Pertanika J. Sci. & Technol. 32 (4): 1565 - 1589 (2024)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

The Green Energy Effect on an HCCI Engine from Used Cooking Oil-based Biodiesel from Malaysia

Muntasser Abdulabbas Mossa*, Abdul Aziz Hairuddin, Nuraini Abdul Aziz and Hasyuzariza Muhamad Tobib

Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia

ABSTRACT

Emissions from internal combustion engines (ICEs) significantly impact the environment, leading continents worldwide to work towards reducing them. The industry is increasingly leaning towards electric powertrains. However, power plants still utilize ICEs as generators, contributing to global pollution. Consequently, ICE emissions are garnering international attention. Alternatives like the Homogeneous Charge Compression Ignition (HCCI) engine and biodiesel fuels are being explored. HCCI engines have not been extensively tested with Used Cooking Oil (UCO) biodiesel. This study investigates the performance and emissions of HCCI engines using UCO-based biodiesel. This study tested an air-cooled, single-cylinder, 4-stroke diesel engine operating at 3600 rpm with a displacement of 0.219 liters. The HCCI mode was activated during preheating and run at 2700 rpm under varying biodiesel blend percentages and intake temperatures. In HCCI mode, brake-specific fuel consumption (BSFC) increased, peaking at a 90°C intake temperature. Diesel fuel in-cylinder pressure reached a maximum of 81 bars at 90°C, decreasing to 79 bars at 70°C. The HCCI mode resulted in lower NOx, CO, and UHC emissions. Higher biodiesel blend ratios further reduced CO emissions. Raising the intake air temperature to 90°C lowered NOx emissions by 96.66%, from 150 ppm to 5 ppm. Using green energy sources as fuel in HCCI engines significantly reduced emissions in this study, suggesting their potential as a future fuel for advanced engines.

Keywords: Biodiesel, CI engine, emissions, HCCI, UCO

ARTICLE INFO

Article history:
Received: 25 June 2023
Accepted: 18 December 2023
Published: 16 July 2024

DOI: https://doi.org/10.47836/pjst.32.4.07

E-mail addresses:
memo.alprince41@gmail.com (Muntasser Abdulabbas Mossa)
ahziz@upm.edu.my (Abdul Aziz Hairuddin)
nuraini@upm.edu.my (Nuraini Abdul Aziz)
hasyuzariza5914@gmail.com (Hasyuzariza Muhamad Tobib)
* Corresponding author

ISSN: 0128-7680
e-ISSN: 2231-8526

INTRODUCTION

HCCI (Homogeneous Charge Compression Ignition) engines have a promising future in various applications. These engines are notable for their fuel efficiency and low NOx emissions. In certain HCCI engines, fuel is injected during the intake stroke to create a homogeneous mixture. Effective control of ignition and combustion in HCCI engines is crucial and requires specific techniques. Studies have shown that using particular fuel blends can control the combustion process in HCCI engines, enhancing efficiency while reducing emissions (Khandal et al., 2019; Özer et al., 2021; Thrlng, 2011). Fuel is injected into the inlet manifold, mixed with hot air, and the air temperature is further increased using an inlet air heater (Özer et al., 2021). The compression ratio is adjusted, and an EGR (Exhaust Gas Recirculation) system is employed to achieve HCCI mode. Challenges in premixed diesel-fueled HCCI engines include early ignition leading to knocking, increased liquid fuel presence in the intake manifold, and reduced combustion efficiency, resulting in higher HC emissions.

Several studies have reported reductions in NOx and other emissions using the premixed technique for diesel-HCCI (Christensen et al., 1999; Garcia et al., 2011; Gray & Ryan, 1997) also used the premixed technique for diesel-HCCI and reported a reduction in NO_x and other emissions. Early direct injection in HCCI allows efficient fuel vaporization and mixing in hot compressed air. Engine combustion is influenced by several factors, including the homogeneity of the air-fuel mixture, inlet temperature, and chemical kinetics (Banapurmath et al., 2008). A lower percentage of biodiesel blend has been found to improve Brake Thermal Efficiency (BTE) and slightly decrease Brake Specific Fuel Consumption (BSFC). Other studies have experimented with methyl esters combined with Honge oil, jatropha oil, and sesame oil in DI diesel engines, often resulting in lower performance (Rashed et al., 2016). Methyl esters were used with Honge oil, jatropha oil, and sesame oil in a DI diesel engine, resulting in low performance. Puhan et al. (2005) improved Brake Power (BP) and BSFC performance in a typical diesel engine fueled with a blend of Pongamia Pinnanta methyl ester and diesel of up to 40% volume compared to just diesel. Further research indicates that biodiesel can be as effective as traditional diesel in CI engines (Abed et al., 2018; Banerjee et al., 2016; Tamilselvan et al., 2018).

However, a study by Rizvi (2009) noted that engine performance is often limited to specific parameters like BSFC, BP, and BTE. Factors such as fuel properties, injection timing and pressure, air-fuel blend, and fuel amount significantly affect engine performance. HCCI engines typically have lower BTE compared to CI engines. Many studies have explored methods to control the start of combustion in HCCI engines, employing techniques like varying inlet air temperature, pressure rates, equivalence ratios, EGR systems, ignition of fuels, compression ratios, and variable valve timing (Janecek et al., 2017; Puškár & Kopas, 2018; Strandh et al., 2004). Intake air heating is a common method to achieve HCCI mode, where the hot mixture is obtained using an electronic air heater. Studies have also shown that methods like EGR can adjust combustion timing, influencing the temperature of the mixture and negative valve overlap (NVO) (Noh & No, 2017; Putrasari et al., 2017). A variable compression ratio (VCR) change can also affect combustion timing (Au et al., 2001; Christensen & Johansson, 1998).

