Impact of compression ratio on combustion, performance and exhaust emissions of diesel engine fueled with Undi methyl ester-diesel and Undi ethyl ester-diesel blends

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Abstract
The current study emphasizes on the influence of nonedible, easily accessible Undi ester blended diesel in single-cylinder, four-stroke, naturally aspirated, direct-injection variable compression ratio diesel engine. All tests were accomplished by varying volumetric proportions of Undi methyl ester (UME) and Undi ethyl ester by 10%, 20%, 30%, 40%, and 50% and compression ratio (CR) from 16:1–20:1. The Undi esters consolidation to diesel, especially enhances brake thermal efficiency (BTE) and decreases brake specific energy consumption (BSEC) of the engine. In comparison with Diesel, ester fuel blends produce lower unburnt hydrocarbons (UHC), carbon monoxide (CO), and particulate matter (PM) emissions with the cost of higher oxides of nitrogen (NOX). With the increase in compression ratio from 16 to 20. All Undi ethyl ester diesel blends have on an average of 1.44% slightly improved brake thermal efficiency, 1.41% lower brake specific fuel consumption and it emits comparatively on an average 7.90% lesser carbon monoxide, 7.21% lower unburnt hydrocarbon, 0.59% lower particulate matter and 1.94% higher oxides of nitrogen emission than UME diesel blends with an increment in CR from 16 to 20. In addition, ester blends showed higher maximum In-cylinder pressure and heat release rate than commercial diesel. Undi ethyl ester diesel blends show 0.82%, 1.08% on an average higher maximum In-cylinder pressure and heat release rate than UME Diesel blends when CR increased from 16 to 20. Undi ester Diesel blends are found to be utmost substitute to commercial diesel fuel in all features such as combustion, performance and emissions characteristics.

Keywords Undi methyl ester · Undi ethyl ester · Variable compression ratio · Performance-emission · Combustion

Abbreviations
rpm Revolutions per minute
HSU Hartridge smoke unit
ppm Parts per million
aTDC After top dead center
BP Brake power
BSEC Brake specific energy consumption
BSFC Brake specific fuel consumption
BTE Brake thermal efficiency
CI Compression ignition
CO Carbon monoxide
CO$_2$ Carbon dioxide
CR Compression ratio
CRDI Common rail direct injection
DI Direct injection
D100 100% Diesel
EGT Exhaust gas temperature
EPA Environmental protection agency
HRR Heat release rate
MFB Mass fraction burn
IC Internal combustion
NO$_X$ Oxides of nitrogen
PM Particulate matter
SD Standard deviation
SOC Start of combustion
SOI Start of Injection
TSU Total sampling uncertainty
UHC Unburned hydrocarbon

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The introduction of Undi biodiesel has been a significant development in the field of renewable energy sources, particularly in India, Southeast Asia, and Australia [22–26]. Undi biodiesel is more economical, more ecological, easily cultivable in any wastelands and has an advantage over many non-edible oils stated by many researchers and investigators [26, 27]. Minimum production cost and plentiful availability are the attractive characteristics of Undi biodiesel. It is obtained in two forms i.e., methyl and ethyl ester, using the transesterification processes by methanol and ethanol as a catalyst, respectively. In addition, a number of research studies have been documented that the physiochemical properties of Undi methyl ester (UME) and Undi ethyl ester (UEE) biodiesels are almost similar and comparable to the commercial diesel [26–38].

Saridemir and Agbulut [29] conducted experimental study using cottonseed methyl ester for evaluating combustion, performance, vibration and noise analysis under various engine loads. It is reported that cottonseed biodiesel can easily substitute the commercial diesel without any alterations in diesel engines. Saridemir et al. [30] examine the influence of corn oil methyl ester–diesel blends on performance, combustion and emission characteristics at variable injection pressure 210 and 230 bar. At low injection pressure due to increase in proportion of corn methyl ester in diesel increases SFC and decreases thermal efficiency because of lower heating value of fuel. Lapuerta et al. [31] studied the effect of waste frying oil methyl and ethyl ester on the direct injection (DI) compression ignition (CI) engine. They concluded that the 100% waste frying oil methyl and ethyl ester had higher brake specific fuel consumption (BSFC) and lower oxides of nitrogen (NOX), unburned hydrocarbon (UHC), smoke opacity, and particular matter emissions than conventional diesel fuel. In the light of this another significant contributor Baiju et al. [32] investigated the production and performance-emission characteristics of Karanja methyl and ethyl ester as an alternative fuel for diesel engines at varying load conditions. Karanja methyl and ethyl ester showed lower brake thermal efficiency (BTE) and NOX at the cost of approximately higher BSFC, CO, and smoke opacity than diesel operation. Research studies of Alptekin et al. [33] revealed that, at varying engine speeds, the methyl and ethyl ester exhibited higher BTE and lower BSFC than commercial diesel. They also concluded that the methyl ester and ethyl ester showed 3% and 3.6% higher In-cylinder pressure than diesel operation, respectively.

