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Exploring the impact of aluminum oxide nanoparticles on waste transformer biodiesel blend under variable injection timing

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Abstract

This study investigated the use of nano-blended biodiesel, made by mixing waste transformer biodiesel with nanoscale aluminum oxide particles. A fuel blend ratio containing both diesel and biodiesel components was created with 100 parts per million of alumina nanoparticles. All tests were conducted at various loads in an engine, using diesel, biodiesel, and nano-blended biodiesel fuel. The outcomes demonstrated that adding nanoparticles improved engine thermal efficiency and reduced emissions, especially at higher fuel injection timings. The greatest increase in brake thermal efficiency, 6% higher than diesel mode, was achieved with a nano-blended biodiesel formulation containing 100 ppm of aluminum oxide, at a fuel injection timing of 27 before top dead center under full load conditions. With a constant nanoparticle-blended biodiesel content and fuel injection timing of 27 before top dead center, reductions of 1.5% in smoke, 33% in hydrocarbon, and 8% in carbon monoxide emissions were observed, with a 9.7% increase in NO emissions.

Keywords Waste transformer oil, Fuel injection timing, Alumina nanoparticle, Before top dead center, Emission

Introduction

The current situation, marked by dwindling fossil fuel reserves (Michaelides, 2024) and increasing fuel costs (Mirjalili et al., 2023), has led to a surge in interest in identifying the most efficient alternative fuels for internal combustion engines. Biodiesel, produced from both edible and non-edible seed oils, emerges as a leading contender (Hassan et al., 2015; Kennedy et al., 2015; Thiruvengadaravi et al., 2012). Considering various fuel choices for compression ignition engines, a blend of biodiesel and standard diesel stands out as the most practical option, largely because it requires the fewest engine modifications. Moreover, these biodiesel blends have a sufficient oxygen content and exhibit thermophysical properties on par with those of conventional diesel fuel (Sarin et al., 2009; Vallinayagam et al., 2014). However, the utilization of biodiesel does have its constraints. These stem from its lower energy content in comparison to diesel, as well as its elevated viscosity and density. Moreover, it leads to heightened fuel consumption and increased emissions of nitrogen oxides. To mitigate these constraints, biodiesel can be enhanced with a range of chemicals. The additives fall into distinct categories, including nanoparticles, metal-based compounds, antioxidants, oxygenated additives, and agents for optimizing cold flow properties. Given the absence of a commercially viable and universally recognized bio-based fuel alternative to fully swap diesel, a great deal of attention has been furnished on additives that can improve combustion and reduce levels of pollution when blended with diesel. As a sustainable energy source, additionally, biodiesel has the ability to lessen engine emissions through sustainable recycling. In both diesel and biodiesel environments, nanoparticles have emerged as a unique and

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notable choice for supplements. As a result, the utilization of fuel incorporating nanotechnology, particularly in internal combustion engines, has drawn considerable attention in the fields of mobility and energy generation. The performance of engines, efficiency, and pollution parameters are all noticeably improved by nano-based fuel (Tamilarasan et al., 2015). Nano-based fuel performs a supplementary function in energy transfer by acting as a conduit for energy while acting as a catalyst within the fuel (Acharya et al., 2017). This is addressed by the numerous advantageous characteristics of nanoparticles, including their higher energy density, substantial surface area-to-volume ratio, augmented availability of active sites crucial for multiple processes and effects, heightened catalytic reaction rate, and enhanced catalytic activity (Contreras et al., 2017). Various nano-additives (Basha & Anand, 2013; Prabu, 2018; Prabu & Anand, 2016; Selvan et al., 2014) have been identified thus far, indicating potential enhancements in engine efficiency and level of pollutants. (Soudagar et al., 2020), demonstrated that incorporating more aluminum oxide into an 80% diesel and 20% biodiesel, B20 blend resulted in a significant reduction in ignition retardation and combustion span. This adjustment also led to elevated piston pressure, greater heat transfer rate, and an increase in emissions of carbon monoxide (CO) and hydrocarbons (HC). However, there was an observed rise in nitric oxide (NO) emissions. (Nouri et al., 2021) investigated the influence of introducing Aluminum oxide (Al_2O_3) nanoparticles on the engine's performance parameters. The inclusion of nano-Al_2O_3 resulted in reduced fuel consumption alongside enhanced engine performance. Furthermore, the emissions of NO and CO declined as the quantity of Al_2O_3 nanoparticles increased. The introduction of nano-aluminum oxide into diesel demonstrated improved brake thermal efficiency compared to B20 fuel. Furthermore, when comparing it to B20 fuel, the B20 blend with 75 ppm of Al_2O_3 exhibited a 17% reduction in fuel consumption, a 21% reduction in the emissions of CO, and a 23% reduction in the emissions of HC (Channappagoudra, 2021). Elevating injection pressures and introducing nanoparticles led to a 14% reduction in the emissions of HC and 15% reduction in NO emissions from the diesel–*Eichhornia crassipes* biodiesel blend (Khan et al., 2022). Improving engine characteristics when using biodiesel blends necessitates a thorough examination of engine operational parameters such as compression ratio, fuel injection timing, and injection pressure (Channapattana et al., 2016).

