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Research Article

Experimental investigation on the effect of varied injection timings in a CRDI diesel engine driven by a biodiesel-diesel blend

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Abstract

The issues with handling high viscosity biodiesel include noise and lack of smoothness in regular diesel engines. The use of Common Rail Direct Injection (CRDI) technology has the potential to significantly remove or reduce difficulties associated with biodiesel handling. In this study, the use of blends comprising waste cooking oil biodiesel was investigated in a CRDI diesel engine with injection timings ranging from 24° to 21° bTDC. For a diesel engine, injection timing is a critical element that influences engine performance, emissions, and durability. This study is the first to try combining the CRDI approach with varying injection timings for waste cooking oil biodiesel blends. The impact of varying injection timing has been assessed for blends of waste cooking oil (WCO) biodiesel fuels, specifically B20 (20% WCO+80% Diesel), and the results were compared to those of baseline mineral diesel fuel. During the experimental assessments, B20 demonstrated optimal performance at retarded injection timing of 22° bTDC (RT22), surpassing the standard injection timing of 23° bTDC. The optimum outcome revealed a 3.78% increase in Brake Thermal Efficiency for B20+RT22, accompanied by a 7.74% decrease in CO and a 3.15% reduction in NO_x emissions. Appropriate injection timing settings led to significant enhancements in both emissions and performance for WCO blends compared to the diesel fuel and standard injection timing. Moreover, this approach holds promise as a potential long-term solution to address the challenge of waste cooking oil disposal.

1. Introduction

The escalating energy consumption attributed to rapid urbanization and industrialization has raised concerns about the depletion of fossil fuels and the detrimental emissions produced by engines, along with the management of waste cooking oil biodiesel (WCO). Despite extensive prior research on potential alternative fuels, there has been a recent shift towards investigating the conversion of waste into fuel. The main sources of waste cooking oil in India are the residential and commercial food sectors. The disposal of WCO contributes to a significant environmental hazard, and as of now, no effective method has been universally adopted for its management. Hence, the need for a feasible alternative fuel for Compression Ignition (CI) engines [1,2]. Among various energy alternatives explored, the adaptation of WCO into liquid fuel has gained substantial attention. CI engines have gained popularity owing to their commendable thermal efficiency. However, they release substantial amounts of nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbon (HC), and smoke, posing environmental and health concerns. Stringent emission regulations have been implemented in response to these issues [3]. Additionally, the escalating demand for energy and the generation of waste contributes to the depletion of natural resources,

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exacerbating the diminishing petroleum reserves [4-7]. The use of biodiesel in CI engines significantly reduces the consumption of fossil fuels [8]. However, a primary drawback of biodiesel is its high viscosity, which can result in incomplete combustion during the premixed combustion stage, ultimately leading to lower brake thermal efficiency (BTE) [9]. Sonachalam et al. [10] analysed the effect of varying dual-fuel mode along with varying injection timing (IT) on the emissions and performance of a diesel engine. Experimental results revealed that the optimal configuration, the brake specific fuel consumption (BSFC) decreased by 7.3%, while BTE increased by 1.6% compared to mineral diesel. Emission wise, a 12.5%, 25.6% and 7.5% reductions in HC, CO and smoke respectively. Sonachalam et al. [11-12] have also investigated multi-walled carbon nanotubes, renowned for their high surface area and unique properties. These blends were subsequently tested in a diesel engine to assess their performance, emissions, and combustion characteristics. The implementation of advanced combustion technologies and optimization of fuel quantity significantly reduces traditional fossil fuel consumption and lowers emission levels.