Also, the change in variable compression ratio (VCR) to influence combustion timing was investigated by Mase et al. (1998) by examining the impact of temperature and equivalence ratio on HCCI engine performance, highlighting the control of ignition timing and combustion as primary challenges and examined the impact of temperature and equivalence ratio on HCCI engine performance, highlighting the control of ignition timing and combustion as primary challenges. Kimura et al. (2001) examined the impact of temperature and equivalence ratio on HCCI engine performance, highlighting the control of ignition timing and combustion as primary challenges. The study revealed that significantly varying the equivalence ratio affects in-cylinder pressure and temperature, with a shorter ignition delay leading to higher peak pressure and temperature (Bedoya et al., 2012). Heating the inlet air is a useful method for controlling ignition timing in HCCI engines, as it reduces air charge density and affects combustion quality (Rahbari, 2016). Heating the inlet air reduces the air charge density, affecting the combustion quality (Hasan & Rahman, 2016; Sundararajan et al., 2016).

However, many researchers prefer installing the heater because it is the easiest method to achieve HCCI mode (Strålin et al., 2003). Late direct ignition in HCCI involves high air-fuel mixing to enhance combustion characteristics. Port-injected HCCI engines create external mixtures operating at 0.6 MPa, and low injection pressure may hinder vaporization in the intake manifold. A homogeneous mixture requires fuel vapor (Urata et al., 2004). A homogenous combination requires fuel vapor (Ghorbanpour & Rasekhi, 2013). In their study, Channapattana et al. (2023) analyzed the energy and exergy of DI-CI engines using nickel oxide nanoparticle-enhanced azadirachta indica biofuel. They uncovered notable findings regarding the influence of fuel injection timing on engine efficiency, demonstrating the potential of advanced biofuels in improving the performance of such engines (Channapattana et al., 2023). Similarly, Srinidhi et al. (2022) explored the effects of fuel injection timing on CI engines fueled with neem biodiesel blends. Combining experimental data with numerical simulations provided insights into optimizing engine performance through precise fuel injection timing in the context of biodiesel usage (Srinidhi et al., 2022).

HCCI engine power depends on various operational factors, including engine thermal management, which controls combustion timing by regulating inlet air temperatures. Higher temperatures accelerate combustion and chemical processes. Factors like inlet pressure, fuel type, engine speed, and heat transfer influenced combustion timing (Rahbari, 2016).

Research on fuel injection strategies in HCCI engines suggests modes that enhance thermal efficiency compared to CI engines. Ganesh et al. (2008) found that using fuel injection techniques and an electromagnetic valve-train allows the HCCI engine to operate effectively at high and low loads. Direct fuel injection in the compression stroke improves engine performance significantly compared to port injection. Engine power depends on heating rates, and intake temperatures affect HCCI combustion (Sivarethinamohan et al., 2022). Running the HCCI engine with lean blends using a low compression ratio and high intake temperature can be effective.

Injecting fuel in the exhaust stroke with re-compression applied on the NVO leads to higher in-cylinder pressure and a high combustion temperature (Singh & Agarwal, 2012). Organized combustion can enhance ignition timing and improve temperatures, thereby improving HCCI combustion (Ganesh & Nagarajan, 2010). The Indicated Mean Effective Pressure (IMEP) is a uniform pressure measure required for an engine's stroke power, equivalent to the work done to achieve pressure inside the chamber. Research indicates that IMEP is an effective metric for evaluating engine performance (Sahu et al., 2021). Studies on four-stroke HCCI engines reveal the possibility of achieving higher IMEP using a lean blend fuel with a high compression ratio (Shi et al., 2006). One method for improving the lower load efficiency in HCCI mode operations is using DI and creating rich combustion (Hunicz et al., 2015; Sivarethinamohan et al., 2022).

The Brake Thermal Efficiency (BTE) of an HCCI (Homogeneous Charge Compression Ignition) engine, which is the output power divided by the input power, indicates the engine's effectiveness based on the energy provided by the fuel. BTE is a common measure of engine performance. CI (Compression Ignition) engines have been observed to have a lower BTE compared to HCCI engines (Ogawa et al., 2003). To address this issue, using a mixture of biodiesel and diesel has been shown to supply higher BTE, as demonstrated in previous studies (Mancaruso & Vaglieco, 2010). NOx production was found to be lower in diesel engines. In some experiments, engine performance using conventional diesel in HCCI engines was compared with CI engines (Sahu et al., 2021).

Different engines, specifically CI and HCCI, were investigated for operating performance (Hwang et al., 2016). Jafarmadar and Nemati (2017) discussed operating a direct injection, four-stroke, 4-cylinder, 16.5:1 compression ratio CI engine using diesel fuel and DME biofuel in both DI (Direct Injection) and HCCI modes. Biodiesel, an alternative renewable fuel made from the chemical reaction of various lipids such as animal fat, algae, soybean oil, vegetable oil, and palm oil with alcohol to produce fatty acid esters, has been researched extensively (Gharehghani, 2019). Biodiesel is easy to store and handle, similar to regular diesel fuel. It has a high flash point, is biodegradable, can help keep the fuel system clean, and has good lubricity with low emissions. Many countries are exploring biodiesel as a replacement for fossil fuels. The homogenous air-fuel combination in HCCI engines reduces emissions and improves combustion. Various biodiesels, such as those derived from palm oil, algae, spent cooking oil, and soybean and animal fat waste, have been used in CI engines to minimize emissions (Fahd et al., 2013; Jiménez-Espadafor et al., 2012; Muhamad Tobib et al., 2021; Singh et al., 2014). Several studies have operated diesel engines on biodiesel to test emissions and performance (Iwashiro et al., 2002; Singh et al., 2014; Zhang et al., 2012), and many have examined biodiesel in HCCI engines to minimize emissions (Rajesh et al., 2020; Sanjid et al., 2013; Urata et al., 2004). Low-oxygen, nitrogen, and cetane fuels have been effective in engines (EL-Seesy et al., 2021; Gad et al., 2020; Tobib et al., 2019).