Due to its higher density and lower volatility in contrast to other alternative fuels, biodiesel requires additional time and a higher self-ignition temperature for achieving cleaner combustion. This underscores its significance as a crucial engine factor in determining the appropriate fuel injection timing (Ozsezen et al., 2009). The engine emission and performance are substantially influenced by the fuel injection timings. The level of nitrogen oxide emissions in a fuel injection system can be minimized using various techniques, which encompass fine-tuning injection timing, adjusting injection rate, and optimizing injection pressure. Several studies have demonstrated that the timing of injection impacts the quantity of gaseous pollutants generated by the engines. Compared to delayed injection, employing advanced injection timing resulted in elevated NO emissions and reduced levels of CO, HC (Shuai et al., 2009), and soot pollutants (Huang et al., 2015). Zhu et al., (2014) utilized rapid fuel injection timing to achieve an improved equilibrium between emissions and efficiency. Cheng et al., (2016) observed that both early and late injections, due to their prolonged premixed period, resulted in decreased soot emissions. Raeie et al., (2014) reported that advancing the fuel injection timing leads to lower soot emissions and higher levels of NO pollutants compared to delayed injection. By adjusting the fuel injection timing in engines running on biodiesel, combustion can be initiated sooner, leading to an increase in cylinder temperature. This, in turn, results in a reduction of engine emissions (Bora & Saha, 2016). Conversely, delaying the fuel injection timing results in a reduced combustion time and a decline in the thermal efficiency and NO emissions (Agarwal et al., 2013).

Krupakaran et al. (2020a) conducted investigations into engine output and emission parameters by varying injection timing with B20 fuel (comprising 20% *Mimusops elengi* methyl ester and 80% diesel). Experimental trials involved introducing 25 ppm concentration of TiO_2 nanoparticles into the B20 fuel, and adjusting the engine injection timing both in advance and retardation. Advancing the injection timing resulted in enhanced brake thermal efficiency, reduced smoke emission and a slight increase in NO emissions. Conversely, retarding the engine injection timing led to increased CO and HC emissions.

While previous research has investigated how the timing of fuel injection affects the efficiency and emissions of internal combustion engines, the current experimental study underscores a significant research gap in understanding the synergies between the timing of fuel injection and the introduction of alumina nanoparticles in waste transformer biodiesel/diesel blends. The uniqueness of this research lies in opting for waste transformer biodiesel enriched with alumina nanoparticles, which was then subjected to experimentation involving various fuel injection timings. The objective of this current study is to carry out experimental research to examine how changes the timing of fuel injection influences the engine characteristics of efficiency and emission, when utilizing alumina nanoparticles in waste transformer biodiesel/diesel blends.

Materials' section

Transesterification of waste transformer oil

Waste transformer oil was recovered from a diesel power facility. The waste transformer oil employed in this study possesses high viscous golden-brown hue, containing a substantial proportion of hydrocarbon constituents. The viscosity of the waste transformer oil is notably high, potentially resulting in suboptimal atomization and hindering its effective use in the engine. Several techniques have been investigated to tackle this concern, including catalytic cracking, pyrolysis, oil preheating, catalyzed transesterification, and mixing it with diesel. In this research, two methods, specifically catalyzed transesterification and diesel blending, were utilized to meet American Society for Testing and Materials (ASTM) standards, enabling its use as diesel engine fuel. The study employed fuel generated through the transesterification of old transformer oil using potassium hydroxide (KOH) and methanol (CH_3OH). One liter of previously used oil from transformer was mixed with 12 g of KOH that had been dissolved in 210 ml of methanol after being heated to 60 °C for 40 min. The mixture was gently stirred for 20 min to facilitate the separation of water. After allowing it to settle, the mixture was then processed to separate the water and other fatty oils, resulting in the isolation of the transesterified waste transformer oil. Figure 1 displays the prepared transesterified waste transformer oil. Table 1 lists the characteristics of diesel and used transformer oil.

