MECHANICAL ENGINEERING | RESEARCH ARTICLE

Combined influence of fuel injection strategy and nanoparticle additives on the performance and emission characteristics of a biodiesel fueled engine

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Abstract: Waste cooking oil (WCO) biodiesel is becoming promising fuel for compression ignition (CI) engines. Due to the poor thermal efficiency, engine modifications and fuel modifications have been adopted over the years to enhance the performance. In the current study, performance from the biodiesel engine at different injection timing has been studied using waste cooking oil biodiesel mixed with cerium oxide (CeO₂) nanoparticles as additives. Experiments are conducted at normal injection timing (27 °bTDC), advanced (30 °bTDC) and retarded injection timing (24 °bTDC) using B20 fuel blended with 80 ppm of nanoparticles. Studies indicated that advancing the injection timing, results in higher brake thermal efficiency (BTE) and reduced brake specific fuel consumption (BSFC) for B20 fuel with nanoparticles as compared to fuel without the use of nanoparticles. Smoke, CO and HC emissions reduced on progressing the injection timings, whereas delaying injection timing shows decreased NOx emissions. By advancing the injection timing and adding CeO₂ nanoparticles to the blend, BTE is increased by 10.9% and BSFC reduced by 11.1% as compared to the neat B20 biodiesel operation. HC and smoke emissions are 35.4% and 14.2%, respectively, reduced for advancing the injection timing with the adding cerium oxide nano particles to the fuel as compared with clean WCO ester with the absence of nanoparticles. Advancing fuel injection timing has no positive influence on the reduction of NOx.

Subjects: Renewable Energy; Energy & Fuels; Bio Energy

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PUBLIC INTEREST STATEMENT

In the present work, combined influence of injection timing and addition of nanoparticles have been investigated. It is seen that, by advancing the injection timing and adding 80 ppm of cerium oxide nanoparticles, engine performance could be enhanced. Simultaneously engine emissions lowered. This contributes to conserve diesel fuel and also helps to preserve the environment clean by least pollutants. Retarding the fuel injection timing has negative influence on engine combustion as the exhaust gas temperature is higher.

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Keywords: biodiesel; brake specific fuel consumption; nanoparticle; emission characteristics

1. Introduction
Fossil fuels have been used as the fuels for internal combustion (IC) engines from decades. The major issues with their usage include they are non-renewable in nature, responsible for increase in pollution level resulting in environmental issues like global warming, green house effects etc. After a thorough research on the alternative fuels, it is concluded that plant oils are the hopeful source of alternative fuels for the IC engines. (Hoang et al., 2021; Singh et al., 2020). They have specific advantages like extra oxygen content in their molecular structure, higher cetane number and higher calorific value etc., which reflects them as an alternative fuel for CI engines. (Demirbas, 2007) Major drawback with vegetable oil is their higher viscosity which limits its direct use in CI engines. Direct utilization of these oils results in nozzle choking, ring sticking, filter clogging and combustion chamber carbon deposits etc. Hence, several methods have been suggested by the investigators to reduce the viscosity of plant-based oils. Out of the several methods, transesterification is an important technique where in, vegetable oil is subjected to a process known as esterification. (Marchetti et al., 2007) The viscosity of the resulting oil will be at par with that of neat diesel. Research results indicated that performance of the biodiesel engine is slightly inferior to that of neat diesel in terms of lower BTE, higher BSFC etc. Hence, constant efforts are being undertaken to improve the efficiency of biodiesel engines simultaneously reducing the engine emissions. (Vallapudi et al., 2018)