Hydrocarbon (HC) emissions result from two factors: excess fuel in the combustion chamber not being fully utilized and incomplete combustion in the engine's cold regions. As HCCI engine fuel is lean, HC is usually fully combusted. HC emissions in HCCI engines typically originate from cracks in the cylinder wall, especially near the piston rings. HCCI engines generally start HC formation at higher fuel-air ratios (Hasan et al., 2015; Khayum et al., 2021; Satyanarayana et al., 2018). The rate of HC can be reduced by blending diesel with biodiesel and using EGR (Exhaust Gas Recirculation). Ali et al. (2021) examined the effects of cooled external and internal EGR on the performance, combustion, and emissions of an HCCI engine, showing decreased cylinder pressure and NOx emissions but increased HC and CO emissions. Giakoumis et al. (2012) utilized a single-cylinder, four-stroke engine with a 19:1 compression ratio at 3000 rpm. The study tested different fuel spray angles and a dual injection strategy, with early timing injection for HCCI operation, resulting in reduced NOx, HC, and CO emissions but increased BSFC (Brake Specific Fuel Consumption).

Dharma et al. (2016), Gad and Ismail (2021) and Li et al. (2021) used Rapeseed methyl ester as fuel to run a CI engine in HCCI mode. The conditions included a constant speed with different EGR rates and loads. The engine, a single-cylinder, four-stroke direct injection diesel engine with a 17.5:1 compression ratio and 1500 rpm speed, showed improved NOx emissions but increased HC and CO emissions at varying EGR rates (0%, 10%, 20%, and 30%). CO emissions generally form in engines due to partial combustion of fuel. In HCCI engines, a high rate of CO is produced compared to CI engines, as demonstrated in various studies (Hasan et al., 2015; Kumar & Rehman, 2016). Blending diesel with biodiesel has somewhat reduced CI emissions (Ali et al., 2021; No, 2016), where low CO emissions in HCCI engines were observed.

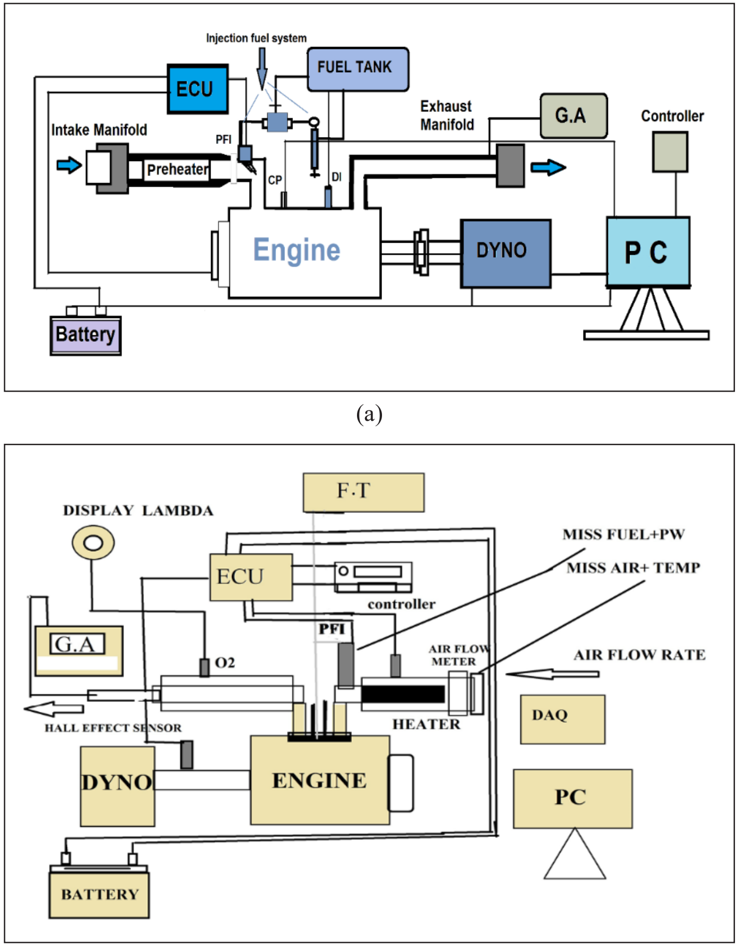
In contrast, emission issues remain in both CI and SI (Spark Ignition) engines. Kumar and Rehman (2016) used a 17.5:1 compression ratio diesel engine with a single-cylinder at 1500 rpm, run at different loads and EGR rates. They used external mixture formation to increase fuel vapor in the HCCI engine, mixing with air in the intake stroke with an injection pressure of 200 bar. The results showed decreased peak pressure and reduced NOx, HC, and CO emissions. Geng et al. (2017) investigated ways to reduce emissions in HCCI engines, which traditionally are inefficient and emit significant CO and UHC (Unburned Hydrocarbons). Using used cooking oil (UCO)--based biodiesel in HCCI engines is limited worldwide, and its emissions levels in HCCI mode have not been extensively researched. In Malaysia and some other countries, UCO is derived from palm oil-based biodiesel (Sahu et al., 2021). The main objective of this study is to reduce emission levels of HCCI engines fueled by UCO-based biodiesel.