Datla et al. [13] studied the engine performance with varying start of main IT by consuming neem oil biodiesel-diesel as fuel in variable geometry turbocharger stationary engine. Transesterification was done to convert raw neem oil to neem oil biodiesel. NB20 (20% Neem biodiesel + 80% diesel) was chosen for investigation. Injection cylinder pressure of 800 bar and 1700 rpm was maintained. The start of IT was varied between 2° and 10° before top dead centre (bTDC). HRR, engine cylinder pressure is higher for mineral diesel compared to NB20 fuel blend at altered IT. Exhaust NO_x emission for NB20 reduced. BSFC and BTE showed better improvement and were close to diesel. Finally, 10° bTDC start of main IT showed an improved 13% of BTE and reduced 21% of BSFC with a reduction in 7.5% of CO_2 emission. Jiaqiang et al. [14] evaluated fish oil as a fuel in a stationary diesel engine. Simulation and experimental methods were used to investigate the influence of fuel IT and fuel injection pressure operating with fish oil and its blends. Raw fish oil is transesterified to produce biodiesel. Various blends ranging from B10 to B50 were utilized for analysis. As the biodiesel concentration increases, NOx emissions rise while soot, HC, and CO emissions decrease. The study was further carried out by increasing fuel IT. It was perceived that BTE increased and emissions like CO, HC, smoke, etc. reduced with the advancement of IT. Fish oil biodiesel was compatible with engine usage and enhanced outputs were noted on varying IT. Zhang et al. [15] experimented with a dual fueling operation in an engine with diesel and Ethylene Glycol (EG) with EG energy ratios of 0%, 10%, and 15% named EG0, EG10, and EG15 respectively. Port IT and direct IT modification strategies were used for performance improvement. Results showed a rise in maximum cylinder pressure and maximum heat release rate (HRR) along with a rise of 19.45% BTE is observed for advanced injection direct IT and increasing EG ratios. Emissions like CO_2, HC, NO_x, and soot are reduced with an increase in CO emissions. Advanced direct injection timing along with a suitable EG energy ratio decreased particulate matter (PM).

Karthic et al. [16] experimented with a diesel engine to investigate the combustion, performance, and emission parameters of Syzygiumcumini oil biodiesel as sole fuel by varying IT. A stationary laboratory water-cooled direct injection (DI) 1500 rpm diesel engine was employed for this work. Various blends B30, B70, and B100 were tested and compared. These fuels were subjected to injection pressures between 200 bar and 260 bar and IT of 21° to 25° bTDC. Net result output was compared with base fuel diesel. B30 fueled with 240 bar showed a 17.85% increase in BTE. On advancement of fuel IT with an increase of injection pressure, emissions of HC and CO were 46.15% and 15.9% less than usual injection timing and injection pressure. The smoke was reduced and an increase of NO_x was noted. B30 with 240 bar injection pressure and 25° bTDC advancing IT was better to operate in the engine. Wei et al. [17] experimented with a 4-cylinder diesel engine with 0%, 10% and 30% of 2,5-dimethylfuran (DMF). Improvement in combustion characteristics, and reduced NO_x and PM for different fuel IT was noted. Particulate size distribution, particulate number, and mass concentration were also measured and improved. The addition of DMF increased the delay period and reduced BSFC. Maximum in-cylinder pressure was obtained for 10% DMF. The accumulation mode of fuel is reduced but nucleation mode increases which has negative health effect on human body. Geometric mean diameter declined with DMF concentration because of an increase in nucleation mode and varying IT have a momentous effect on engine outputs. How et al. [18] experimented with unmodified medium-duty diesel engine using biodiesel blends of B20 and B50. Emission reduction and combustion enhancement strategies were implemented by altering IT and split injection of fuel inside cylinder. A remarkable reduction in NO_x less than 100 ppm is obtained and less smoke for retarded injection timing and multiple injection timing for blends B20 and B50 are obtained. Emissions like HC, CO, CO_2, and PM decreased for both B20 and B50 with retarded IT and multiple injections reducing emissions more than individual operations. Thus combined effect of the two injection strategies reduced emissions and improved the performance of biodiesel than diesel.