Test procedure

Studies suggest that the integration of nanoparticles into biodiesel improves engine combustion and overall engine operational efficiency. The aim of this study is to assess the influence of a novel fuel, specifically B25 blends (consisting of 25% waste transformer biodiesel and 75% diesel), enriched with 100 parts per million (ppm) of aluminum oxide nanoparticles, on the performance of a diesel engine. Simultaneously, an emissions analysis will be conducted. Furthermore, a research study was conducted to evaluate the impact of different fuel injection timings bTDC (before top dead center) at normal (23 bTDC), advanced (19 bTDC), and retarded (27 bTDC) engine operated conditions. This study involved the use of a mixture of biodiesel (B25), alumina nanoparticle-enhanced B25 blend and diesel fuel. This study stands out for employing a fuel mixture containing 25% waste transformer oil (WTO) and diesel in diesel engines, while also integrating aluminum oxide.

Fig. 1 Transesterified waste transformer oil

Experimental segment

Assessment of fuel characteristics

The study involves an assessment of the physical and thermal parameters of the waste oil from transformer. Furthermore, an FTIR analysis is conducted to identify functional categories and conduct a compositional study.

Fourier transform infrared (FTIR) evaluation

Figures 2 and 3 exhibit the spectra of FTIR for conventional diesel and WTO. The prominent absorption peaks at 2922.11 and 2850.18 cm^{-1} correspond to stretching of C–H bond noticed when using diesel fuel. The robust absorbance peaks at 2920.20 $cm^{¯}1$ and 2851.26 cm^{-1} observed in the transformer oil indicate stretching of

Table 1 Properties of test fuels

Properties	Standard methods	D100	WTO100	B25	Accuracy
Kinematic viscosity at 40 °C (mm^2/s)	ASTM D445	2.85	11.1	3.89	±0.35
Density (g/m^3)	ASTM D941	0.829	0.852	0.857	±0.1
Flash point (°C)	ASTM D92	37	144	58	±0.1
Fire point (°C)	ASTM D92	40	151	67	±0.1
Calorific value (MJ/kg)	ASTM D240	41.8	42	41.9	±0.1
Cetane Number	ASTM D613	52.8	52.1	52.5	±0.5