MATERIALS AND METHODS

This study employed a single-cylinder, 4-stroke, air-cooled diesel engine with a rotational speed of 3600 rpm. The engine, with a capacity of 0.219 liters, was converted to operate in HCCI (Homogeneous Charge Compression Ignition) mode. Engine power was measured using an eddy current dynamometer. A Port Fuel Injection (PFI) system and a preheater were installed in the intake manifold. Figure 1(a) depicts the engine setup and various sensors and actuators. The setup schematic and engine specifications are presented in Figure 2 and Table 1, respectively. Figure 2 illustrates the experimental engine configuration, including its connections to the fuel supply system with Direct Injection (DI), PFI, and return fuel lines. Figure 1(b) shows the connection of the dynamometer and the Engine Control Unit (ECU) to all the engine sensors. Exhaust gas emissions were analyzed using exhaust gas analyzers.

This study used two different fuel types: diesel and cooking oil (UCO). The properties of diesel and UCO-based biodiesel fuel are detailed in Table 2. The fuel was mixed in the laboratory to create a biodiesel blend, varying the diesel volume with UCO biodiesel percentages of 5%, 10%, 15%, and 20%. The biodiesel was tested up to B20 blend due to fuel stability issues and the current biodiesel market conditions in Malaysia, where B10 blended fuel will soon be introduced. Engine modifications for conversion to HCCI mode included the installation of a heater and PFI, as shown in Figure 2. A 5 kW heater was installed in the intake manifold to ensure high inlet temperatures entering the combustion chamber. A high-pressure (200 bar) Volkswagen injector with a 60° angle was used as the PFI to achieve a fine mist fuel spraying pattern. The ECU controlled the PFI, adjusting the amount of fuel injected by changing its pulse width. A temperature sensor was employed to measure the intake air temperature and was connected to a dedicated reader. The engine transition from DI to HCCI mode involved using the PFI and heater, where the direct injection valve was closed, and the PFI was opened to deliver fuel from the tank to the high-pressure port injector (Jiménez-Espadafor et al., 2012).

This experiment examined the performance and emissions of diesel and UCO (Used Cooking Oil)–based biodiesel in an HCCI (Homogeneous Charge Compression Ignition) engine. Various tests were conducted to determine the optimal intake temperature for



(a)

(b)

Figure 1. (a) Schematic representation of this study's experimental engine configuration; (b) ECU schematic coupled to sensors and PFI

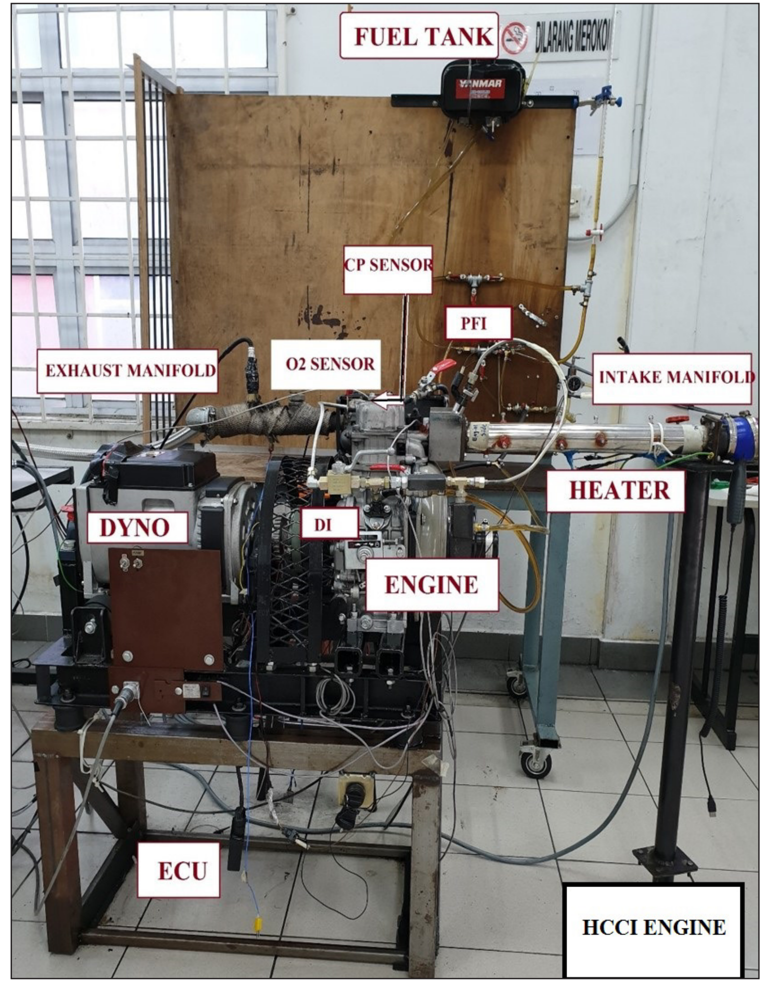


Figure 2. 10-kW dynamometer with a controller connected to the engine in the laboratory

the HCCI engine. The engine was preheated to 65°C using a pulse width of 2.5 ms. In HCCI mode, a consistent speed of 2700 rpm was maintained. The study evaluated the HCCI engine's speed stability under varying lambda conditions (air-fuel ratio), intake temperatures, and biodiesel mixtures. Each biodiesel blend was tested across four different lambda settings. After the warm-up phase, the direct injection valve was closed, and the PFI (Port Fuel Injection) system was engaged to supply fuel, thereby transitioning the engine to HCCI mode. Subsequently, the inlet temperature was maintained from 70°C to 90°C. It was necessary to reduce the intake temperature if it exceeded 95°C to avoid the engine entering the knocking region. Each set of operating conditions was replicated three times for each biodiesel blend (EL-Seesy et al., 2021; Rajesh et al., 2020).