On juxtaposing the present-day converging vehicular exhaust emission norms and economic crisis, the CI engine operation needs to perform effectively so that higher engine performance can be obtained alongside lower exhaust emissions. However, employing biodiesel to achieve lower exhaust emissions along with comparable or higher engine performance is a very arduous operation with the fuel alteration alone. Biodiesels generally have approximately lower calorific value than conventional diesel that sometimes results in lower BTE than diesel. An increase in the compression ratio (CR) for various biodiesel blends exhibits

| UME  | Undi methyl ester |
|------|-------------------|
| UME10 | 10% Undi methyl ester + 90% diesel |
| UME20 | 20% Undi methyl ester + 80% diesel |
| UME30 | 30% Undi methyl ester + 70% diesel |
| UME40 | 40% Undi methyl ester + 60% diesel |
| UME50 | 50% Undi methyl ester + 50% diesel |
| UEE  | Undi ethyl ester |
| UEE10 | 10% Undi ethyl ester + 90% diesel |
| UEE20 | 20% Undi ethyl ester + 80% diesel |
| UEE30 | 30% Undi ethyl ester + 70% diesel |
| UEE40 | 40% Undi ethyl ester + 60% diesel |
| UEE50 | 50% Undi ethyl ester + 50% diesel |
| VCR  | Variable compression ratio |
comparable performance characteristics with respect to the conventional diesel fuel operation of the CI engine [34]. Higher CR helps in delivering higher In-cylinder temperature and pressure that ultimately results in higher brake BTE [35–39]. An experimental study of Sayin et al. [40] varied the CR from 17:1 to 19:1 of a Diesel engine and reported that an increase in CR resulted in better BTE, BSFC, and BSEC than lower CR. Their studies also documented that the higher CR also assisted to reduce the CO, UHC, and smoke opacity emissions of the engine. Moreover, Vasudeva et al. [41] investigated the performance, exhaust emissions, and combustion characteristics of a variable compression ratio (VCR) engine fuelled with esters of crude rice bran oil. Their investigation concluded that higher CR helps in improving BTE, BSFC, CO, In-cylinder pressure at the cost of higher NOX and carbon dioxide (CO2). Dubey et al. [42] and Rosha et al. [43] also documented similar results of CI engines under varying CR. In the context of the aforementioned research studies, the present research, thus endeavors assessment of ethyl and methyl esters produced from Undi oil by varying compression ratio was hardly explored. To shelter this innovative issue, biodiesels from Undi oil based on ethyl and methyl alcohols were verified by means of a VCR engine. Consequences about their effect on the engine performance, exhaust emissions, and combustion characteristics of bio-based UME and UEE under varying CR and compared to those of each other and to those of pure diesel fuel under present-day vehicular exhaust emission mandates.

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The motivation and objective of the present work

The abrupt rise in diesel power train demand, fuel price policies, stringent vehicular exhaust emission norms and economic recession due to the COVID-19 pandemic instigate the CI engine developers to look for the alternative and viable path of energy supply to fully or partially supplant the conventional diesel fuel. In reference to this alternative fuel can be a reliable option to support the converging exhaust emission mandates and economy of the nation. Due to the lockdown in the industrial and transportation sectors during the COVID-19 pandemic, the global pollution level has drastically reduced. To keep up the pollution level reduction rate, biofuel-based non-edible biodiesels are the effective choice for supporting the global energy demand. In light of the availability and easy extraction of biodiesel, its production cost is very low. Moreover, utilization of available biofuels would make an approach to strengthen the economy of the nation. A number of researchers [15, 22–25] have documented the effectiveness of UME and UEE under the CI engine domain. As discussed earlier, in order to achieve lower exhaust emissions engine modification is required under a higher amount of replacement of conventional diesel fuel by biodiesel. Varying CR has an aspect in improving the performance, combustion, and exhaust emission parameters of the CI engine using higher amount biodiesel blends. On the other hand, the feasibility and comparison of UME and UEE on the detailed performance, combustion, and exhaust emission characteristics of the CI engine under higher CR has not been extensively and specifically archived. Consequently, the engine experimentation is conducted with UME and UEE under varying CR to fill these gaps.

In the perspective of the above discussion the following are the proposed objectives based on the aforementioned motivation of the current experimental investigation:

- To minutely compare the performances, combustion, and exhaust emissions of UME and UEE diesel blends with respect to commercial diesel fuel operation
- To briefly explore and compare the impact of CR on the performance, combustion, and exhaust emission paradigms of an existing CI engine under UME and UEE diesel blends.

