion lead to increased CO levels since the primary fuel takes more time to generate the fuel-air combination for combustion at the completion of the compression cycle [33]. Nonetheless, this problem is solved by incorporating hydrogen, which has a fast flame rate, and

Please cite this article as: Thiruselvam K et al., Hydrogen-enriched palm biodiesel as a potential alternative fuel for diesel engines: Investigating performance and emission characteristics and mitigation strategies for air pollutants, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.256

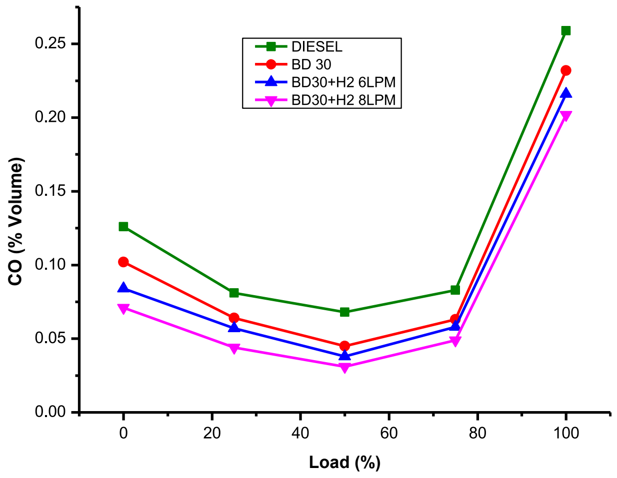


Fig. 6 – CO emission variation with load.

premature combustion can be avoided by combining at low speeds [34].

Hydrocarbon emission

In all load conditions, Fig. 7 shows that a lack of oxygen content in diesel results in a high unburned HC emission, when compared to the O_2 content of BD, blended with diesel. Incomplete combustion produces CO and HC emissions. The increasing load on the engine increases the fuel-to-air equivalence ratio and oxygen deficiency in the combustion zones, resulting in increased CO and HC emissions [31,47]. However, a small segment of the literature suggests that maintaining a higher temperature in the combustion chamber at full load reduces these emissions [52]. The engine explored in this research was a single-cylinder water-cooled engine, which was insufficient to maintain the higher combustion chamber temperature. As a result, in this study, the CO and HC emissions increase proportionally to the load. A blend of palm biodiesel reduced HC emissions by 14.8 ppm on average when compared to neat diesel. The addition of 6 and 8LPM hydrogen intake in the inlet manifold further reduced it to 23.6 and 29.2 ppm levels on average. Because hydrogen has a shorter quenching length than diesel, its inclusion reduces HC levels. It moves the flame closer to the cylinder wall, allowing for complete ignition. Additionally, hydrogen's considerable dispersion allows it to spread more freely into the air, enabling the production of a better and uniform fuel-air composition [17]. The increased oxygen content resulted in complete and cleaner combustion, and the higher cetane number reduced combustion delay, which was found to be responsible for biodiesel's reduced HC levels. The complete combustion was improved further by introducing enriched hydrogen and air into the inlet manifold.

Nitrogen oxide emission

The NOx levels in all the evaluated fuels were minimal as a result of the low temperature in part load conditions, as shown in Fig. 8. Except for diesel, all blended biodiesel has a maximum NOx emission above the part load. The cetane number, iodine value, and oxygen content of biofuel particles are all linked to NOx emissions during biofuel combustion [35,37]. The NOx produced by blended biodiesel (BD 30) is 146 ppm higher than that of neat diesel. Similarly, combining 6 and 8LPM of hydrogen with biodiesel produced average levels of 242 and 297.6 ppm higher than diesel. Hydrogen has nearly four times the calorific value of diesel fuel, and its high flammability is the cause of higher NOx emissions [36]. The increase in NOx levels is caused by increasing the hydrogen levels in the combustion chamber as cylinder pressure and HRR. Low-temperature combustion techniques can reduce NOx emissions, but they may increase smoke, CO, and fuel consumption.