Table 1
Specification of the diesel engine

Engine model	Yanmar L48N
Engine type	Vertical cylinder, 4-stroke air-cooled diesel engine
Combustion	Direct Injection
Displacement	0.219 litres
Bore × Stroke	70 × 57 mm
Number of cylinders	1
Compression ratio	20.1

Table 2
Measured properties of diesel and used cooking oil

Properties	Unit	Test Method	Diesel	B5	B10	B15	B20	B100
Density at 15°C	kg/L	ASTM D 4052-11	0.8409	0.8431	0.8449	0.8475	0.8495	0.885
Kinematic viscosity 40°C	mm^2/s	ASTM D 445-14	3.650	3.698	3.759	3.820	3.921	5.285
Calorific value	MJ/kg	ASTM D 240-14	44.022	44.068	43.425	42.626	42.094	36.036
Cetane number	-	ASTM D 4737-10	55	50	47	45	43	-

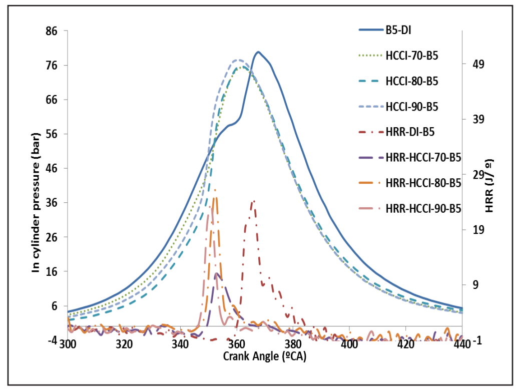
RESULTS AND DISCUSSION

Engine Performance

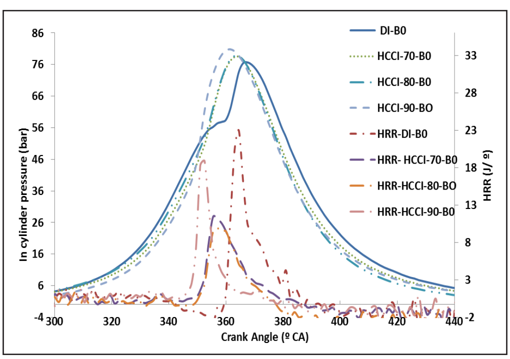
In diffusion mode, HCCI engines spontaneously ignite the mixture when it reaches the chemical activation energy point anywhere in the combustion chamber. A rich air-fuel mixture or high intake temperature can cause significant in-cylinder pressure and knock in HCCI engines. The in-cylinder pressure increases with load but decreases to its lowest at 0% load. Biodiesel blends affect in-cylinder pressure and Heat Release Rate (HRR) in both CI and HCCI engines. Figure 3 illustrates the impact of each mixture on in-cylinder pressure. An increase in intake temperature raises cylinder pressure. At 90°C in HCCI mode, the in-cylinder pressure reaches 81 bar. Diesel fuel raises in-cylinder pressure in CI and HCCI engines from 76 to 81 bar at varying input temperatures. The impact of the B5 blend on CI/HCCI cylinder pressure is notable.

In HCCI mode, higher intake temperatures result in increased in-cylinder pressure and HHR. Biodiesel accelerates the combustion of hydrocarbons and oxygen. UCO B20 biodiesel raises in-cylinder pressure from 77 to 79 bar and HRR from 13 to 25 J/°CA. The intake air temperature elevates the in-cylinder temperature during the compression stroke, facilitating earlier auto-ignition. Garcia et al. (2011) demonstrated the influence of varying intake air temperatures and lambda values on in-cylinder pressure using diethyl ether-ethanol fuel blends. Additional studies also observed that oxygen and hydrocarbons ignite more readily under these conditions (Gad et al., 2020; Singh et al., 2021; Sivarethinamohan et al., 2022).

Figure 4 shows the peak pressure in the HCCI engine and examines the effects of varying intake temperatures and biodiesel blend ratios (B0, B5, B10, B15, and B20). The peak in-cylinder pressure of diesel fuel is 81 bars at 90°C, which decreases to 79 bars at 70°C. Both a lower intake temperature and a higher UCO-based biodiesel blend ratio contribute to a reduction in peak pressure across all fuels. With an increase in blend percentage, the



(a)



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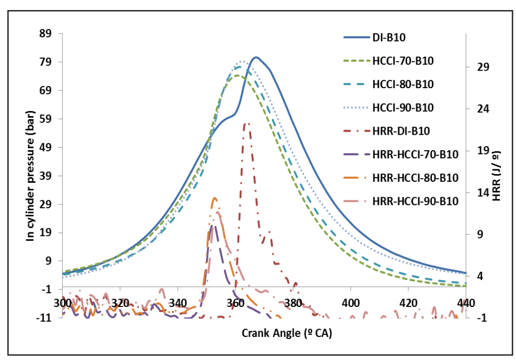

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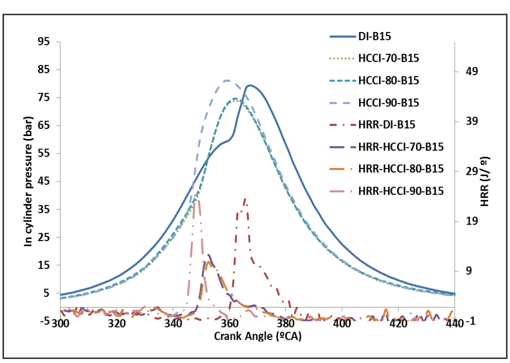