Experimental setup and procedure

The experiments were carried out on a single-cylinder, four-stroke, direct injection, naturally aspirated, water-cooled, stationary VCR CI engine. With the help of an eddy current dynamometer, the VCR engine was operated at 100% of full load condition with a constant speed of 1500 (± 10) rpm for CR 16:1, 17:1, 18:1, 19:1, and 20:1. Figure 1 portrays the schematic of the VCR CI engine experimental setup, and Table 1 details its specifications. The exhaust fumes of the VCR engine, namely, NOX, UHC, CO, and smoke opacity were measured by using Netel (India) Limited (Model: NPM-MGA-1) exhaust gas analyzer and smoke meter, respectively. Using the governing equation, the smoke opacity is further converted into a particular matter (PM). With the purpose of recording reference data, the VCR engine was first operated with commercial Diesel fuel. Later, 10%, 20%, 30%, 40%, and 50% UME and UEE were added to diesel fuel in volumetric proportions and tested separately. The UME blended diesel fuels were denoted as UME10, UME20, UME30, UME40, and UME50 and the UEE blended diesel fuels were denoted as UEE10, UEE20, UEE30, UEE40, and UEE50, respectively. The engine experimental program is presented in Table 2. The comparison of physicochemical properties of the base fuels is presented in Table 3. After the completion of the engine experiments with Diesel fuel, the whole fuel supply was cleaned up for keeping away the blended fuel from contamination. This was repeated for each of the blended fuels and each of the operating conditions was repeated and recorded six times.
**Table 1** Specifications of the VCR CI engine

| Engine type | Four-stroke, naturally aspirated, water-cooled, direct injection compression ignition engine |
|-------------|--------------------------------------------------------------------------------------------------|
| Make        | Kirloskar                                                                                       |
| Stroke × bore | 110 mm × 80 mm                                                                                  |
| Rated power | 1500 rpm@3.7 kW                                                                                 |
| Compression ratio | 16:1–20:1                                                                               |
| Method of starting & loading | Manual crank starting & eddy current dynamometer                                                   |

**Table 2** Engine experimental program

| Sl. No | Biodiesel used | Volumetric proportions | Engine load % & speed (RPM) | Compression ratio |
|--------|----------------|-------------------------|----------------------------|------------------|
| 1      | Diesel         | D100                    | Full load (100%) & 1500 (± 10) RPM | 16:1 to 20:1 |
| 2      | Undi methyl ester | UME 10, UME 20, UME 30, UME 40, UME 50 | Full load (100%) & 1500 (± 10) RPM | 16:1 to 20:1 |
| 3      | Undi ethyl ester | UEE 10, UEE 20, UEE 30, UEE 40, UEE 50 | Full load (100%) & 1500 (± 10) RPM | 16:1 to 20:1 |

**Table 3** Physicochemical properties of base fuel

| Biodiesel | Density/kg m⁻³ | Viscosity/cSt at 20 °C | Cetane number | Oxygen content/mass. % | Calorific value/kJ kW⁻¹ | Flash point/°C | Fire point/°C | Ash content/% |
|-----------|-----------------|-------------------------|---------------|------------------------|--------------------------|---------------|--------------|---------------|
| Diesel    | 836             | 2.65                    | 50            | 0                      | 42,500                   | 80            | 110          | 0.01          |
| UME       | 856             | 3.58                    | 60            | 10.6                   | 39,210                   | 160           | 170          | 0.006         |
| UEE       | 857             | 3.56                    | 61            | 10.8                   | 39,420                   | 180           | 188          | 0.007         |
The average value of the repeated data was preferred as the final output of the VCR engine operation which was conducted at an ambient temperature of 298–303 K and relative humidity of ~70%.

**Uncertainty analysis**

Uncertainties are a common and vital measurement in any experimental investigation to verify the accuracy of the experiment that takes place because of the chosen instrument, calibration, environmental condition, observations, scrutiny, and testing plan [8, 13–15]. The uncertainty of the existing engine performance parameters was analyzed using root-mean-square method. The total uncertainty \( U \) of a quantity \( Q \) was projected, contingent on the independent variables \( x_1, x_2, \ldots, x_n \) having individual errors \( \Delta x_1, \Delta x_2, \ldots, \Delta x_n \) is given by Eq. (1) [13, 14]) is applied to study and measure the uncertainties of outputs of the VCR CI engine operation under UME and UEE blends. Table 4–6 detail the uncertainties of the VCR CI engine performances, computing ranges and precisions of the NPM-MGA-1 exhaust emission analyzer and smoke meter, and total sampling uncertainty (TSU) and standard deviation (SD) of the exhaust emission parameters, respectively.

\[
\Delta U = \sqrt{\left( \frac{\partial U}{\partial x_1} \Delta x_1 \right)^2 + \left( \frac{\partial U}{\partial x_2} \Delta x_2 \right)^2 + \ldots + \left( \frac{\partial U}{\partial x_n} \Delta x_n \right)^2}
\]