Smoke opacity

The difference in smoke opacity for various tested fuel conditions is shown in Fig. 9. The addition of hydrogen 6 and 8LPM flow rate in the intake manifold along with a blend of biodiesel produced smoke at an average of 1.85% and 6.52% lower than neat diesel fuel, correspondingly at an average of 1.03% and 5.07% lower than palm biodiesel blend (BD30). Lower smoke

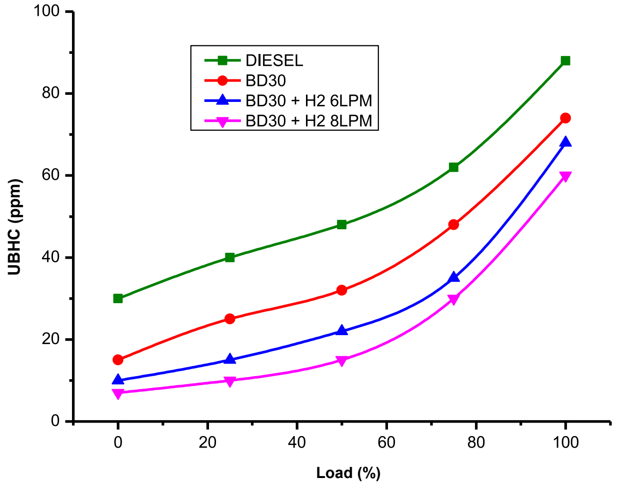


Fig. 7 – Hydrocarbon emission variation with load.

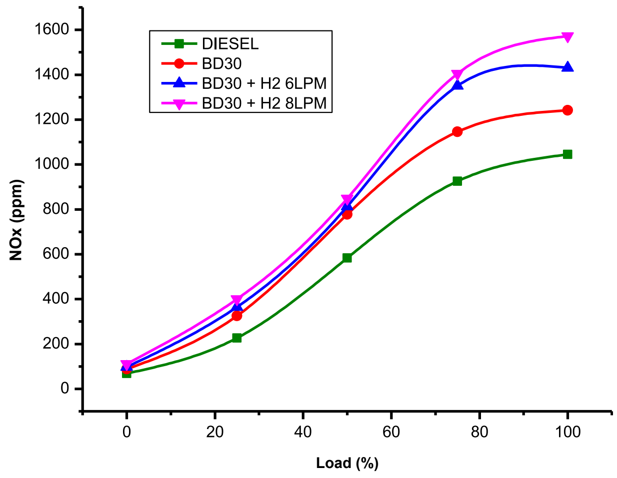


Fig. 8 – Nitrogen oxide emission variation with load.

Please cite this article as: Thiruselvam K et al., Hydrogen-enriched palm biodiesel as a potential alternative fuel for diesel engines: Investigating performance and emission characteristics and mitigation strategies for air pollutants, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.256

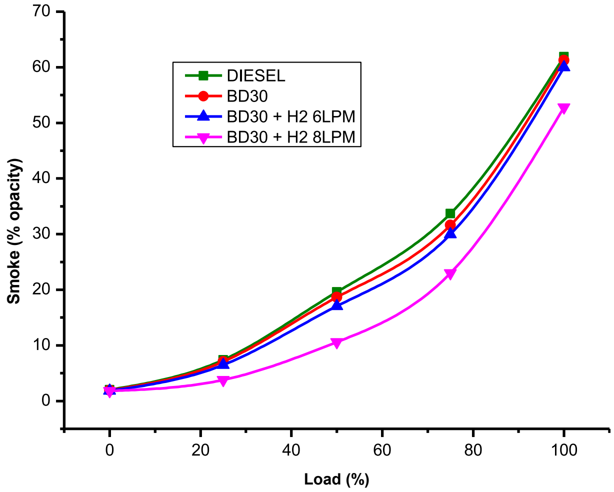


Fig. 9 – Smoke variation with load.

levels were attributed to oxidized fuel inhibiting soot deposition, improved soot oxidation with rapid responsiveness, and biodiesel fuels having significantly lower aromatic concentrations [38]. Furthermore, because hydrogen fuel contains no aromatic substances, it reduced smoke opacity emission to a greater extent by preventing incomplete combustion.