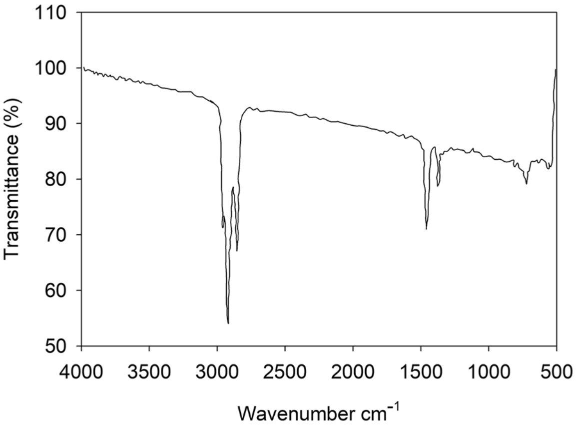

Fig. 2 FTIR analysis of diesel

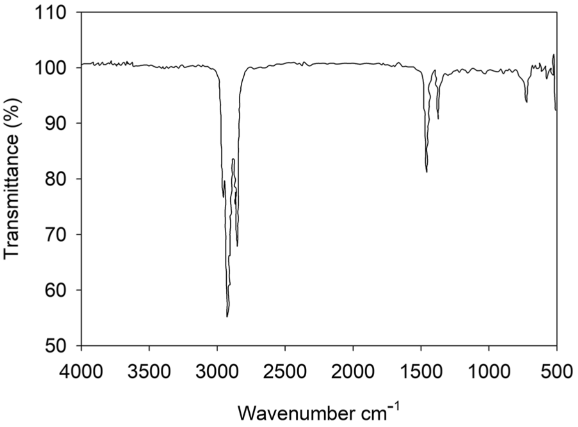

Fig. 3 FTIR analysis of waste transformer oil

Table 2 FTIR analysis of waste transformer oil and diesel

Waste transformer oil		
Bond	**Family**	**Frequency range (cm^{-1})**
C–H bend	Alkanes	654.39
C–X	Fluoride	1348.75
C–H bend	Alkanes	1457.16
C–H Stretch	Alkanes	2920.20–2851.26
Diesel		
C–H bend	Alkanes	752.0
C–X	Fluoride	1375.32
C–H bend	Alkanes	1458.01
C–H Stretch	Alkanes	2922.11–2850.18

Table 3 Engine specifications

Make/model	Kirloskar TV1
Brake power (kW)	5.2
Speed (rpm)	1500
Cylinder bore (mm)	87.50
Stroke length (mm)	110
Swept volume	661.45 (cc)
Compression ratio	17.5:1
Injection timing	23 bTDC
Injection pressure	215 bar

C–H bond. The presence of alkanes is confirmed by the peaks in absorbance at 1457.16 cm^{-}1 for bending C–H bond and at 654.39 cm^{-}1 for the C–H out-of-plane bend. The FTIR graph indicates that the main transmittance spectrum peaks for both fuels correspond to alkanes. As discussed earlier, both oils are ample with hydrocarbons. Given the existence of C–H bond categories in the liquid, it suggests its potential as a viable fuel source. Table 2 presents the chemical families and bond types for the waste transformer oil and diesel fuel, respectively.

Engine analysis

Table 3 outlines the specifications of the study's Kirloskar TV-I compression ignition engine, which is a direct injection system, one piston, quad stroke, steady speed, straight up, water cooled system. The engine was connected to a dynamometer based on eddy current technology, which imposed varying loads. The configuration used for the experiment is depicted in Fig. 4. Engine injection timing was adjusted by altering the shim

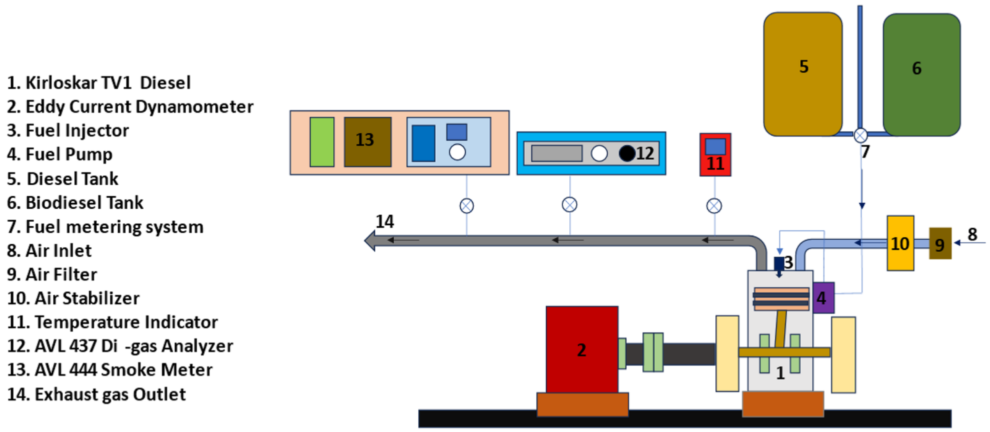

Fig. 4 Configuration of the experimental setup

thickness at the base of the fuel pump. More specifically, a reduction of 0.3 mm in shim thickness leads to a 2° crank angle advancement in engine injection timing.

To keep tracking the temperature of the exhaust gas, chromel–aluminum (k-type) thermostats was fitted at the outflow ducts. The engine speed was calculated using a frequency-modulated meter and an internal magnetic pickup transducer. Nitric oxide (NO), carbon monoxide (CO), and hydrocarbon (HC) levels were quantified using the Di gas analyzer of model AVL 444, while the intensity of smoke was recorded using a smoke meter of model AVL 413. The exhaust gas analyzer and smoke meter specifications are listed in Table 4.