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**Table 4** Uncertainties of the existing engine performance parameters

| Computed performance parameter | Measured variables | Instrument involved in the measurement | Percentage uncertainty of the measuring instrument | Calculation | Total percentage uncertainty of calculated parameter |
|-------------------------------|--------------------|---------------------------------------|-----------------------------------------------|------------|---------------------------------------------------|
| Brake power (BP)             | Load, rpm          | Load sensor                           | 0.1, 0.1                                      | \( \sqrt{0.1^2 + 0.1^2 + 1^2} \) | 1.01                                             |
|                               |                    | Load indicator                        |                                               |            |                                                   |
|                               |                    | Speed ensuring Unit                   |                                               |            |                                                   |
| Brake specific fuel consumption | Specific fuel consumption (SFC) | Fuel measuring unit, fuel flow transmission, As for BP | 0.05, 1                                           | \( \sqrt{0.05^2 + 1.5^2 + 1.01^2} \) | 1.81                                             |
|                               |                    |                                       |                                               |            |                                                   |
|                               |                    | As for SFC                            | 1.5                                            | 1.01       |                                                   |
|                               |                    | As for BP                             | 1.01                                           |            |                                                   |
| BSEC                          | SFC                | As for SFC, As for BP                 | 1.81                                           | \( \sqrt{1.81^2 + 1.01^2} \) | 2.07                                             |

**Table 5** Accuracy of exhaust gas analyzer and smoke meter

| Instrument measuring range | Measuring range | Accuracy |
|----------------------------|-----------------|----------|
| **Exhaust gas analyzer**   |                 |          |
| CO                         | 0–9.99%         | \(< 0.5\%\) volume: \( \pm 0.03\% \) \> 0.5 \% volume: \( \pm 3\% \) |
| CO₂                        | 0–2000%         | \(< 10\%\) volume: \( \pm 0.04\% \) \> 10\% volume: \( \pm 4\% \) volume |
| UHC                        | 0–20,000 ppm    | \(< 200 \text{ ppm}\) volume: \( \pm 10 \text{ ppm}\) \> 200 ppm volume: \( \pm 5\% \) |
| NOₓ                        | 0–5000 ppm      | \(< 500 \text{ ppm}\) volume: \( \pm 25 \text{ ppm}\) \> 500 ppm volume: \( \pm 5\% \) |
| Oxygen                     | 0–25%           | \(< 2\%\) volume: \( \pm 0.1 \text{ volume%}\) \> 2\% volume: \( \pm 3\% \text{ volume%}\) |
| **Smoke meter**            |                 |          |
| Smoke opacity              | 0–500 HSU       | \(< 50 \text{ HSU}\) volume: \( \pm 25 \text{ HSU}\) \> 50 HSU volume: \( \pm 5\% \) |

**Table 6** Average TSU and SD of the exhaust fumes

| Exhaust emission parameter | Average TSU/% | Average SD |
|----------------------------|---------------|------------|
| NOₓ                        | 1.556         | 0.701      |
| UHC                        | 1.609         | 0.899      |
| CO                         | 0.724         | 0.302      |
| Smoke opacity              | 1.155         | 0.399      |
Results and discussion

Performance parameters

Brake thermal efficiency

The variation of BTE of the UME and UEE blended diesel fuels at VCR is shown in Fig. 2a, b. The BTE of all tested UME and UEE blended diesel fuels were increased with the increasing CR and biodiesel share in the blend. From the findings shown in the figure mentioned below, it is evident that the brake thermal efficiency (BTE) of UME blends (on an average 8.38% higher) and UEE blends (on an average 10.24% higher) were higher than commercial diesel at all tested compression ratios. The average increase in BTE for diesel, UME10, UME20, UME30, UME40 and UME50 is 8.60%, 7.29%, 7.65%, 7.62%, 5.61%, and 5.47%, respectively, noted for increase in compression ratio from 16:1 to 20:1. Also, 8.33%, 6.73%, 6.78%, 5.49%, and 5.51% average increase in BTE found with the rise in compression ratios from 16:1 to 20:1 for UEE10, UEE20, UEE30, UEE40 and UEE50 blends, respectively. The higher BTE was found at CR of 20:1 for higher biodiesel blended diesel i.e., for UME50 and UEE50 than other CRs. It was recorded that the BTE of UME50 and UEE50 was 9.28% and 11.47% higher than baseline diesel fuel operation at CR of 20:1. The higher CR could be the reason for higher BTE with UME and UEE blends. As CR increases, In-cylinder pressure and temperature increase inside the combustion chamber. The increased In-cylinder temperature along with the assistance of higher cetane number and oxygen content of the UME and UEE promoted better combustion of the blended fuels and resulted in higher BTE than that of the commercial diesel fuel operation. It may be noted that the In-cylinder pressures (discussed in sub-sub Sect. 3.3.1) of the UME and UEE blends are higher than the diesel operation. When the results of UME and UEE diesel blends are compared separately, it is observed that the BTE of UEE diesel blends is higher than that of the UME diesel blends at all tested CRs. UEE diesel blends have an average of 1.44% higher BTE than UME Diesel blends when CR is increased from 16:1 to 20:1. The higher viscosity and lower volatility of methyl ester could be the reason for the lower BTE of UME diesel blends than UEE diesel blends which influenced the formation of fine droplets and deteriorated the combustion efficiency [13, 22]. The lower calorific value and oxygen content may also be the reason for the lower BTE of UME diesel blends.