Many international research has been conducted on the performance and emissions of DI diesel engines using different types of biodiesel derived from animal fat and non-edible vegetable oil. However, little research has been done on the performance of CRDI diesel engines. There have only been a few studies that examine the efficiency, emissions, and combustion behavior of WCO biodiesel blends in CRDI engines [19]. This study aims to analyze the engine performance and emissions of biodiesel derived from used WCO tested at varied IT. One of the biggest challenges in industrial biodiesel production is determining the ideal engine conditions for running efficient, eco-friendly blends. CRDI engines use a high-pressure fuel rail to accurately distribute high viscosity biodiesel fuel into the combustion chamber, resulting in increased fuel efficiency and lower usage. CRDI engines run quieter and smoother with biodiesel blends because of the timing flexibility. Controlled injection decreases stress on engine components, resulting in durability and reliability. In a diesel engine, injection timing is a significant factor influencing engine performance, emissions, and durability. This might be the first study to combine the CRDI technique with different IT for WCO biodiesel blends. Over the past three decades, researchers have extensively investigated the use of alternate fuels. Additionally, studies on engine modification have been conducted. However, there is a need for further exploration of investigation on alternate fuels and suitable engine modification to achieve anticipated performance and minimize emissions. Limited work has been conducted on the utilization of WCO blended fuel in CI engines and its influence on engine characteristics of emissions and performance. Therefore, in this work, a single-cylinder CRDI diesel engine was employed to examine the influence of injection timing on both engine performance and exhaust emissions when utilizing WCO-diesel blended fuel.

2. Materials and methods

2.1 Fuel Blend Preparation

In this research, WCO involved utilizing a method known as splash blending, which includes adding fuels a specified amount to a vessel and stirring the mix for 5 min. Various testing fuels were obtained, which containing 90%, 80% & 70% of diesel, and 10%, 20% & 30% of WCO, and then compared with mineral diesel. Throughout the research, B20 (WCO 20% + Diesel 80%) blends, were taken into consideration based on aforementioned literature. It's noteworthy that compared to diesel, WCO exhibits higher viscosity, thus increase in the proportion of WCO in the test fuel could potentially lead to critical issues such as separation of phase owing to density differences and abridged performance parameters [20]. Therefore, to mitigate these concerns, the proportion of WCO in the assessment fuels was capped at 20%. Table 1 provides a summary of the physicochemical properties of the test fuels.

Table 1. Properties of test fuels

Property	Diesel	WCO	B20	ASTM method
Kinematic viscosity (cSt)	2.8	2.62	2.24	D-445
Density (kg/m^3)	846	831	838	D-1298
Flashpoint (°C)	67	46	52	D-93
Cetane number	52	48	45	D-613
Heating value (kJ/kg)	44200	42630	43160	D-240

2.2 Experimental Setup

The current study employed a CRDI diesel engine for conducting tests. CRDI engines employ a high-pressure fuel rail to accurately distribute high viscosity biodiesel fuel into the combustion chamber, resulting in increased fuel efficiency and lower usage. Direct Injection is a fuel delivery technology that employs a mechanical pump to feed gasoline into the engine's ignition chamber. DI engines provide less power than CRDI engines. CRDI engines run quieter and smoother with biodiesel blends because of the timing flexibility. Controlled injection decreases stress on engine components, resulting in longevity and dependability. The increased refinement results in smoother running and reduced wear and tear on the engine's body. As a result, CRDI engines can claim superior long-term longevity over direct injection. CRDI emits less pollutants than standard diesel engines, however it still produces certain dangerous compounds. The test engine specifications are detailed in Table 2, and Fig. 1 shows the engine setup. The IT was varied from 24° to 21° bTDC, maintaining 600 bar of injection pressure at loads from 25% to 100%, with B20 blends.

Table 2. Engine specifications

Particulars	Specifications
Type	Kirloskar – 4S CRDI diesel engine
Number of cylinders	One
Compression ratio	17.5:1
Standard injection timing	23°bTDC
Bore	87.5 mm
Stroke	110 mm
Power	3.7 kW
Injection pressure	600 bar
Speed	1500 rpm