Fuel Injection timing (FIT) is one of the several parameters affecting the engine combustion. Condition of air in the engine cylinder with the fuel will change as FIT is varied. This changes the ignition delay and hence combustion characteristics. If the injection is too early, then pressure and temperature of the air will be inferior, so that the delay period may rise. Similarly, if the injection timing is too late, it will cause reduced ignition delay and may cause abnormal combustion due to the huge rise in the values of pressure, temperature of the air. When a diesel engine is run with the biodiesel, proper study on the injection timing is essential as this is a detrimental factor for combustion. Several researchers have conducted studies on varying the injection timing to realize their impact on the engine combustion. (Bala Prasad et al., 2020; Harun Kumar et al., 2020) Sayin et al. (Sayin et al., 2008) carried out experiments with ethanol mixed with conventional diesel from 0 to 15%. The outcomes showed that the advancement of the injection time, reduced NOx and carbon dioxide. Nwafor et al. (Nwafor, 2007) observed the influence by the variation in FIT on the operation of a biodiesel engine using rapeseed blends. By advancing the timing of the injection, the thermal efficiency reduced as compared with the standard timing. A noteworthy decrease in CO and CO2 were observed for advancing FIT. Sathiyamoorthi et al. (Sathiyamoorthi & Sankaranarayanan, 2015) conducted engine experiments using lemon grass as biodiesel at normal, advanced and retarded injection timing. They observed on advancing FIT, BTE increases, BSEC reduces and HC emission decreases, whereas NOx emission increased.

Addition of additives to the biodiesel engine over comes some of the limitations from the engine such as reduced power output, increased NOx, increased ignition delay etc. Several researchers have used both solid and liquid additives along with base fuel. (Izquierdo et al., 2012) Earlier studies said that usage of large sized additive particles affected combustion performance leading to an increase in emissions and decreasing efficiency. (Izquierdo et al., 2012; Qi et al., 2009) Sedimentation and longer ignition delay are the common problems associated with large sized additives. This limited the usage of large sized additives in bio diesel blend. On suspending very small nano-sized particles (size varying between 10 and 100 nm) in biodiesel blend it is possible to overcome the above said limitations. Relatively small diameter of nanoparticle reduced sedimentation by increasing the dispersion and also increased chaotic movements. Improvement in cetane number is observed by using these additives and it lowered oxidation temperature by improving ignition characteristics. Engine performance is dependent on type of biodiesel and nanoparticle.
Several researchers have used various types of nanoparticles in engines and evaluated the engine characteristics. (Dhana Raju et al., 2018; Soudagar et al., 2021; Venu et al., 2021) Kumar et al. (Kumar et al., 2017) studied the influence of ferric nanoparticle on the combustion characteristics of the engine. They reported on adding ferrofluid additive by 1% improved the performance with maximum BTE, lower SFC and lesser CO and HC emissions. Prabu et al. (Prabu, 2018) conducted experiments for studying the working characteristics of DI diesel engine using Al₂O₃ and CeO₂ nanoparticle. They reported Al₂O₃ as nanoparticle additive yielded a better brake thermal efficiency than CeO₂ nanoparticle additive and nanoparticles presence decreased ignition delay and accelerated earlier initiation of combustion. Sajith et al. (Sajith et al., 2010) performed an experiment to investigate properties of cerium oxide nano-sized particles as fuel additive on jatropha biodiesel and they reported that at full loading conditions, BTE of nanoparticle dispersed biofuel possessed higher brake thermal efficiency than plain biodiesel and with CeO₂ nanoparticle, reduction in NOx emission was noticed.

Ignition delay is one of the vital parameters to be controlled especially in a biodiesel engine. (Shrivastava & Verma, 2020) Injection timing is the major factor decides the nature of combustion in diesel engines. Advanced timing will give sufficient time for combustion. On advancing the injection timing, air temperature will be lower, vaporization of fuel will be hindered. Addition of nanoparticles will enhance the fuel dispersion characteristics and improve the heat transfer among fuel droplets and compressed air. Limited literature is available on the study related to combined influence of nanoparticles and FIT on the performance of a biodiesel engine. Hence an effect has been made in the present study to investigate the combined influence of FIT with CeO₂ nanoparticle addition on the engine combustion characteristics. Engine experiments are carried in a biodiesel engine fuelled with WCO biodiesel added with 80 ppm of CeO₂ nanoparticles. Experiments are conducted at normal, advanced and retarded FIT and the outcomes are compared with the clean B20 process without the addition of additives.