Brake specific energy consumption

The BSEC differs with respect to CR’s for different UME and UEE blended diesel fuels is shown in Fig. 3a, b. The BSEC of all UME and UEE blended diesel fuels decreases with an increase in CR and proportion of Undi esters in the blend. From the figure, it is concluded that BSEC of all UME and UEE blends (on an average of 7.73% and 9.28% lower) are lower than commercial diesel. By increasing compression ratio from 16:1 to 20:1 the average decrement found in BSEC for diesel, UME10, UME20, UME30, UME40 and UME50 would be 7.85%, 7.56%, 7.08%, 7.04%, 5.27% and 5.16%. Furthermore, UEE10, UEE20, UEE30, UEE40 and UEE50 provide 7.62%, 6.25%, 6.31%, 5.17%, and 5.19% average decrement in BSEC with increasing CR’s.
from 16:1 to 20:1. As seen in the figure, the UME50 and UEE50 blended Diesel fuel showed lower BSEC at 20:1 CR. The improvement in BSEC is noticed at higher CR and with higher UME and UEE diesel blends is due to increase in In-cylinder temperature decreases the viscosity of inlet charge which leads to better atomization rate of ester fuel. In addition to this deliverance of more oxygen molecules from ester fuels through combustion helps combustibility characteristics of fuel.

When comparing UME and UEE diesel blends to each other, it is realized that BSEC of UEE diesel blends (on an average 1.40%) is found lower than UME diesel blends with the rise in CR from 16:1 to 20:1. UME diesel blends have higher viscosity and lower calorific value which lead to the requirement of more amount of fuel for getting the same power output. Also, the Heat release rate graph shows better combustibility for all UEE diesel blends than UME diesel blends [24]. The reduction in BSEC may have been triggered due to the higher cetane number of UEE diesel blends helps in better combustion thus realizing a higher amount of energy.

**Engine emission characteristics**

**Oxides of nitrogen emissions and unburned hydrocarbon emissions**

The formation of NOX emissions primarily depends upon the combustion duration, cylinder temperature, and oxygen molecules present in tested fuels. Also, many factors such as compression ratio, injection timing, injection pressure, and physiochemical properties of tested fuel effects the NOx formation in diesel engines. The variations of NOX emissions with respect to CR for UME and UEE blended diesel fuels are shown in Fig. 4a, b. The NOX emissions for UME and UEE diesel blend comparably more (on an average 41.26% and 44.67% higher) than commercial diesel for all tested CRs. Concerning the consequence of distinct biodiesel content on the NOX emissions, it is found that the NOX emission increases with the rise in UME and UEE biodiesel proportion in the fuel blend [26, 34–36] and CR. On an average NOX emission is increased by 8.33%, 15.19%, 11.35%, 11.61%, 14.10%, 27.87% for diesel, UME10, UME20, UME30, UME40 and UME50, respectively, for the variation of compression ratio from 16:1 to 20:1. In addition, an average increment in NOX emissions for UEE10, UEE20, UEE30, UEE40 and UEE50 are 12.75%, 11.55%, 12.84%, 17.82% and 24.20%, respectively, when CR is increased from 16:1 to 20:1. The UME50 and UEE50 biodiesel blends have higher NOX emissions at CR of 20:1 than other CRs and biodiesel blends. The UME50 and UEE50 give 83.38% and 83.49% higher NOX emissions than baseline diesel operation at 20:1 CR.

An increment in CR increases In-cylinder combustion temperature. Also, the presence of a higher quantity of oxygen molecules in UME and UEE blended diesel fuel blends favored higher formation in NOX emissions and consequently increases the BTE for all UME and UEE blended diesel fuel blends compared to commercial diesel. All UEE diesel blends showed (on an average 2.01%) higher NOX emissions than UME diesel blends when CR increases from 16:1 to 20:1. The earlier start of combustion for UEE diesel blends (higher cetane number and lower density) compared to UME diesel blends has resulted in higher NOX emissions.
Figure 5a, b represents the variation of unburned hydrocarbons (UHC) emissions with respect to CR for UME and UEE blended diesel fuels. The formation of UHC emissions mainly depends on the equivalence ratio, operational conditions, and physiochemical properties of the fuel. The UHC emissions of UME Diesel blends (on an average 33.06% lower) and UEE diesel blends (on an average 33.06% lower) were lower than diesel fuel operation for all tested CR’s from 16:1 to 20:1. With the increase in CR from 16:1 to 20:1 the UHC emissions decrease on an average of 13.07%, 17.07%, 19.47%, 31.12%, 29.92% and 19.18% for diesel, UME10, UME20, UME30, UME40 and UME50 blends, respectively. Moreover, for UEE10, UEE20, UEE30, UEE40 and UEE50 blends gives 18.77%, 17.98%, 20.03%, 12.85% and 23.97% on an average lower UHC emissions when compression ratio is increased from 16:1 to 20:1. The UHC emissions are decreased with the increment in CR and quantity of UME and UEE in diesel. It is noticed that higher In-cylinder temperature along with additional oxygen content in UME and UEE blended diesel fuel blends improves the rate of combustion process and oxidation of UHC emissions. Also, high HRR’s and lower ignition delay were observed for all UME and UEE blended diesel fuel blends which conclude the better combustion characteristics of ester fuels. All UME
diesel blends emit an average of 7.22% higher UHC emissions than UEE diesel blends when CR increased from 16:1 to 20:1. The lower UHC emissions observed for UEE diesel blends are due to its higher cetane number which decreases the ignition delay. The shortened ignition delay confines the quantity of UHC disposed of by fuel.