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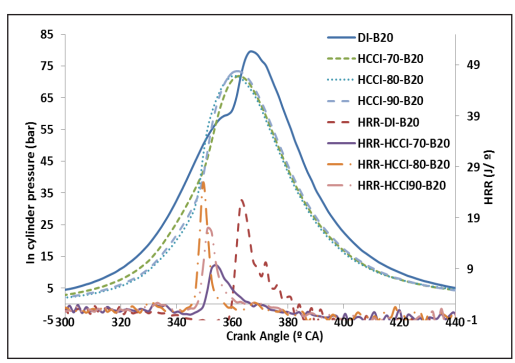


(e)

Figure 3. Intake temperatures and in-cylinder pressure in HCCI and CI modes at 2700 rpm, 2.4, and several biodiesel blends: (a)B0; (b)B5; (c)B10; (d)B15; and (e)B20

viscosity and density of biodiesel rise, making it more challenging to mix and combust. Intake temperature positively influences combustion chamber in-cylinder pressure (Gowthaman & Sathiyagnanam, 2016; Wei et al., 2017). This finding is further supported by additional studies, which varied air temperature control in an HCCI engine (Cinar et al., 2015; How et al., 2018; Hunicz et al., 2015; Khandal et al., 2019).

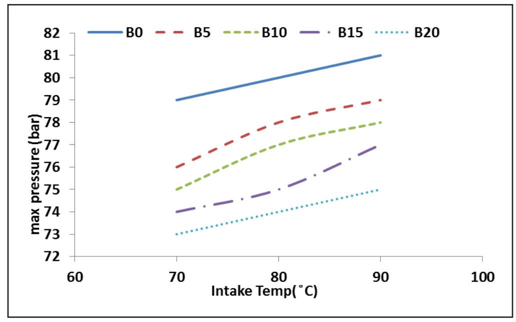
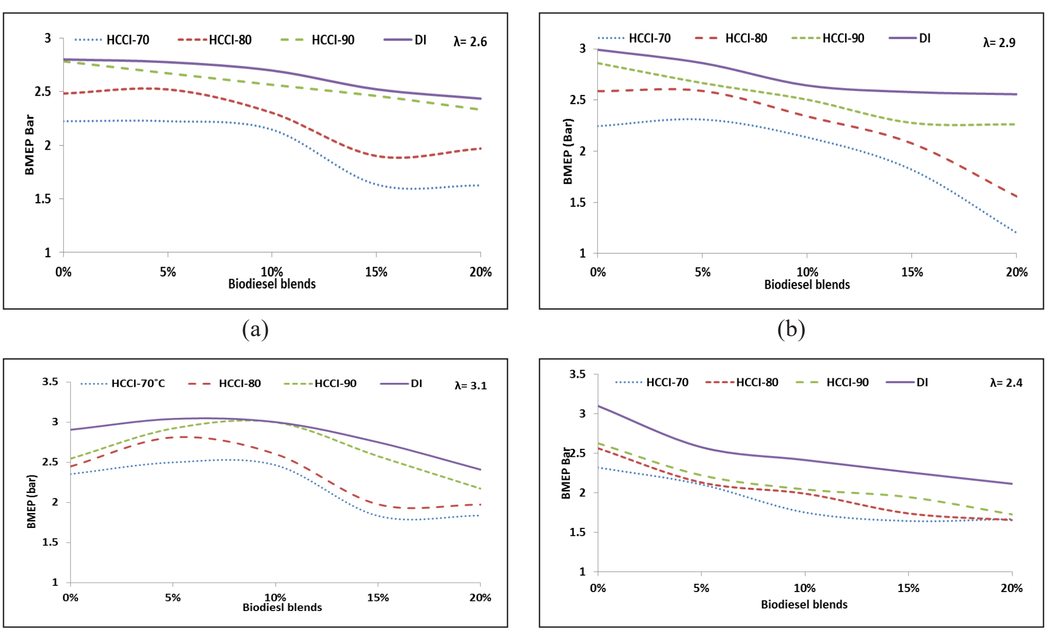


Figure 4. The effects of intake temperature on peak in-cylinder pressure in the HCCI engine for diesel and biodiesel fuel

The modes of CI/HCCI engines affect Brake Mean Effective Pressure (BMEP). In CI mode, diesel fuel exhibits the highest BMEP at 2.9 bars. Using B20 biodiesel results in a reduction of BMEP. However, an increase in intake temperature does not significantly impact BMEP. BMEP tends to be highest in Direct Injection (DI) mode. At low loads, HCCI engines operate efficiently. The energy in the fuel-air mixture enhances combustion temperature and consequently increases BMEP. The operating range of an HCCI engine is dependent on intake temperature and is typically constrained between misfiring and knocking, as shown in Figure 5 (Adam et al., 2017; Khandal et al., 2019; Krishnamoorthy et al., 2018; Zhang et al., 2012).



(a) (b) (c) (d)

Figure 5. Different biodiesel mixes and intake temperatures and lambda affect BMEP in HCCI and CI modes at 2700 rpm: (a) λ = 3.1; (b) λ = 2.9; (c) λ = 2.6; and (d) λ = 2.4

Changes influence the brake-specific fuel consumption (BSFC) of the engine in terms of intake temperature and biodiesel blends. As depicted in Figure 6, the BSFC increases when the engine runs in HCCI mode. In HCCI mode at 70°C, the BSFC was 350 g/kWh, but it decreased to 256 g/kWh with B20 biodiesel. It was further reduced to 152 g/kWh in Direct Injection (DI) mode using B20 biodiesel. Additionally, higher air temperatures in the HCCI engine reduce volumetric efficiency and air mass flow rate, leading to advanced and uncontrolled combustion. The increased fuel consumption in HCCI mode is attributed to operating with reduced air density at all loads, which results in lower engine power due to the air's lower oxygen content. A study by Gowthaman and Sathiyagnanam (2016) focused on using biodiesel in HCCI mode and confirmed similar findings.