2. Experimental setup
Engine experiments are executed in a Kirloskar TV1 four stroke engine. It is a single cylinder engine with water as the coolant used. Figure 1 shows the engine set up and Table 1 shows the specifications of the engine. Engine is loaded by eddy current dynamometer. Sensors are attached to determine temperatures. Measurements of jacket water and calorimeter water flow rate are noted using a rotameter. It is linked to a computer which records the pressure variation per crank angle readings with the help of a software. An AVL gas analyzer is used to note the engine emissions such as NOx, CO, HC and AVL smoke meter are used to measure smoke data. The details of the instruments used in the experimentation are provided in Table 2.

Esterified WCO biodiesel is procured from a nearby biodiesel development centre. The physico-chemical properties of neat B20 have been determined and given in Table 3. CeO₂ nanoparticles have been procured from a vendor. Neat B20 biodiesel is mixed with 80 ppm of CeO₂ nanoparticles.
Size of the nanoparticles is maintained constant at 30 nm. 2% by volume of surfactant triton-X100 is added and the solution is subjected to sonification in an ultrasonicator for 60 minutes in order to increase the stability of nanoparticles. Initially engine experiments are conducted with neat B20 fuel without adding the nanoparticles. Experiments are conducted at rated FIT of 27 °bTDC which is considered as normal FIT. Fuel flow rate, engine load etc. are measured and similarly CO, HC, NOx and smoke emissions are noted. Using the above readings engine performance parameters like BP, BTE and BSFC etc. are calculated. Engine experiments are repeated with advanced injection timing (30 °bTDC) as well as retarded injection timings (24 °bTDC) with modified fuel (B20+ nanoparticle additives). Engine characteristics together with emission levels are noted and compared with the base line data and have been discussed in the further sections.

3. Uncertainty analysis
Uncertainty for the experimental results have been determined using Eq. (1) and the values are tabulated in Table 4.

$$W_R = \left( \frac{\partial R}{\partial X_1} W_1 \right)^2 + \left( \frac{\partial R}{\partial X_2} W_2 \right)^2 + \ldots + \left( \frac{\partial R}{\partial X_n} W_n \right)^2 \right)^{1/2}$$  (1)
4. Results and discussion

4.1. Brake Thermal Efficiency (BTE)

Figure 2 represents the BTE values for the different fuel variants tested. Generally, it is seen that BTE increases as the as the load is increased. It is found to be maximum for B20 WCO ester added with CeO$_2$ nanoparticles with advancing the injection timing by 3°. When the FIT is advanced, even though the temperature of air is lesser, due to the addition of nanoparticles, whose thermal conductivity is greater than the base fluid, causes enhanced energy transfer between air and fuel particles.(Kalaimurugan et al., 2020) This allows quickly the mixture to reach the auto ignition temperature or in other words the ignition delay will be reduced. Hence more uniform combustion will be achieved, and hence higher heat release takes place, whereas, BTE during retarding FIT, is lower than the earlier. During retarding, the delay period will be so short such that combustion continues even during the power stroke. This reduces the power output or reduced BTE. In the

| Measured quantity                  | Percentage uncertainty |
|------------------------------------|------------------------|
| Load                               | 0.65                   |
| Speed                              | 0.51                   |
| Fuel flow rate                     | 0.8                    |
| Brake specific fuel consumption    | 1.4                    |
| NOx                                | 2.0                    |
| HC                                 | 2.1                    |
| CO                                 | 1.4                    |
| Smoke opacity                      | 0.65                   |

Table 4. Uncertainty analysis of the measured parameters used in the study

Figure 2. BTE vs load.
absence of nanoparticles, physical delay as well as chemical delay will be increased resulting in higher delay period. Hence much of the fuel burns in the premixed stage resulting in inefficient combustion. Due to this reason BTE will be reduced. The highest BTE value of 29.77 % is observed for 30 °bTDC+B20 + 80 ppm CeO₂ and is 10.9 % higher as compared to 30 °bTDC+B20.