The combined form of NO$\text{\textsubscript{x}}$ and UHC emissions is represented as NOHC emissions which are introduced in EPA Tier 4 CI engine exhaust emission standards for below 8 kW engines with 7.5 g kWh$^{-1}$ upper limit value. When CR and UME and UEE blended diesel fuel blends are analyzed separately all ester blends show higher NOHC emissions than commercial diesel which is less than EPA Tier 4 emissions norms shown in Fig. 6a, b. The NOHC emissions of UME diesel blends (on an average 28.90% higher) and UEE diesel blends (on an average 30.64% higher) are higher than commercial diesel for all tested CRs from 16:1 to 20:1. UME diesel blends show 1.5% less NOHC than UEE diesel blends when CR increased from 16:1 to 20:1.

**Carbon monoxide emission**

The air–fuel ratio is a very important constraint that influences the formation of CO emissions in the diesel engine. Furthermore, the inadequacy of oxygen molecules and time essential for oxidizing the CO to CO$\text{\textsubscript{2}}$, inefficacious mixing of air and fuel situated in a rich zone of the combustion chamber are also considerable constraint influences on CO

![Fig. 6 a, b Variations of NOHC for UME and UEE blends with respect to CR](image)

![Fig. 7 a, b Variations of CO for UME and UEE diesel blends with respect to CR](image)
emissions. The variations of CO emissions with respect to different CR for UME and UEE blended diesel fuels are shown in Fig. 7a, b. The CO emissions of UME diesel blends (on an average 38.18% lesser) and UEE diesel blends (on an average 43.24% lesser) are lesser compared to commercial diesel at all tested CR’s from 16:1 to 20:1. The lower CO emissions were found at CR of 20:1 for UME50 and UEE50 than other CRs and diesel blends. It was noted that the CO emissions of UME50 and UEE50 were 62.90% and 67.96% lower than baseline diesel fuel operation at CR of 20:1. The reduction in viscosity with an increase in temperature of the combustion chamber atomizes all fuel droplets which becomes good enough to decrease the concentration of CO emissions for all UME and UEE blended diesel fuels. Also, a higher amount of oxygen content and cetane number of ester blends improves the combustion quality with a reduction in the ignition delay period. For diesel, UME10, UME20, UME30, UME40 and UME50 on an average CO emission is decreased with 12.68%, 11.48%, 23.04%, 27.55%, 21.60%, and 17.72%, respectively, with increase in CR from 16:1 to 20:1. Moreover, an average decrease in CO emission is obtained 14.44%, 7.04%, 17.79%, 12.38% and 15.52% for UEE10, UEE20, UEE30, UEE40 and UEE50 ester blends, respectively, when CR increased from 16:1 to 20:1. With increases in CR and mass fraction of UME and UEE in diesel blend, CO emissions decrease. It is due to oxygen affluence and increases in In-cylinder temperature that bids a promising environment for combustion and oxidation of UME and UEE blended diesel fuels in the combustion chamber.

When comparing UME and UEE blended diesel fuels separately, it is clear that all UME diesel blends offer on an average 7.90% higher CO emissions than UEE diesel blends when CR increases from 16:1 to 20:1. The lower CO emissions for UEE blends are due to their higher cetane number and lower ignition delay period.

**Particulate matter emission**

Soot is an unwanted byproduct of the combustion process in the diesel engine. Figure 8a, b represents the variation of soot particulate emissions with respect to CR for UME and UEE blended diesel fuels. As CR increases from 16:1 to 20:1, all the diesel blends of UME (on an average 26.07% lower) and UEE (on an average 26.67% lower) show lower soot particulate emissions compared to commercial diesel operation. It is also clear from the figure; soot particulate emissions decrease with an increase in the proportion of ester fuel in blend and CR. On an average soot particulate emission decreases 15.26%, 16.67%, 18.94%, 25.4%, 28.94% and 20.99% for Diesel, UME10, UME20, UME30, UME40 and UME50 biodiesel bends, respectively, for the rise of compression ratio from 16:1 to 20:1. Furthermore, for UEE10, UEE20, UEE30, UEE40 and UEE50 biodiesel blends when CR increased from 16:1 to 20:1 average soot particulate emission decreases 1.82%, 18.83%, 24.94% 27.43% and 22.16%, respectively. As CR is increased In-cylinder temperature also is increased due to the higher rate of burning of fuel inside the combustion chamber which results in the disintegration of ester fuel blends and releases more oxygen molecules. The presence of oxygen molecules reduces the probability of soot formation and promotes further oxidation of soot in the case of ester fuel blends. CO emissions for UME and UEE blended diesel fuels (shown in Fig. 7a, b) confirm the lower soot particulate emissions than commercial diesel operation.
The variations of unburned hydrocarbon particulate and particulate matter emissions (PM) with respect to CR for UME and UEE blended diesel fuels are shown in Figs. 9a, b and 10a, b, respectively. By relating the effects of ester proportion and increment in CR to the PM emissions, it is found that the increase in ester concentration and CR results decrease in PM emissions for all UME (on an average 26.86% lower) and UEE (on an average 27.44% lower) diesel blends. The reduction in PM emissions for diesel, UME10, UME20, UME30, UME40 and UME50 biodiesel blends reported on an average 15.11%, 16.73%, 18.90%, 25.12%, 28.22% and 21.07% for rise in CR from 16 to 20, respectively. In addition to this on an average reduction of 18.83%, 18.78%, 24.68%, 28.69% and 22.24% PM emission for UEE10, UEE20, UEE30, UEE40 and UEE50, respectively, is found with increase in CR from 16:1 to 20:1. The reduction in PM emissions occurs due to higher In-cylinder temperature in the combustion chamber and oxygen content in ester fuel blends tends to better combustion and oxidation of carbon particles.