It aligns with other research indicating variations in BSFC (Godiño et al., 2018; Jafarmadar & Nemati, 2016; Sundararajan et al., 2016; Yousefi & Birouk, 2017). BSFC decreases in HCCI mode with increased intake temperature and biodiesel blend ratio, as shown in Figure 6, leading to higher fuel consumption at elevated temperatures. Port injection in HCCI mode consumes more fuel than in DI mode. Poor vaporization of biodiesel requires higher intake temperatures for improved combustion. Elevated

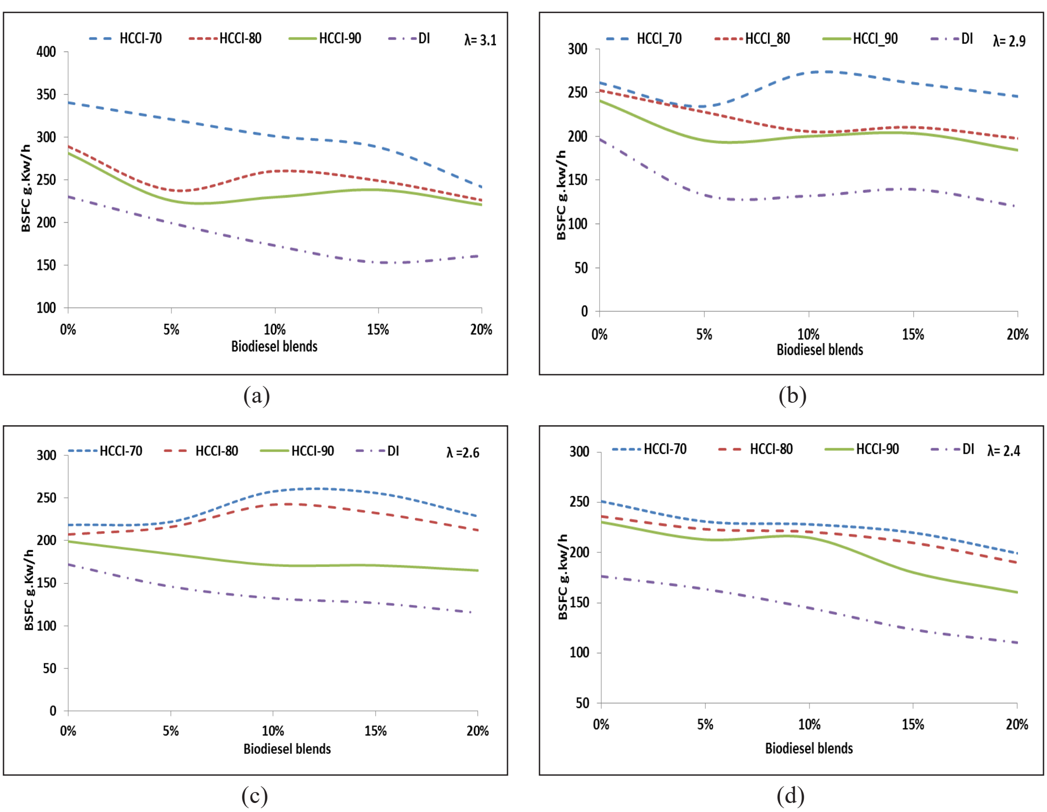


Figure 6. Different biodiesel blends and intake temperatures with lambda affect BSFC in HCCI and CI modes at 2700 rpm: (a) λ = 3.1; (b) λ = 2.9; (c) λ = 2.6; and (d) λ = 2.4

inlet air temperatures cause uncontrolled engine combustion and reduced engine power, necessitating a specific temperature range (Nalgundwar et al., 2016; Singh et al., 2017; Zhang et al., 2012).

Figure 7 shows the impact of varying lambda values on Brake Thermal Efficiency (BTE) in relation to intake temperature and biodiesel ratios. It is observed that biodiesel blends generally reduce BTE. A lower intake temperature also reduces BTE, whereas an intake temperature of 90°C increases BTE. Using diesel fuel in Direct Injection (DI) mode enhances engine BTE by 26.1%. In contrast, the Homogeneous Charge Compression Ignition (HCCI) mode, combined with UCO B20 biodiesel at an intake temperature of 70°C, decreases BTE to 14.2%—however, intake temperatures of 80°C and 90°C boost BTE. The decrease in BTE with biodiesel can be attributed to its higher viscosity, density, and cetane number, which complicates the fuel's interaction with air and leads to less efficient vaporization and incomplete combustion prior to ignition. These factors contribute to reduced combustion efficiency, corroborating findings from previous studies (Hasan et al., 2015; Khandal et al., 2019; Zhang et al., 2012; Riyadi et al., 2023).