Conclusions

In this study, the efficiency of hydrogen-enriched palm biodiesel on the performance and emission parameters of the CI engine was studied. The engine was operated with palm biodiesel (PBD) and hydrogen induction through the intake air at flow rates of 6 and 8LPM. To attain the best results on performance and emission, a comparison was made on the CI engine using 6 and 8LPM addition of hydrogen flow rate along with PBD blends that are correlated with neat diesel fuel. The following conclusions were drawn.

- The SFC was minimized by an average of 13% and 19%, respectively.
- The BTE increased by an average of 3.38%.
- The CO levels were minimized by an average of 0.033% and 0.044% of volume, respectively.
- The HC levels were minimized by an average of 23.6 ppm and 29.2 ppm, respectively.
- The NOx emissions minimized by an average of 242 ppm and 297.6 ppm, respectively.
- The smoke opacity was lessened by an average of 1.852% and 6.52%, correspondingly.

The higher flammability and diffusion speed of hydrogen induction, along with the addition of palm biodiesel, lead to the conclusion that diesel engines can operate efficiently in lean mixtures and with reduced permissible amounts of pollutant gases, except NOx. The air pollution level from vehicular emissions can be reduced by the application of innovative and technical methods, and more so, with alternative fuels. As a result, the health illnesses caused by these air pollutants from vehicular emissions can be drastically minimized. This study can offer a technical foundation for developing efficient air pollution regulation measures as well as aid in understanding how vehicle emissions contribute to air pollution. Future studies must examine the influence of vehicle releases on O_3, their addition to VOCs, and the physical and chemical processes of local distribution of near-surface source releases.

The proposed approach of palm biodiesel blend (BD30) and hydrogen enrichment is not as cost-effective as neat diesel usage in CI engines due to the limited use of palm biodiesel blend and hydrogen enrichment. The utilization of 100% neat palm biodiesel in the engine with a properly designed fuel delivery system and a higher flow rate of hydrogen with a modification of the engine's desirable compression ratio, on the other hand, could be very cost-effective.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Declarations

This manuscript has been read and approved by all the authors, who have agreed to submit and publish it in this journal.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] Millo F, Bensaid S, Fino D, Marcano SJC, Vlachos T, Debnath BK. Influence on the performance and emissions of an automotive Euro 5 diesel engine fueled with F30 from Farnesane. Fuel 2014;138:134–42. https://doi.org/10.1016/j.fuel.2014.07.060.
[2] Amesho KTT, Lin YC, Chen CE, Cheng PC, Shangdiar S. Kinetics studies of sustainable biodiesel synthesis from Jatropha curcas oil by exploiting waste oystershells derived CaO-based heterogeneous catalyst via microwave heating system as a green chemistry technique. Fuel 2022;323:123876. https://doi.org/10.1016/j.fuel.2022.123876.
[3] Demirbas A. Biodiesel from waste cooking oil via base-catalytic and supercritical methanol transesterification. Energy Convers Manag 2009;50:923–7.
[4] Lang X, Dalai AK, Bakhashi N, Reaney M, Hertz P. Preparation and characterization of biodiesels from various bio-oils. Bioresour Technol 2001;80:53–62. https://doi.org/10.1016/S0960-8524(01)00051-7.
[5] Buyukkaya E. Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics. Fuel 2010;89:3099–105. https://doi.org/10.1016/j.fuel.2010.05.034.

[6] Peng YP, Amesho KTT, Chen CE, Jhang SR, Chou FC, Lin YC. Optimization of biodiesel production from waste-cooking-oil using waste eggshell as a base catalyst under the microwave heating system. Catalysts 2018;8(2). https://doi:10.3390/catal8020081.

[7] Millo F, Debnath BK, Vlachos T, Ciaravino C, Postrioti L, Buitoni G. Effects of different biofuels blends on performance and emissions of an automotive diesel engine. Fuel 2015;159:614–27. https://doi.org/10.1016/j.fuel.2015.06.096.

[8] Jhang SR, Chen KS, Lin SL, Lin YC, Amesho KTT, Chen CB. Evaluation of the reduction in carbonyl emissions and ozone formation potential from the exhaust of a heavy-duty diesel engine by hydrogen-diesel dual fuel combustion. Appl Therm Eng 2018;132(5):586–94. https://doi.org/10.1016/j.applthermaleng.2017.12.126.