4.2. Brake-Specific Fuel Consumption (BSFC)
It represents the fuel spent per brake power and is usually expressed in kg/kWh. For advanced injection timing with nanoparticles BSFC is least amongst various fuels tested. When the injection is advanced, and nanoparticles are added better fuel preparation takes place due to increased dispersion and enhanced heat transfer. Delay period will be reduced and hence peak pressure will be attained just after TDC. This increases the power output of the engine or BSFC reduces as shown in Figure 3. For the fuel blend without the nanoparticles, ignition delay is increased due to the poor mixing and reduced heat transfer rate among fuel and air. This reduces the power output or increases BSFC. On delaying the injection timing from the rated value, ignition delay will be too shortened such that little burning will even continue in the power stroke also reducing the engine power or increasing the BSFC (Channappagoudra et al., 2020; Rami Reddy et al., 2021) Lowest BSFC is observed for 30 °bTDC+B20 + 80 ppm CeO₂, and is 11.1% lower than 30 °bTDC+B20.

4.3. Peak cylinder pressure and cumulative heat release
Figure 4 shows peak pressure achieved for 50% and 100% load conditions for different test fuels. It is seen that, lowest peak pressure will be obtained for 30 °bTDC+B20 operation. When nanoparticles are added to the fuel mixture, higher cylinder pressure is obtained. Even at retarded fuel injection timing condition. This clearly shows the advantage of adding CeO₂ nanoparticle to the fuel blend. Metallic nanoparticles having higher thermal conductivity between air and fuel mixture, thus decreasing delay period. Hence, smooth combustion is achieved, increasing the peak pressure values. Cylinder peak pressure values obtained for 30 °bTDC+B20 + 80 ppm CeO₂ is 14.1% higher than 30 °bTDC+B20 operation. On comparing various injection timings with CeO₂ added fuel
blends, 30 °bTDC+B20 + 80 ppm CeO₂ is 10.2% and 5.73% higher than 24 °bTDC+B20 + 80 ppm CeO₂ and 27 °bTDC+B20 + 80 ppm CeO₂, respectively.

Cumulative heat represents the amount of heat released due to the combustion of fuel. From Figure 5, it is seen that, injection timing and nanoparticle addition have a combined influence on cumulative heat release. It is observed that advancing the fuel injection and addition of nanoparticles release more heat energy during combustion, as seen highest value of cumulative heat release for 30 °bTDC+B20 + 80 ppm CeO₂, which is 11.7% higher than 30 °bTDC+B20. On comparing various injection timings with CeO₂ added fuel blends, 30 °bTDC+B20 + 80 ppm CeO₂ is 7.8% and 4.1% higher than 24 °bTDC+B20 + 80 ppm CeO₂ and 27 °bTDC+B20 + 80 ppm CeO₂ respectively.

4.4. Exhaust Gas Temperature (EGT)

Figure 6 shows the deviation of $T_{exh}$ for the different fuel blends measured at 100 % loading. Lowest EGT is observed for advancing the injection timing with the addition of nanoparticles whereas highest temperature is observed for retarding the injection timing. As seen from the figure that on delaying the FIT, fuel continues to burn even in the power stroke due to reduced delay period. This causes considerable loss of power and hence exhaust gas temperature will be higher. When the FIT is advanced together with the addition of nanoparticles, a better quality fuel preparation takes place and delay period will be reduced and hence proper combustion takes place releasing higher amount of energy. This reduces the exhaust gas temperature. This value is found to be lesser than the normal injection timing with the addition of nanoparticles as well as neat B20 operation without nanoparticles justifying higher BTE and reduced BSFC for the same combination. The lowest EGT is observed for 30 °bTDC+B20 + 80 ppm CeO₂ and is 6.2% lower as compared to 30 °bTDC+B20.
Figure 5. Cumulative heat release for the test fuels at full load.