All the UME diesel blends show higher soot particulate, unburned hydrocarbon particulate, and PM emissions than UEE diesel blends for all tested CR from 16:1 to 20:1. UME diesel blends have an average of 0.61% of soot particulate, 0.3% of unburned hydrocarbon particulate, and...
0.59% PM emissions higher than UEE diesel blends when CR increases from 16:1 to 20:1.

**Combustion parameters**

**In-cylinder pressure**

The variations of In-cylinder pressure for all diesel fuel blends of UME and UEE at different CR are shown in Figs. 11a-e and 12a-e. As seen in figures, UME (on an average 5.88%) and UEE (on an average 4.84%) diesel blended fuels were found higher In-cylinder pressure than commercial diesel for all tested CRs. The peak In-cylinder pressure occurred nearer to the top dead center (shown in Fig. 14a, b) for all UME and UEE diesel blended fuels. This may be happened because of the advanced SOC of ester fuels. As UME and UEE diesel blends have higher cetane number which decreases ignition delay (shown in Fig. 17a, b) resulting in early SOC for all ester fuels. With the increment in CR and proportion of biodiesel in diesel blend peak of maximum In-cylinder pressure rises (shown in Fig. 13a, b) for diesel and all UME and UEE diesel blends. At a higher compression ratio, the temperature and pressure of air in the combustion chamber are higher which leads better evaporation of inlet fuel results in better combustion and higher maximum In-cylinder pressure. From all UME diesel blend, UME50 shows higher maximum cylinder pressure (92.71 bar) at 20 CR is attained at 5.77º aTDC. Likewise, UEE50 has higher maximum cylinder pressure at 20 CR and 5.61º aTDC. The average increase in maximum In-cylinder pressure for diesel, UME10, UME20, UME30, UME40 and UME50 are 16.24%, 12.57%, 15.24%, 15.56%, 16.18%, and 16.39%, respectively, when CR is increased from 16:1 to 20:1. Furthermore, an average increase in maximum cylinder pressure of 13.78%, 14.44%, 14.92%, 16.88% and 16.96%, respectively, for UEE10, UEE20, UEE30, UEE40 and UEE50 is obtained when CR increased from 16:1 to 20:1.

From Fig. 11a, b-14a, b, it is found that when CR is increased from 16:1 to 20:1, all the diesel blends of UME and UEE show a slightly close peak of maximum In-cylinder pressures. This may be ascribed to attain closer SOI and SOC near the top dead center as CR increased from 16:1 to 20:1. Comparable results are found in several kinds of literatures using biodiesel in direct injection and CRDI diesel engines [19, 21].

**Heat release rate (HRR)**

The HRR of the VCR engine is investigated based on the changes in crank angle variations of the cylinder. Evaluation of heat release rate of UME and UEE blended diesel fuels for various CR are shown in Figs. 15a-e and 16a-e. The negative heat release rate is noted for all the UME and UEE
blended diesel fuels at each CR is due to the absorption of heat for evaporation of fuel rather than procreation during ignition delay.

When examining the heat release rate of UME and UEE blended diesel fuels it is clear that SOC is earlier for all UME and UEE diesel blends. Therefore, diesel shows a lesser peak of heat release rate than UME (on an average 57.15% higher) and UEE (on an average 64.18% higher) diesel blends. Another reason for the higher value of the maximum heat release rate is the higher amount of oxygen content and higher density of ester fuel blends leads to improvement in the combustion of fuel. Also, from the figure, it is found that the maximum peak of heat release rate increases with an increase in CR and proportion of ester fuels in diesel. It is also noticed that an increment in the CR, the peak of heat release point moving toward the TDC leads to the early SOC may be due to the decrement in the ignition delay period (shown in Fig. 17a, b). As CR increases, the temperature inside the cylinder increases which helps in the fuel evaporation process. Average increment in maximum peak of heat release rate for diesel, UME10, UME20, UME30, UME40 and UME50 are 9.63%, 2.44%, 6.63%, 6.62%, 8.59% and 5.40%, respectively, when CR is increased from 16:1 to 20:1. In addition to this average rise in heat release rate found 6.18%, 3.01%, 6.67%, 6.26% and 5.82%, respectively, for UEE10, UEE20, UEE30, UEE40, and UEE50 when CR increases from 16:1 to 20:1.