During each phase, the temperature of the cold water was kept constant as the combustion process initiated and gradually warmed up. Subsequently, under various engine loads, consumption of fuel (BSFC), engine exhaust temperature (EGT), and pollutants including nitric oxide, along smoke and carbon monoxide were measured and recorded. The examinations were conducted over three sessions, each spanning 3 h. The final calculations were determined based on the average value obtained from these three readings.

Uncertainty assessment

Equipment selection, ambient factors, calibration, testing protocols, measurements, and the method of recording are the possible sources of uncertainty and mistake. It is important to note that reproducibility inherently involves a degree of uncertainty, and random errors can be assessed through analytical calculations. Table 5 furnishes details regarding the instruments employed. The computation for this experiment's overall percentage of

Table 4 Exhaust gas analyzer and smoke meter specifications

Digas 444 gas analyzer

Make	**AVL**
Measuring method	CO, CO$_2$, HC, NDIR method NO, O$_2$—electrochemical method
Measuring parameter	CO, CO$_2$, O$_2$, HC, NO, λ
Measuring range and resolution	CO—0…10% vol and 0.01% CO$_2$—0…20% vol and 0.1% NO$_X$—0…5000 ppm vol and 1 ppm vol HC—0…20,000 ppm and 1 ppm vol λ—0…9.999 and 0.001%
Power consumption	About 25 W
Operating temperature	5–50 ℃
Response time	Within 15 s
Voltage	22 V DC
Interfaces	RS 232 communication cable, printer
Relative humidity	≤ 95%, non-condensing
Bosch smoke meter	
Type and make	Type and make T1 diesel tune, 114-smoke density tester T1
Calibrated reading	5.0 ± 0.2
Range	0–10 Bosch Smoke Number
Minimum time period	30 cc
Stabilization time	2 min

Table 5 Uncertainty of engine parameters and instruments

Measurement	Accuracy	% Uncertainty
Fuel consumption	± 0.2 cc	± 1.2
Engine load	± 10 N	± 0.2
Exhaust gas temperature	± 2 ℃	± 1
Engine speed	± 10 rpm	± 1 rpm
CO	± 0.02%	± 0.1
HC	± 10 ppm	± 0.1
NO	± 12 ppm	± 1
Smoke density	± 1	± 0.5

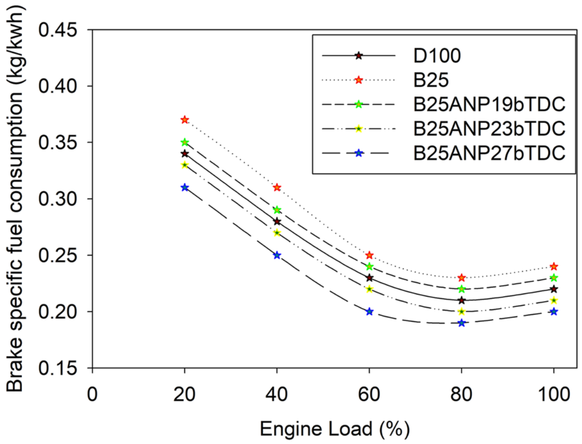

Fig. 5 Variation of brake-specific fuel consumption against engine load

uncertainty (Krupakaran et al., 2020b; Prabu, 2024) is shown as follows:

$$
\begin{aligned}
&\text{Comprehensive uncertainty} \\
&\quad = [(\mathrm{HC})^2 + (\mathrm{CO})^2 + (\mathrm{NO})^2 \\
&\qquad + \left(\text{Smoke Opacity}\right)^2 \\
&\quad + (\mathrm{EGT})^2 + (\mathrm{BSFC})^2 + (\mathrm{BTE})^2]^{1/2} \\
&= \Big[(0.1)^2 + (0.1)^2 + (1)^2 + (0.5)^2 \\
&\qquad + (0.5)^2 + (0.01)^2 + (1)^2\Big]^{1/2} \\
&= \pm 1.58\%.
\end{aligned}
$$