[9] Lin YC, Amesho KTT, Chen CE, Chou FC, Cheng PC. A cleaner process for green biodiesel synthesis from waste-cooking-oil using oyster shells as a sustainable base heterogeneous catalyst under the microwave heating system. Sustainable Chemistry & Pharmacy 2020;17:100310. https://doi.org/10.1016/j.scp.2020.100310.

[10] McGartland MA, Philbert A, Qualters J. Case study: the palm oil example, roundtable on environmental health sciences, research, and medicine; board on population health and public health practice; institute of medicine. Washington (DC): National Academies Press (US); 2014.

[11] Devarajan Y, Mahalingam A, Munuswamy DB, Arunkumar T. Combustion, performance, and emission study of a research diesel engine fuelled with palm oil biodiesel and its additive. Energy Fuel 2018;32:8447–52.

[12] Mahalingam A, Munuswamy D, Devarajan Y, Radhakrishnan S. Investigation on the emission reduction technique in acetone-biodiesel aspirated diesel engine. Journal of Oil Palm Research 2008;30(2):345–9. https://doi.org/10.21894/jopr.2018.0020.

[13] Fangsuwannarak K, Triratanasirichai K. Improvements of palm biodiesel properties by using nano-TiO2 additive, exhaust emission and engine performance, the Romanian review precision mechanics. Optics & Mechatronics; 2013. p. 43. 2013.

[14] Joy N, Devarajan Y, Nagappan B, Anderson A. Exhaust emission study on neat biodiesel and alcohol blends fueled diesel engine. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 115-119 2017. https://doi.org/10.1080/15567036.2017.1405119.

[15] Kolbow JD, Lindquist NC, Ertsgaard CT, Yoo D, Oh SH. Nano-optical tweezers: methods and applications for trapping single molecules and nanoparticles. ChemPhysChem 2021;22(14):1409–20. https://doi.org/10.1002/cph.

[16] Samuel S, McCormick G. Hydrogen enriched diesel combustion. 2010. https://doi.org/10.4271/2010-01-2190. SAE Technical Paper 2010-01-2190.

[17] Mathur HB, Das LM, Patro TN. Hydrogen fuel utilization in CI engine powered end utility systems. Int J Hydrogen Energy 1992;17(5):369–74. https://doi.org/10.1016/0360-3199(92)90174-U.

[18] Verhelst S, Wallner T. Hydrogen-fuelled internal combustion engines. Prog Energy Combust Sci 2009;35:490–527. https://doi.org/10.1016/j.pecs.2009.08.001.

[19] Suzuki Y, Tsujimura T. The combustion improvements of hydrogen/diesel dual fuel engine. 2015. https://doi.org/10.4271/2015-01-1939. SAE Technical Paper 2015-01-1939.

[20] Chang KL, Amesho KTT, Lin YC, Jhang SR, Chou FC, Chen HC. Effects of atmospheric-plasma system on energy efficiency improvement and emissions reduction from a diesel engine. J Environ Manag 2019;234:336–44. https://doi.org/10.1016/j.jenvman.2019.01.017.

[21] Dincer Akal, Oztuna Semiha, Buyukakın Mustafa Kemalettin. A review of hydrogen usage in internal combustion engines (Gasoline-Lpg-Diesel) from combustion performance aspect. Int J Hydrogen Energy 2020;45(60):35257–68. https://doi.org/10.1016/j.ijhydene.2020.02.001.

[22] Dimitriou P, Tsujimura T. A review of hydrogen as a compression ignition engine fuel. Int J Hydrogen Energy 2017;42:24470–86. https://doi.org/10.1016/j.ijhydene.2017.07.232.

[23] Korn T, Nobile RF, Grassinger D. Zero-emission, maximum performance-the latest generation of hydrogen combustion engines. In: Proceedings of the 42nd international vienna motor symposium, vienna, Austria, 29–30 april 2021; 2021.

[24] Pauer T, Weller H, Schünemann E, Eichlseder H, Grabner P, Schaffer K. H2 ICE für Zukünftige PKWs und Leichte Nutzfahrzeuge. In: Proceedings of the 41st internationales wiener motorensymposium, vienna, Austria, 22–24 april 2020; 2020.