When UME and UEE blended diesel fuels are analyzed independently it is realized that UEE diesel blends burn earlier than UME diesel blends due to their higher cetane number. Therefore, UEE diesel blends have a higher peak of heat release rate than UME diesel blends. UEE diesel blends have on an average 1.08% higher peak of maximum heat release rate than UME diesel blends when CR is increased from 16:1 to 20:1.

**Ignition delay**

In a CI engine, the ignition delay period significantly influences performance, smoke existence in the exhaust, and engine operating parameters. Figure 17a, b denotes the variations in the ignition delay for UME and UEE blended diesel fuels with respect to CR. From the figure, it is seen that ester fuel blends show lower ignition delay than commercial diesel. It is also observed that for UME and UEE blended diesel fuels ignition delay decreases with an increase in CR. The reason may be the enhancement in the density of air during the compression stroke, which allows more interaction of fuel molecules and oxygen molecules which decreases the time of reaction. Also, increment in CR increases the In-cylinder temperature which provides faster evaporation of fuel and leads to an early approach of autoignition temperature and reduces the ignition delay. The average decrease in
ignition delay period for diesel, UME10, UME20, UME30, UME40 and UME50 blends are found 13.02%, 11.81%, 8.07%, 9.99%, 10.92% and 10.95%, respectively, for the increment in CR from 16:1 to 20:1. Furthermore, average decrease in ignition delay is found 9.61%, 7.33%, 10.21%, 9.96% and 8.35% for UEE10, UEE20, UEE30, UEE40 and UEE50 blends with increase in compression ratio from 16:1 to 20:1.

From the comparison of the ignition delay period for tested UME and UEE blended fuels, it is found that all UEE blends recorded a lower ignition delay period than UME diesel blends. This may be due to the higher cetane number of UEE diesel blends.

**Combustion duration**

Combustion duration is characterized by the difference of crank angle position for 90% MFB and 10% MFB. The variations of combustion duration with different CR for UME and UEE blended diesel fuels are shown in Fig. 18a, b. All UME and UEE diesel fuel blends show lower combustion duration than commercial diesel. It is because of the presence of additional oxygen content in ester fuels which promotes faster combustion and higher combustion rate along with the reduction in ignition delay (shown in Fig. 17a, b). From Fig. 18a, b, it is also observed that with the increase in CR combustion duration is decreased.
Fig. 15 a-e Variations of HRR for UME diesel blends

Fig. 16 a-e Variations of HRR for UEE diesel blends
for ester fuel blends and commercial diesel. When CR is increased the In-cylinder temperature is also increased which increases the rate of vaporization of fuel resulting shorter combustion duration for UME and UEE diesel fuel blends.

UEE diesel blends show lower combustion duration than UME diesel blends at all tested CR from 16:1 to 20:1. UEE diesel blends show an average 4.32% lower combustion duration than UME diesel blends when CR increases from 16:1 to 20:1.

![Fig. 17 a, b Variations of ignition delay for UME and UEE Diesel blends with respect to CR](image1)

![Fig. 18 a, b Variations of combustion duration for UME and UEE Diesel blends with respect to CR](image2)

**Conclusions**

The present study investigates and compares the impact of VCR on the performance-emissions and combustion attributes of multifuel VCR engine fueled with UME and UEE blended diesel fuels and compared with commercial diesel. The prominent conclusions of current investigations are drawn as follows:
Undi ester fuel addition to diesel fuel improves the In-cylinder pressure, HRR, BTE, and reduced the BSEC of the engine as compared with base diesel operation, which designated possible replacement potential of diesel by a bio-based Undi ester fuel and its blends.

The UEE diesel blends show 1.44% average higher BTE and 1.41% average lower BSEC than UME diesel blends when CR increased from 16:1 to 20:1.

The Undi ester diesel blends emitted less CO and UHC emissions with the cost of higher NOX emissions than commercial diesel.

All Undi ester diesel bends show slightly decrement in ignition delay which improves the combustion characteristics of the engine.

All UEE diesel blends have better emission profiles (on an average 7.90% lower CO, 7.21% lower UHC, and 1.94% higher NOX) over UME diesel blends when CR increases from 16:1 to 20:1

The PM emissions of UME and UEE blended diesel fuels show lower than commercial diesel for all CR. A comparison of ester fuels revealed that UME diesel blends have an average of 0.59% more PM emissions than UEE diesel blends.

The additional inclusive and powerful study on the Undi methyl and ethyl ester practice must be accomplished by means of diesel engines furnished with electronically-controlled common-rail direct injection system, especially for varying injection timing and pressure with EGR. Thus the future study aimed to examine the effect of varying injection timing and pressure with EGR to compare the effects on the performance, emissions and combustion parameters using Undi methyl and ethyl ester diesel blends.

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