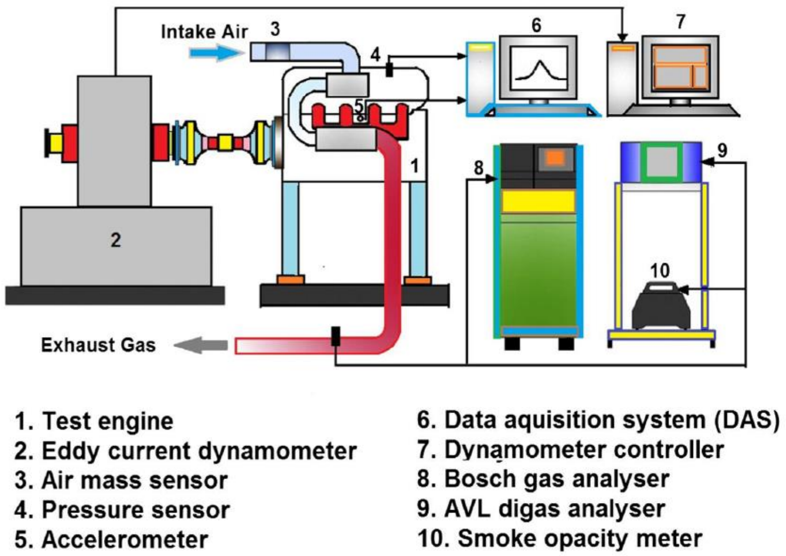

Fig. 1. Engine setup layout

2.3 Modification in Injection Timing

The standard IT was attuned by employing the number of shims inside the fuel pump. The fuel IT could be altered by either increasing or decreasing the number of shims in the fuel pump. Upon the initial assembly of the engine, 3 shims were already fitted in the injection pump. To achieve retarded IT, a shim (0.3 mm thick) was added, while advanced IT was achieved by taking away the shim. Every shim, equivalent to 1° crank angle (CA), could provide either advancement or retardation, depending on the shims existing in the fuel pump. The IT was physically attuned after each change to the shims, whether they were added or removed. These alterations to the fuel IT had significant effects on the engine. Advanced IT leads to a more pronounced enhancement in mixture turbulence, facilitating quicker and immediate combustion. This adjustment also results in a prolonged ignition delay, contributing to decreased temperature and pressure. Retarded IT caused delayed engine combustion, slower combustion rate, shortened ignition delay period, and heightened temperature and pressure.

3. Results and Discussion

Through minimal engine adjustments, WCO exhibits the prospective to reduce emissions. In CI engines, IT significantly influences both emissions and performance. The initial tests on WCO were conducted at the standard injection timing (ST) set at 23° bTDC to establish baseline values. Test findings indicated that NO_x emissions produced at the ST of WCO exceeded those generated by diesel fuel. Four variable IT settings (ranging from 24° bTDC to 21° bTDC) were implemented at different engine loadings from 25% to 100%. Advanced IT revealed inferior results for WCO blend fuels compared to ST. Conversely, retarded injection timing (RT) exhibited improved results for WCO blends. Some insights were also derived from existing literature, emphasizing the focus on RT in the current research work. The ST for diesel engine is 23° bTDC. This IT is suitable for diesel fuel, but biofuel whose viscosity is higher and has higher oxygen and therefore leads to higher NO_x. At RT of 22° bTDC and 21° bTDC, it is found to exhibit lowered NO_x emissions. So, the Research is focused more on RT till 21° bTDC. Beyond that, the performance reduces because of drop in engine cylinder temperatures. Advancing an engine's IT causes the injection process to begin earlier than the manufacturer's parameters. In contrast, retarding occurs when adjustments are made to cause the fuel to release later than expected. Although retarding is less common than advancing, it can resolve a lag or smoking issue in a biodiesel engine. It can also help with performance and fuel efficiency issues. The present study used one advanced IT of 24° bTDC and RT of 22° bTDC and 21° bTDC in order to assess the influence on both sides, in addition to the ST of 23° bTDC as specified by the engine manufacturer. It is also crucial to conduct investigation at full load. During the optimization of IT, the speed was held steady at 1500 rpm, and fuel pressure was maintained at consistently at 600 bar. The present research is conducted with standard IT of 23° bTDC, retarded IT of 22° bTDC, 21° bTDC and advanced IT of 24° bTDC.

3.1 Performance Characteristics

Fig. 2 displays the variations of BTE for B20 at different IT with engine load. The maximum BTE is 32.31% reported for B20+RT22 at full load condition. In retarded IT of 22° bTDC, the B20 blends performance is increased by 3.78%, while more retardation IT of 21° bTDC was found to drop in BTE by 5.27% at 100% engine load condition owing to variations in ignition delay period within the combustion chamber. BTE increases with the retardation in IT were already reported by Jaichandar et al. [21]; Agarwal et al. [22].