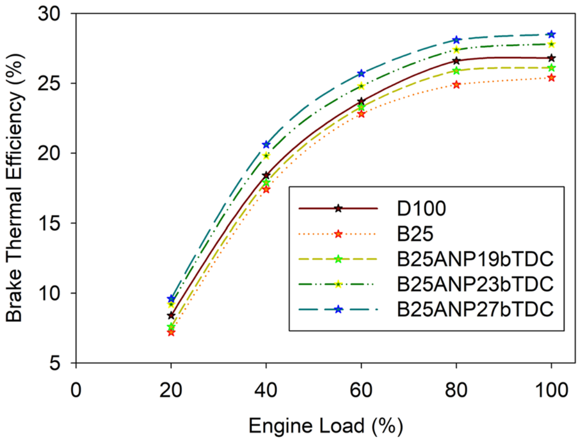

Fig. 6 Variation of brake thermal efficiency against engine load

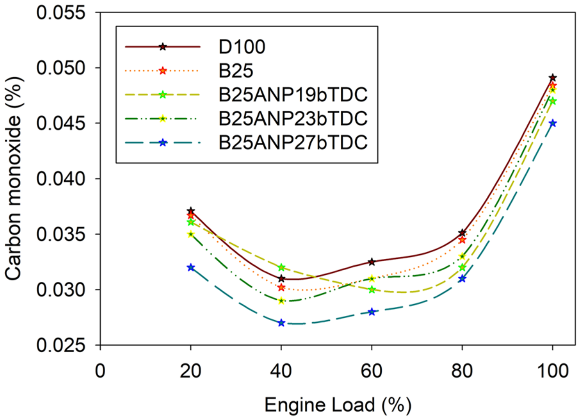

Fig. 7 Variation of CO emission against engine load

Outcomes and evaluations

Performance evaluation

Figure 5 depicts how brake-specific fuel consumption (BSFC) of nanoparticle dispersed waste transformer biodiesel changes for both conventional, advanced and delayed injection timing. In contrast to B25ANP19bTDC, which indicates advanced injection timing, and B25ANP27bTDC, which represents delayed advanced timing, the graphs D100, B25, and B25ANP23bTDC reflect standard injection timing. At minimal load, the B25ANP27bTDC, characterized by delayed injection timing, exhibits a brake-specific fuel consumption ranging from 0.32 kg/kWh to 0.20 kg/kWh at maximum load. Regarding the B25ANP19bTDC, the BSFC ranges from 0.34 kg/kWh at minimal load to 0.23 kg/kWh with advanced injection timing. The delayed injection timing resulted in a postponed combustion process, leading to increased fuel consumption to maintain a constant engine speed (Nghia et al., 2022).

Figure 6 illustrates how the BTE of nanoparticle dispersed waste transformer biodiesel varies with both conventional, advanced and delayed injection timing. The engine demonstrates an enhanced brake thermal efficiency (BTE) when running on B25ANP27bTDC with delayed injection timing. The graph illustrates that under standard injection timing, the thermal efficiency for B25ANP23bTDC is 27.8% at maximum load, whereas with delayed injection timing, it increases to 28.5% for B25ANP27bTDC. This may be accounted for by the fact that delaying the injection timing prompts a swifter initiation of the combustion process, sustaining it further into the power stroke. This leads to thorough combustion, enabling the operation with delayed injection timing while still attaining heightened efficiency.

Emission analysis

Figure 7 illustrates the variation in emissions of CO, from waste transformer biodiesel dispersed with nanoparticles, comparing conventional, advanced and delayed injection timing. When employing delayed injection timing, B25ANP27bTDC allows ample time for the excess oxygen content of the waste transformer biodiesel to thoroughly blend with the air. The combustion of waste transformer biodiesel has the capacity to reduce CO emissions by transforming a portion of it into CO_2 through the absorption of excess oxygen molecules during the process (Kidoguchi et al., 2000; Oner & Altun, 2009).

Figure 8 illustrates the variation in smoke emissions from waste transformer biodiesel with dispersed nanoparticles, comparing both conventional, advanced and delayed injection timing. As per the chart, under conventional injection timing, smoke emissions for B25ANP23bTDC reach 60% at maximum load. However, with delayed injection timing in B25ANP27bTDC, it slightly decreases to 58%. The potential increase could be given credit for the aromatic component in the biodiesel derived from waste transformers.