Figure 6. Exhaust gas temperature vs load.
5. Emissions

5.1. Hydrocarbon (HC) emission
HC unburnt hydrocarbons are mainly caused due to the carbon deposits at the cylinder walls and liners quenching effect near the walls of the cylinder etc., carbon deposits due to the lubricating oil etc. Figure 7 shows the HC emission for all tested fuel variants. For the fuel with adding nanoparticles, for the advanced injection timing, HC emission is lowest and fuel without nanoparticles showed highest. When the injection is advanced and CeO$_2$ nanoparticles are added, quality of the fuel blend mixture will improve which results in reduced delay period. Catalytic action of CeO$_2$ nanoparticles also ensure the efficient combustion. (Perumal Venkatesan et al., 2019; Shanmugam et al., 2020) These factors contribute for reduced HC emission. For the normal FIT and retarded FIT, fuel preparation will be affected resulting in higher delay period. This reduces the operating cylinder temperature and hence non-efficient combustion which may result in increased HC emission. The lowest HC emission is observed for 30 °bTDC+B20 + 80 ppm CeO$_2$ and is 35% lower as compared to 30 °bTDC+B20.

5.2. NOx emission
NOx emission is most severe pollutant from the biodiesel engine. Detrimental factors responsible for NOx emission are the cylinder operating temperature and availability of Oxygen.(Agarwal & Rajamanoharan, 2009) Higher oxygen content and higher cylinder temperature favour NOx formation. Figure 8 shows the deviation of NOx pollutants for the various fuels tested. It is seen that NOx emission is found to be maximum for B20 fuel without the addition of nanoparticles. With adding nanoparticles, it is seen that NOx emission reduces. This may be due to the catalytic action of CeO$_2$ nanoparticles where in cerous oxide that is formed during reduction of HC will be again converted to cerium oxide by their action with NOx releasing N$_2$ as shown in Eq. (1). As the FIT is

![Figure 7. HC vs load.](image-url)
advanced, NOx emission increases. During advancing the injection, ignition delay decreases resulting in higher peak pressure and operating temperature. This helps to reduce unburnt hydrocarbons to CO2. On the other hand on retarding FIT, due to the late burning of the mixture, cylinder temperature will reduce which reduces NOx. (Janakiraman et al., 2020; Leach et al., 2021) But this also results in loss of useful power output as discussed in the previous section. On comparing various injection timings with CeO2 added fuel blends, 24 °bTDC+80 ppm CeO2 shows lowest NOx emission and is 15.8% lower than 30 °bTDC+B20. Among the nanoparticle added fuel blends, 24 °bTDC+B20 + 80 ppm CeO2 exhibits lowest NOx emission and is 11.4% and 13.4% lower than 27 °bTDC+B20 + 80 ppm CeO2 and 30 °bTDC+B20 + 80 ppm CeO2, respectively.

\[ \text{Ce}_2\text{O}_3 + \text{NO} \rightarrow 2\text{Ce}_2\text{O}_2 + \frac{1}{2}\text{N}_2 \]  

(2)

5.3. CO emission

Variation of CO emission is depicted in Figure 9. CO formation is mainly due to incomplete combustion fuel in the cylinder. The reasons being, lack of oxygen, shortage of time available for combustion etc. In general, CO emission is lower at part load conditions, and increases sharply at higher loads, since more fuel rich mixture is supplied for combustion. When nanoparticles are added to base fuel, due to improved dispersion, vaporisation and effective heat transfer, better combustion will be achieved. This prevents the formation of CO. As seen from the Fig. injection timing also has an influence on CO formation. Addition of nanoparticles to the fuel blend and advancing the injection timing, improves combustion and hence formation of CO will be reduced. From the results obtained, it is observed that, 30 °bTDC+B20 + 80 ppm CeO2 having lowest CO emission and is 22% lower than 30 °bTDC+B20.
Figure 9. CO vs load.