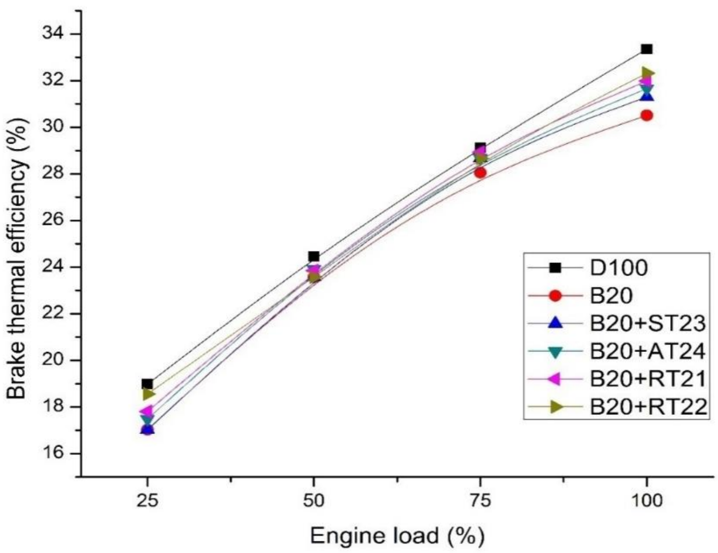

Fig. 2. BTE vs Engine load

This shows the efficiency of the B20 blend at retarded RT. This could be probably the standard IT of 23° bTDC favoring only diesel fuel combustion, but not the oxygenated blends. While retarding IT, the injection of fuel begins very late after the TDC which could have provided sufficient residence time for the formation of the air-fuel mixture thereby ensuring the O_2 utilization in B20 blend followed by higher BTE. Advancing the IT of 24° bTDC was found to reduce the BTE of 1.13% very marginally concerning B20+ST23. BTE trend is always lesser due to reduced cylinder temperature prevailing at lower loads where the occurrence of combustion is very early with respect to TDC diminishing the output power via losses of pumping.

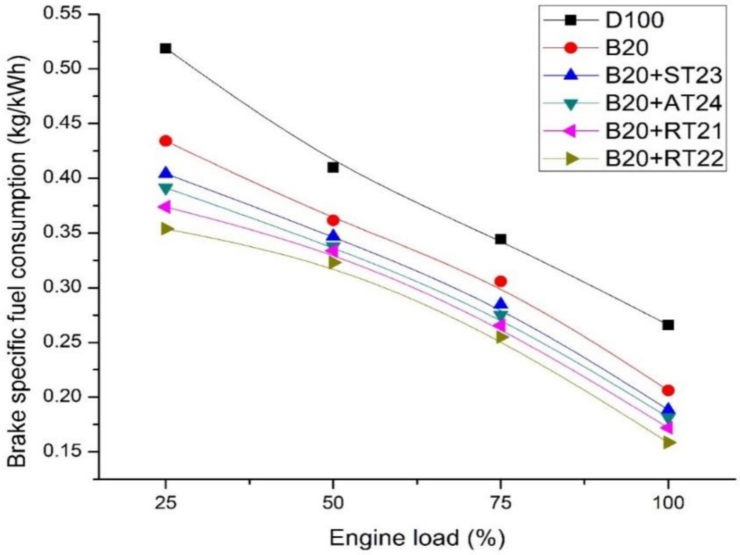

Fig. 3. BSFC vs Engine load

Fig. 3 displays the variation of BSFC for B20 at different IT with engine load. It can be perceived that maximum BSFC is for B20 blend throughout the load condition which is evidence of poor mixture formation and abundant fuel congregation in the zone of combustion followed by higher energy required to maintain constant engine speed of 1500 rpm. At full load, the BSFC of B20+AT24 and B20+RT21 were higher than B20+ST23 by about 3.68% and 8.70% respectively, while the least fuel consumption of 158 g/kWh is recorded for B20+RT22. However, retarding injection timing further to about 21° bTDC named as B20+RT21 which is not lower the BSFC further, and in contrast, it is increased. These BSFC reductions for retard injection timing were on par with the outcomes of Mani & Nagarajan [23], and Agarwal et al. [22] who indicated that optimum fuel injection timing required for biofuel blends will favoring the combustion efficiency.