Figure 9 contrasts conventional, delayed and advanced injection timing to demonstrate the variation in HC emissions when using waste transformer biodiesel with dispersed nanoparticles. As indicated in the chart, under standard injection timing and at peak load, B25ANP23bTDC shows a measurement of 38 ppm for HC emissions. Despite this, utilizing delayed injection timing in B25ANP27bTDC leads to a marginal reduction to 34 ppm. More combustible regions created in the combustion chamber prior to the premixed combustion phase results in the improved injection timing. This facilitated extensive blending, which increased the possibility of complete combustion and reduced the levels of hydrocarbon pollutants (Hossain et al., 2013). Conversely, with advanced injection timing (B25ANP19bTDC), the HC emissions increase to 42 ppm.

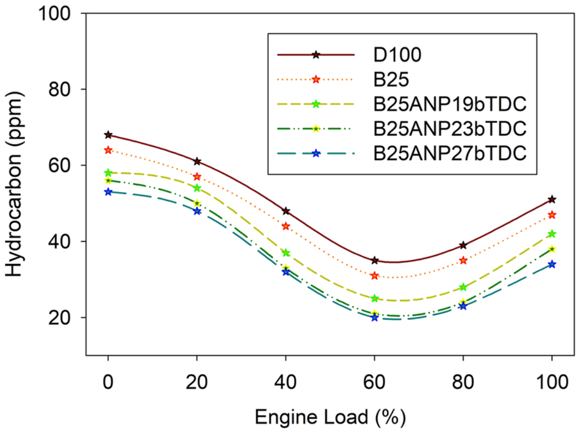

Fig. 9 Variation of HC emission against engine load

Figure 10 compares conventional, advanced and delayed injection timing to illustrate the fluctuation in NO emissions when utilizing waste transformer biodiesel with dispersed nanoparticles. The combination of oxygen and nitrogen in the air through successive reactions leads to the formation of NO. These reactions are notably influenced by temperature, largely due to their high activation