[25] Boretti A. Transient positive ignition internal combustion engines have now surpassed the 50% fuel conversion efficiency barrier. Int J Hydrogen Energy 2019;44:7051–2. https://doi.org/10.1016/j.ijhydene.2019.01.237.

[26] Devarajan Y, Munuswamy DB, Mahalingam A, Nagappan B. Performance, combustion, and emission analysis of neat palm oil biodiesel and higher alcohol blends in a diesel engine. Energy Fuel 2017;31(12):13796–801. https://doi.org/10.1021/acs.energyfuels.7b02939.

[27] Devarajan Y, Radhakrishnan S, Mahalingam A, Nagappan B. Emission analysis on Diesel engine fuelled with palm oil biodiesel and Pentanol blends. Journal of Oil Palm Research 2017;29(3):380–96. https://doi.org/10.21894/jopr.2017.2903.11.

[28] Ilbas M, Crayford AP, Yılmaz I, Bowen PJ, Syred N. Laminar-burning velocities of hydrogen–air and hydrogen–methane–air mixtures: an experimental study. Int J Hydrogen Energy 2006;31:1768–79. https://doi.org/10.1016/j.ijhydene.2005.12.007.

[29] Akar MA, Kekilli E, Bas O, Yildizhan S, Serin H, Ozcanli M. Hydrogen enriched waste oil biodiesel usage in compression ignition engine. Int J Hydrogen Energy 2018;43(38):18046–52. https://doi.org/10.1016/j.ijhydene.2018.02.045.

[30] White CM, Steeper RR, Lutz AE. The hydrogen-fueled internal combustion engine: a technical review. Journal of Hydrogen Energy 2006;31:1292–305. https://doi.org/10.1016/j.ijhydene.2005.12.001.

[31] Muthukumaran N, Saravanan CG, Yadav SPR, Vallinayagam R, Vedharaj S, Roberts WL. Synthesis of cracked Calophyllum inophyllum oil using fly ash catalyst for diesel engine application. Fuel 2015;155:68–76. https://doi.org/10.1016/j.fuel.2015.04.014.

[32] Karavalakis G, Johnson KC, Hajbabaei M, Durbin TD. Application of low-level biodiesel blends on heavy-duty (diesel) engines: feedstock implications on NOx and particulate emissions. Fuel 2016;181:259–68. https://doi.org/10.1016/j.fuel.2016.05.001.

[33] Yadav VS, Sharma D, Soni SL. Performance and combustion analysis of hydrogen-fuelled C.I. engine with EGR. Int J Hydrogen Energy 2015;40(12):4382–91. https://doi.org/10.1016/j.ijhydene.2015.01.162.

[34] Geo VE, Nagarajan G, Nagalingam B, Aloui F, Tazerout M. A comparative analysis of different methods to improve the performance of rubber seed oil fuelled compression ignition engine. Fuel 2020;280:118644. https://doi.org/10.1016/j.fuel.2020.118644.

[35] Pullen J, Saeed K. Factors affecting biodiesel engine performance and exhaust emissions – Part II: experimental study. Energy 2014;72:17–34. https://doi.org/10.1016/j.energy.2014.02.034.

Please cite this article as: Thiruselvam K et al., Hydrogen-enriched palm biodiesel as a potential alternative fuel for diesel engines: Investigating performance and emission characteristics and mitigation strategies for air pollutants, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.256

[36] Dimitriou P, Tsujimura T. Evaluation of hydrogen as a compression ignition engine fuel. Int J Hydrogen Energy 2017;42(38):24470–86. https://doi.org/10.1016/j.ijhydene.2017.07.232.

[37] Anbu M, Balakichenin R, Muthaiyan P, Sundaramoorthy S, Amesho KTT, Subramani V. Experimental investigation on the performance characteristics and emissions of a CI engine fueled with enhanced microwave-assisted Karanja seed bio-oil. Environ Sci Pollut Res 2022. https://doi.org/10.1007/s11356-022-24283-z.

[38] Senthil Kumar TS, Kumar PS, Annamalai K. Experimental study on the performance and emission measures of direct injection diesel engine with Kapok methyl ester and its blends. Renew Energy 2015;74:903–9. https://doi.org/10.1016/j.renene.2014.09.022.