3.2 Emission Characteristics

Fig. 4 displays the fluctuation of CO emissions for B20 at different IT with engine load. D100 possess the highest CO emissions among other oxygenated blends owing to the lack of O_2 in mineral diesel which makes the blend unable to sustain oxidation. Whereas with B20, the CO emissions are reduced substantially indicating significant improvement in combustion. Retarding the injection timing of 22° bTDC along with B20 results in lowering CO emissions in comparison with the B20 blend at engine loads of 25%, 50%, 75%, and 100% by about 42.01%, 86.74%, 33.04% and 60.2% respectively. Lowered CO emissions with retardation in IT were on par with the research findings of Mani & Nagarajan [21], and Agarwal et al. [22]. It is found that further retardation from 22° bTDC to 21° bTDC is not effective and found to increase CO emissions as found in similar studies of Sayin et al. [25] and Ganapathy et al. [26]. Also, advanced timings of 24° bTDC are found to increase the CO emissions by about 35.63% in comparison with B20+ST23 as a result of poor rate of oxidation and existence of more rich fuel zones in the bowl especially at varied timings of 21° bTDC, and 24° bTDC causing hindrance in the oxidation of CO to CO_2 followed by higher CO emissions.

Fig. 5 displays the variation of HC emissions for B20 at different IT with respect to load. It can be found that diesel fuel displays the highest HC emissions throughout the load condition. The HC emission profile of B20 is very low compared with diesel fuel. With injection timing retardation, the HC emissions were found to lower significantly, especially with B20+RT22 at 25%, 50%, 75%, and 100% load conditions which possess HC emissions of 0.065, 0.0525, 0.056, and 0.04 g/kWh respectively. Similar reductions in HC emissions with IT retardation are found in some literature [21-22]. Whereas, some literature also proved to increase the HC with injection timing retardation such as Hwang et al. [24]. Further, fuel injection timings of 24° bTDC and 21° bTDC were found to increase the HC emission signifying the insufficient residence time for preparation of mixture and more possibility of formation of fuel-rich zones thereby resulting in high HC emissions.