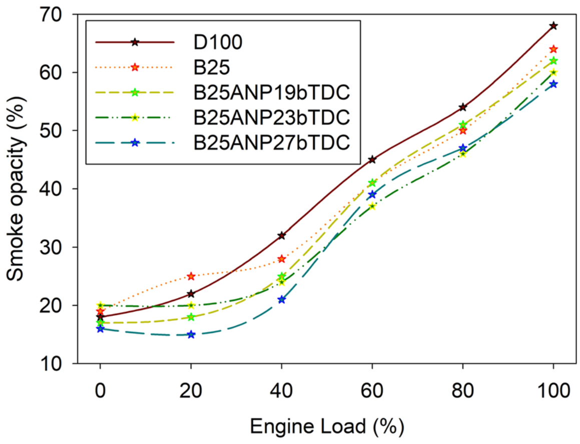

Fig. 8 Variation of smoke emission against engine load

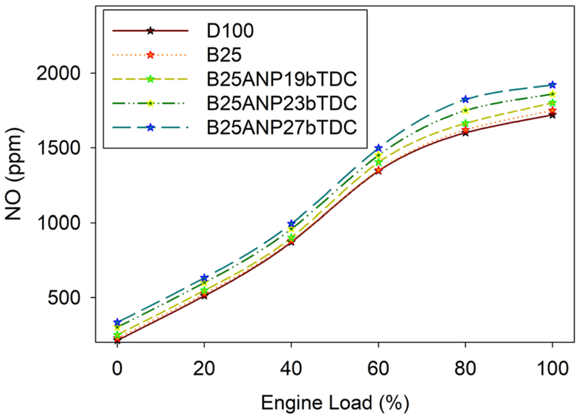

Fig. 10 Variation of NO emission against engine load

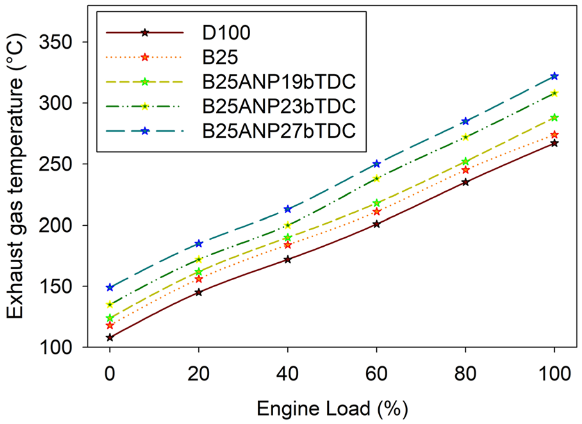

Fig. 11 Variation of NO emission against engine load

energy. The primary factors influencing NO emissions are the temperature of the mixture and the duration it stays within the engine (Prabu, 2020). Advancing the fuel injection timing led to an increase in NO emissions at all load levels. With increased advancement in injection timing, a larger quantity of the fuel–air mixture becomes available for combustion during the ignition delay (Rani et al., 2022). Employing waste transformer oil containing dispersed nanoparticles (B25ANP27bTDC) and implementing delayed injection timing led to NO emissions reaching 1921 ppm. At standard injection timing and maximum load, B25ANP23bTDC registers 1860 ppm, whereas B25ANP23bTDC records 1801 ppm of NO emission. This development could be given credit to the synergistic interplay between the catalytic properties of Al_2O_3 and the postponed fuel injection timing. This combination serves to decrease the cylinder temperature, resulting in a slight decline in NO production.

Figure 11 contrasts conventional, delayed and advanced injection timing to depict the variation in EGT when utilizing waste transformer biodiesel with dispersed nanoparticles. At normal injection timing and maximum load, B25ANP23bTDC registers an EGT of 308 °C. In contrast, under identical operating conditions, B25ANP27bTDC and B25ANP19bTDC engines record EGTs of 322 °C and 288 °C, respectively.

Assessment of the results concerning existing literature

In a prior study by Krupakaran et al., (2020a, 2020b), titanium dioxide nanoparticles were introduced at a concentration of 25 ppm in B20 fuel (20% *Mimusops elengi* methyl ester + 80% diesel), and the engine injection timing was varied at 19, 21, 23, 25, and 27 crank angles. When the injection timing was advanced, it resulted in reduced smoke emissions and an enhancement in brake thermal efficiency, accompanied by a slight increase in NO emissions. Conversely, retarding the engine injection timing led to increased hydrocarbon and carbon monoxide emissions.

The current experimental findings, obtained through the incorporation of alumina nanoparticles at a concentration of 100 ppm in waste transformer biodiesel blends, combined with the adjustment of engine injection timing, resulted in a 1.3% increase in brake thermal efficiency and elevated NO emissions. Conversely, the retardation of engine injection timing led to a 6.2% increase in CO, 3.3% in smoke, and 10.5% in HC emissions.

Upon evaluating these results in comparison to previous literature, it was concluded that the synergistic collaboration of nanoparticles with varying engine injection timing proves to be more effective in enhancing engine performance and reducing exhaust emissions.

Conclusion

This experiment explored the effects of infusing nanoparticles into used transformer oil at regular, advanced, and delayed fuel injection intervals. The key findings are outlined as follows when the time of fuel injection was shifted from 23 to 19 bTDC (advanced) and from 23 to 27 bTDC (retarded).

- This study demonstrated that the inclusion of waste transformer oil in a diesel fuel mixture containing nanoparticles does not adversely affect engine performance or emissions.
- The examination of waste transformer oil uncovered physical traits and FTIR analysis outcomes similar to those observed in regular diesel fuel, implying a resemblance between them.
- Drawing on the experimental investigation, it was noted that in an event of delayed injection timing (B25ANP27bTDC) in WTO operation, there is a 1.3% rise in braking thermal efficiency compared to conventional injection timing (B25ANP19bTDC).
- However, it's important to note that with a fixed-speed diesel engine, this enhanced thermal performance comes at the expense of increased NO emissions.
- When employed delayed injection timing (B25ANP27bTDC) in WTO operation, there was a notable reduction in exhaust emissions compared to the conventional injection timing (B25ANP23bTDC). Specifically, under maximum load conditions, it led to a decrease of 6.2% in CO, 3.3% in smoke, and 10.5% in HC emissions.

Scope of the future work

In the development of pioneering alternative fuels, the incorporation of chemical and nano-additives as innovative engine fuels has the potential to enhance the chemical attributes, thereby influencing the significant engine characteristics. Furthermore, the adjustment of engine operational parameters, including compression ratios, injection pressure techniques, and exhaust gas recirculation, may additionally contribute in achieving the lowest possible emission levels.

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Author contributions

The author is solely responsible for all the contributions.

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Not applicable.

Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The author declare that they have no competing interests.

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