[39] Krishnamoorthi T, Vinayagasundram G. Performance and emission characteristics analysis of thermal barrier coated diesel engine using palm biodiesel. Environ Sci Pollut Control Ser 2019;26(9):9176–92. https://doi.org/10.1007/s11356-019-04637-w.

[40] Shi C, Chai S, Di L, Ji C, Ge Y, Wang H. Combined experimental-numerical analysis of hydrogen as a combustion enhancer applied to Wankel engine. Energy 2023;263:125896. https://doi.org/10.1016/j.energy.2022.125896. Part C).

[41] Shi Cheng, Zhang Peng, Ji Changwei, Di Liming, Zhu Zhaojun, Wang Huaiyu. Understanding the role of turbulence-induced blade configuration in improving combustion process for hydrogen-enriched rotary engine. Fuel 2022;ume 319. https://doi.org/10.1016/j.fuel.2022.123807.

[42] Akar Mustafa Atakan, Kekilli Emine, Bas Oguz, Yildizhan Safak, Hasan Serin, Mustafa Ozcanli. Hydrogen enriched waste oil biodiesel usage in compression ignition engine. Int J Hydrogen Energy 2018;43(38):18046–52. https://doi.org/10.1016/j.ijhydene.2018.02.045. 20 September 2018.

[43] Korakianitis T, Namasivayam AM, Crookes RJ. Hydrogen dual-fuelling of compression ignition engines with emulsified biodiesel as pilot fuel. Int J Hydrogen Energy December 2010;35(Issue 24):13329–44. https://doi.org/10.1016/j.ijhydene.2010.08.007.

[44] Stepie'n ZA. Comprehensive overview of hydrogen-fueled internal combustion engines: achievements and future challenges. Energies 2021;14:6504. https://doi.org/10.3390/en14206504.

[45] Lee KJ, Kim YR, Byun CH, Lee JT. Feasibility of compression ignition for hydrogen fueled engine with neat hydrogen-air pre-mixture by using high compression. Int J Hydrogen Energy 2013;38:255–64. https://doi.org/10.1016/j.ijhydene.2012.10.021.

[46] Dimitriou Pavlos, Tsujimura Taku. A review of hydrogen as a compression ignition engine fuel. Int J Hydrogen Energy 2017;42(38):24470–86. https://doi.org/10.1016/j.ijhydene.2017.07.232.

[47] Ozcanli Mustafa, Akar Mustafa Atakan, Calik Ahmet, Hasan Serin. Using HHO (Hydroxy) and hydrogen enriched castor oil biodiesel in compression ignition engine. Int J Hydrogen Energy 7 September 2017;42(Issue 36):23366–72. https://doi.org/10.1016/j.ijhydene.2017.01.091.

[48] Uludamar Erinc, Yıldızhan Safak, Aydın Kadir, Ozcanlı Mustafa. Vibration, noise and exhaust emissions analyses of an unmodified compression ignition engine fuelled with low sulphur diesel and biodiesel blends with hydrogen addition. Int J Hydrogen Energy 2016;41(26):11481–90. https://doi.org/10.1016/j.ijhydene.2016.03.179.

[49] Uludamar E. Effect of hydroxy and hydrogen gas addition on diesel engine fuelled with microalgae biodiesel. Int J Hydrogen Energy 2018. https://doi.org/10.1016/j.ijhydene.2018.01.075.

[50] I.T. Yilmaz, A. Demir, M. Gumus, Effects of hydrogen enrichment on combustion characteristics of a.

[51] Ogunkoya D, Roberts WL, Fang T, Thapaliya N. Investigation of the effects of renewable diesel fuels on engine performance, combustion, and emissions. Fuel 2015;140(5):541–54. https://doi.org/10.1016/j.fuel.2014.09.061.

[52] Ritchie H, Roser M. Forests and deforestation. 2021. OurWorldInData.org. Retrieved from: https://ourworldindata.org/forests-and-deforestation [Online Resource].

[53] Veza I, Zainuddin Z, Tamaldin N, Idris M, Irianto I, Fattah IMR. Effect of palm oil biodiesel blends (B10 and B20) on physical and mechanical properties of nitrile rubber elastomer. Results in Engineering 2022;16:100787. https://doi.org/10.1016/j.rineng.2022.100787.