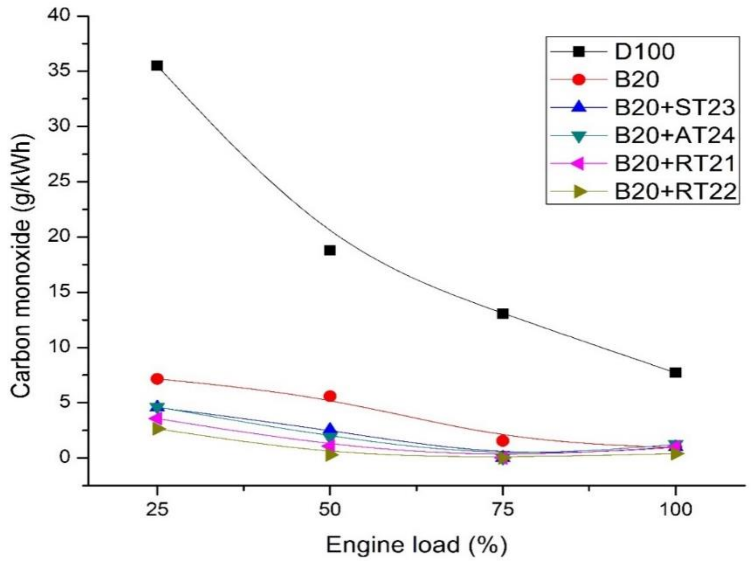

Fig. 4. CO emission vs Engine load

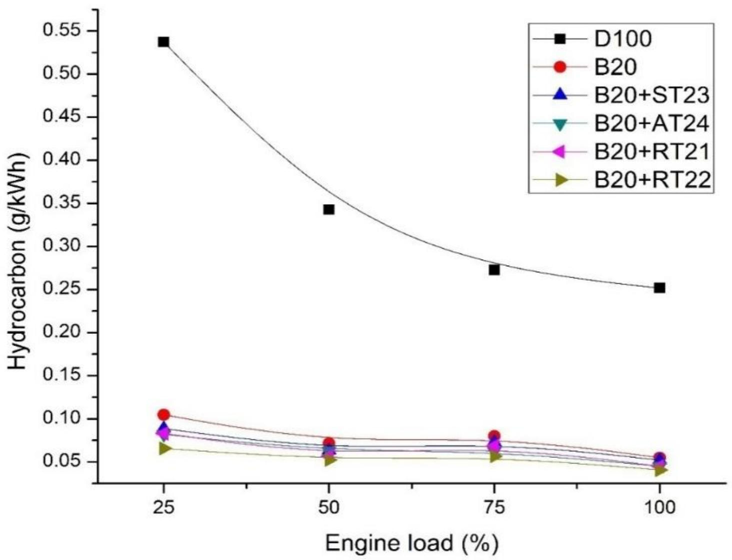

Fig. 5. HC emission vs Engine load

Fig. 6 portrays the variation of NO_x emission for B20 at different IT with respect to load. The prime reason for the variation of NO_x emissions is characterized by higher burning rate, excess O_2 content, and improved adiabatic flame temperature at which O_2 and N_2 tend to form NO emissions. It can be seen that B20 blends tend to liberate more NO_x emissions in comparison with mineral diesel blends indicating an increase in combustion rate along with higher in-cylinder temperatures. It is found that the NO_x emissions of B20+RT21 and B20+RT22 were higher at about 5.06% and 6.25% respectively at 100% load. This can be perhaps due to an improvement in residence time of fuel accumulation followed by higher adiabatic flame temperature and thereby overall improvement in O_2 and N_2 reacting in the air followed by higher NO_x emissions. Further retardation in IT 21° bTDC drops the NO_x emission subsequently as seen in some similar research by Mani & Nagarajan [21] and Sayin et al. [25]. When the fuel injection timing is advanced to 24° bTDC for B20, there is a marginal NO_x emission improvement in comparison with B20+ST23 such a marginal improvement and NO_x emission is attributed to B20 blends earlier start of combustion concerning TDC thereby causing improved cylinder pressure, HRR and adiabatic flame temperature along with higher NO_x emissions. These results are on par with the results of Hwang et al. [24], Ganapathy et al. [26] and Sayin et al. [25].