Figure 10. Smoke emission vs load.
5.4. Smoke opacity
Smoke emission is mainly influenced by the air fuel equivalence ratio, spray behaviour of the fuel and cylinder temperature. Figure 10 shows variation in smoke levels with the load for all fuels tested. It is seen in general at low loads smoke emission will be very marginal and after around 50% of loading condition it increases rapidly, and maximum value occurs at 100% of the loading. When the fuel is injected under FIT advanced by 3°, and CeO₂ nanoparticles are doped into the blend, it is seen that smoke emission considerably reduces. Increased temperature and pressure due to advancing the injection timing, reduced the delay period and catalytic influence of CeO₂ nanoparticles as shown in Eq. (2), are responsible for the reduced smoke emission.(Karthic et al., 2020; Selvan et al., 2009) similarly, when the injection is retarded, delay period will be increased leading to inefficient combustion and this contributes to the increase in smoke emission. This is suppressed by the catalytic action of CeO₂ nanoparticles for these fuels as it is clearly visible that for the non-doped fuel blend smoke emission is maximum. In the present study, the lowest smoke opacity is observed for 30 °bTDC+B20 + 80 ppm CeO₂ and is 14.2 % lower as compared to 30 °bTDC+B20.

\[ 4\text{CeO}_2 +\text{C}_{\text{soot}} \rightarrow 2\text{Ce}_2\text{O}_3 + \text{CO}_2 \]  

(3)

6. Conclusions
In the current study, experimental investigation in a biodiesel engine is conducted to study the impact of injection timing on the engine combustion. Fuel blend is prepared by doping 80 ppm of nanoparticles to B20 WCO biodiesel mixture. Current study reports can be concluded as:

- By advancing the injection timing and adding CeO₂ nanoparticles to the blend, BTE is increased by 10.9% and BSFC reduced by 11.1% as compared to the neat B20 biodiesel operation.

- HC and smoke emissions are 35.4% and 14.2% respectively reduced for advancing the injection timing with the adding nanoparticles to the fuel as compared with B20 WCO operation without adding nanoparticles.

- Retarding FIT by 3° as compared to the normal FIT consequences in reduced NOx. On retarding the injection timing and with adding cerium oxide nanoparticles NOx emission declined by 15.8% as compared with neat B20 operation.

- Hence, it can be concluded that by advancing FIT and by adding nanoparticles engine combustion can be improved simultaneously engine emissions can be lowered. This contributes to conserve diesel fuel and also helps to preserve the environment clean by least pollutants.

- Further studies can be conducted by varying the volume fraction and particle size of nanoparticles, to investigate their effect on engine combustion at different fuel injection timings.

Funding
The authors received no direct funding for this research.

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Nomenclature and abbreviations

| Abbreviation | Description                                      |
|--------------|--------------------------------------------------|
| B20          | 20% waste cooking oil biodiesel and 80% mineral diesel |
| BSFC         | brake specific fuel consumption (kg/kWh)         |
| BTE          | brake thermal efficiency (%)                     |
| CeO₂         | cerium oxide                                     |
| Ce₂O₃        | cerous oxide                                     |
| HC           | hydrocarbon (ppm)                                |
| HSU          | Hartridge smoke unit                             |
| NOx          | oxides of nitrogen (ppm)                         |
| WCO          | waste cooking oil                                |
| FIT          | fuel injection timing                             |
| T Parenthood | temperature of the exhaust gas (°C)              |

Disclosure of potential conflicts of interest
No potential competing interest was reported by the authors.

Citation information
Cite this article as: Combined influence of fuel injection strategy and nanoparticle additives on the performance and emission characteristics of a biodiesel fueled engine, Shiva Kumar & Pujikala Dinesha, Cogent Engineering (2021), 1(1), 1999515.

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