[54] Kumar RS, Loganathan M, Gunasekaran EJ. Performance, emission and combustion characteristics of CI engine fuelled with diesel and hydrogen. Front Energy 2015;9(4):486–94.

[55] Pullagura G, Kumar KR, Verma PC, Jaiswal A, Prakash R, Murugan S. Experimental investigation of hydrogen enrichment on performance and emission behaviour of compression ignition engine. Int J Eng Sci Technol 2012;4(4):1223–32.

[56] Saravanan N, Nagarajan G, Kalaiselvan KM, Dhanasekaran C. An experimental investigation on hydrogen as a dual fuel for diesel engine system with exhaust gas recirculation technique. Renew Energy 2008;33(3):422–7.

[57] Gnanamoorthi V, Vimalananth VT. Effect of hydrogen fuel at higher flow rate under dual fuel mode in CRDI diesel engine. Int J Hydrogen Energy 2020;45(29):14806–20.

[58] Castro N, Toledo M, Amador G. An experimental investigation of the performance and emissions of a hydrogen-diesel dual fuel compression ignition internal combustion engine. Appl Therm Eng 2019;156:660–7.

[59] Kumar RS, Loganathan M, Gunasekaran EJ. Performance, emission and combustion characteristics of CI engine fuelled with diesel and hydrogen. Front Energy 2015;9(4):486–94.

[60] Kumar CB, Lata DB, Mahto D. Analysis of ignition delay by taking Di-tertiary-butyl peroxide as an additive in a dual fuel diesel engine using hydrogen as a secondary fuel. Int J Hydrogen Energy 2020;45(29):14806–20.

[61] Jamrozik A, Grab-Rogalinski K, Tutak W. Hydrogen effects on combustion stability, performance and emission of diesel engine. Int J Hydrogen Energy 2020;45(38):19936–47. https://doi.org/10.1016/j.ijhydene.2020.03.155.

[62] Saravanan N, Nagarajan G, Narayanasamy S. An experimental investigation on DI diesel engine with hydrogen fuel. Renew Energy 2008;33(3):415–21. https://doi.org/10.1016/j.renene.2007.05.004.

[63] Karagoz Y, Sandalcı T, Yüksek L, Dalkılıç AS. Engine performance and emission effects of diesel burns enriched by hydrogen on different engine loads. Int J Hydrogen Energy 2015;40(20):6702–13. https://doi.org/10.1016/j.ijhydene.2015.03.132.

[64] Zhou JH, Cheung CS, Leung CW. Combustion, performance, regulated and unregulated emissions of a diesel engine with hydrogen addition. Appl Energy 2014;126:1–2. https://doi.org/10.1016/j.apenergy.2014.03.055.

[65] Kumar MS, Ramesh A, Nagalingam B. Use of hydrogen to enhance the performance of a vegetable oil fuelled compression ignition engine. Int J Hydrogen Energy 2003;28(10):1143–54. https://doi.org/10.1016/S0360-3199(03)00048-9.

[66] Verma S, Suman A, Das LM, Kaushik SC, Tyagi SK. A renewable pathway towards increased utilization of hydrogen in diesel engines. Int J Hydrogen Energy 2020;45(8):5577–87. https://doi.org/10.1016/j.ijhydene.2020.01.108.

[67] Loganathan M, Madhavan VM, Balasubramanian KA, Thanigaivelan V, Vikneswaran M, Anbarasu A. Investigation on the effect of diethyl ether with hydrogen-enriched cashew nut shell (CNS) biodiesel in direct injection (DI) diesel engine. Fuel 2020;277:118165. https://doi.org/10.1016/j.fuel.2020.118165.

[68] Serin H, Yıldızhan S. Hydrogen addition to tea seed oil biodiesel: performance and emission characteristics. Int J Hydrogen Energy 2018;43(38):18020–7. https://doi.org/10.1016/j.ijhydene.2018.08.117.

Please cite this article as: Thiruselvam K et al., Hydrogen-enriched palm biodiesel as a potential alternative fuel for diesel engines: Investigating performance and emission characteristics and mitigation strategies for air pollutants, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2023.04.256