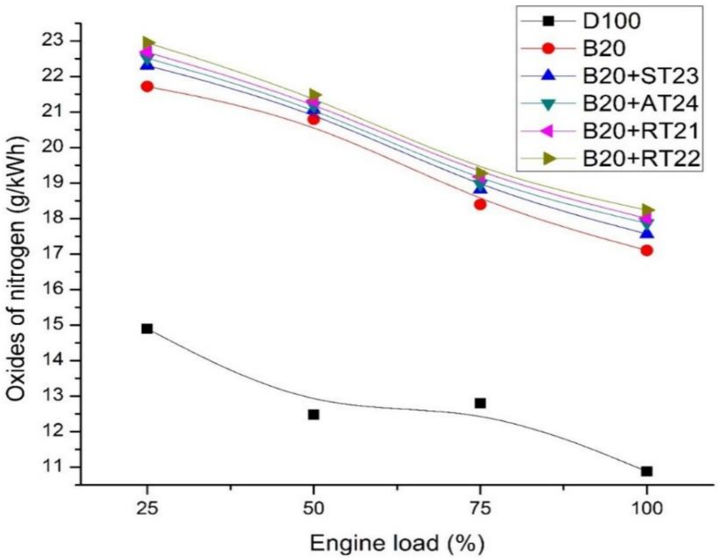

Fig. 6. NO_x emission vs Engine load

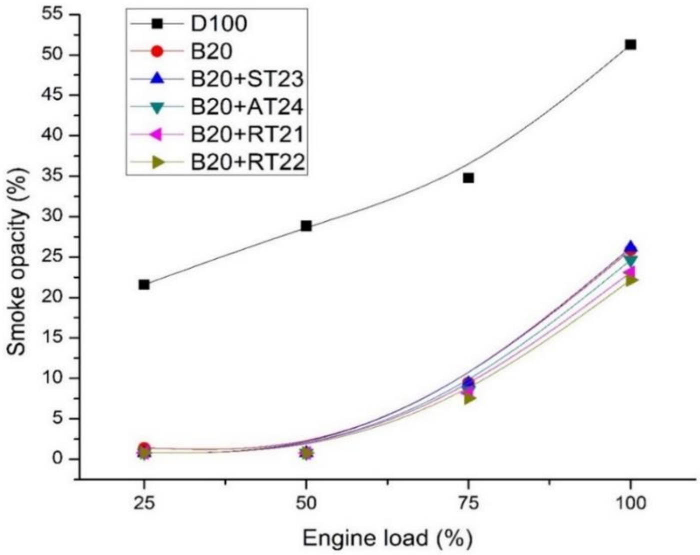

Fig. 7. Smoke opacity vs Engine load

Fig. 7 depicts the fluctuation of smoke for B20 at different IT concerning load. The fluctuation in smoke opacity is on par with the NO_x-smoke trade of characteristics. Lowermost profile of smoke emission is found for B20+RT22 of about 0.79%, 0.77%, 7.5%, and 22.17% at engine loads of 25% - 100% respectively compared to B20. This can be ascribed to the presence of higher residence time for accumulation of test fuel leading to improvement in in-cylinder pressure and HRR, excellent spray characteristics followed by lowered fuel-rich zones, and thereby reduced smoke. Further, when the IT is advanced, more chances of soot oxidation are there due to higher cylinder temperatures leading to evaporation in B20 blend, thereby improving in combustion rate and reducing smoke. These are on par with the research findings of Gnanasekaran et al. [27] and Sayin et al. [25]. When the fuel injection timing is retarded, the smoke increases which is on par with characteristics of NO_x-smoke trade-off. B20+ST23 possesses higher smoke opacity than B20+RT21 and B20+RT22 about 23.1% and 22.17% respectively. Lowered smoke opacity with retardation in injection timing is alike with the findings of Mani & Nagarajan [23].

4. Conclusion

The increasing demand for fossil fuels and the prevailing geopolitical situation have raised significant global concerns. As a result, there is an increasing need for alternative fuels for IC engines. By making slight adjustments to fueling systems, this biodiesel can potentially be transformed into an alternative fossil fuel. In this research, a Common Rail Direct Injection diesel engine was operated at different injection timings using waste cooking oil blends with mineral diesel. The study aimed to assess the impact of injection timing variations, including advanced, standard, and retarded settings, on both engine emissions and performance. The outcomes indicated that changes in injection timing had a substantial influence on the performance and emission characteristics. The blend B20+RT22 was found to have improved brake thermal efficiency along with the lowered brake specific fuel consumption owing to retarded injection timing of fuel yielding proper residence time for fuel-air mixture formation leading to higher combustion efficiency and improved performance. Also the blend B20+RT22 has 60.2% lowered CO, 18.8% lowered HC, and slightly higher NO_x emissions by 6.25% as a result of advancing injection timing. Overall, it is perceived that the B20+RT22 is found to be superior in terms of improved performance, and minimized emissions. The current study has a limitation on the biodiesel concentration of 20%. Hence higher biodiesel concentration blends are need to be assessed. By adopting appropriate injection timing settings led to significant enhancements in both emissions and performance for waste cooking oil blends compared to the diesel fuel and standard injection timing. Moreover, this approach holds promise as a potential long-term solution to address the challenge of waste cooking oil disposal. Further, studies on the effect of Nano additives in waste cooking oil biodiesel blended fuel on CI engine performance are also need to be investigated. In future, Influence of Silicon Catalytic Reduction and the use of Exhaust Gas Recirculation on a waste cooking oil biodiesel engine could also be explored for effective NO_x reduction.

Abbreviations

ASTM - American Society of Testing and Measurement
AT24 - 24° bTDC advanced injection timing
B20 - 20% biodiesel + 80% diesel
BSFC - Brake Specific Fuel Consumption
bTDC - before Top Dead Centre
BTE - Brake Thermal Efficiency
CA - Crank Angle
CI - Compression Ignition
CO - Carbon monoxide
CRDI - Common Rail Direct Injection
D100 - Diesel
DMF - Dimethylfuran
EG - Ethylene Glycol
HC - Hydrocarbon
HRR - Heat Release Rate
IT - Injection Timing
NO_x - Oxides of nitrogen
O_2 - Oxygen
PM - Particulate Matter
RT21 - 21° bTDC retarded injection timing
RT22 - 22° bTDC retarded injection timing
ST23 - 23° bTDC standard injection timing
TDC - Top Dead Centre
WCO - Waste Cooking Oil

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