A high BTE of 27.1% was noted at an intake temperature of 70°C in DI mode. When lambda was adjusted from 2.4 to 3.1 at the same temperature, BTE decreased to 23.4%

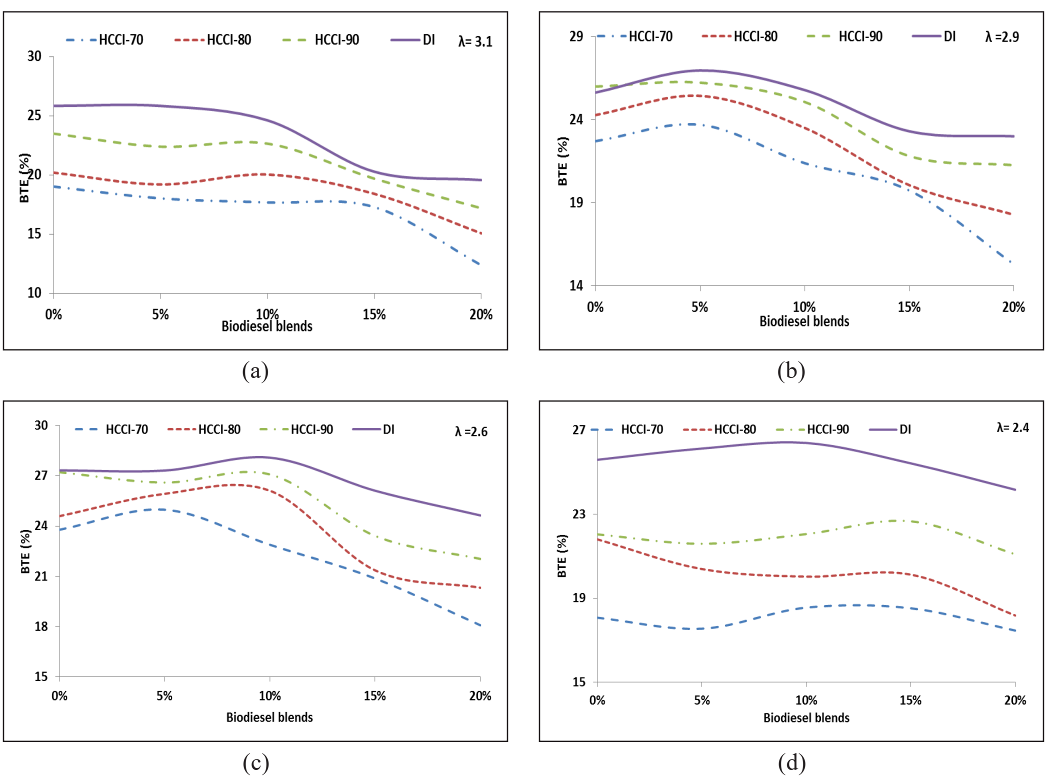


Figure 7. Different biodiesel blends and intake temperatures with lambda affect BTE in HCCI and CI modes at 2700 rpm: (a) λ = 3.1; (b) λ = 2.9; (c) λ = 2.6; and (d) λ = 2.4

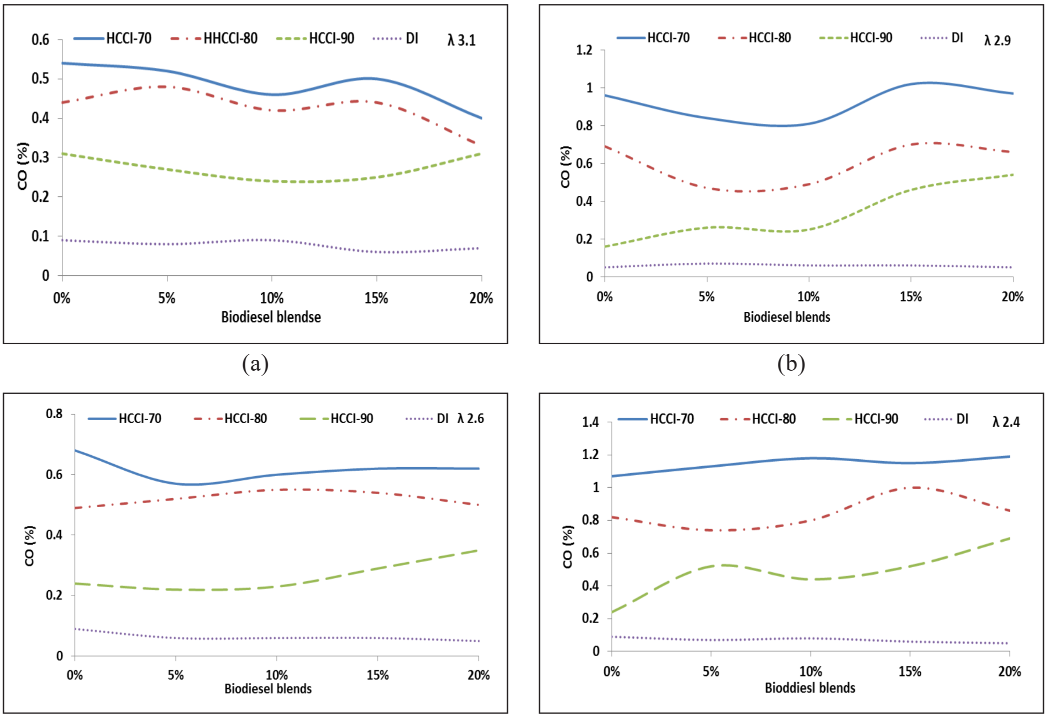
and 19.8% at a lambda of 3.1. These results demonstrate the influence of lambda on BTE; specifically, biodiesel's high viscosity and density adversely affect fuel injection and combustion completeness. In the HCCI mode, the effect of biodiesel on BTE was analyzed at various blend ratios and intake temperatures. BTE was recorded at 25.1% with an intake temperature of 70°C, increasing to 28% at 90°C. A lower biodiesel rate corresponded with a higher BTE, which improved with increased intake temperature to 90°C. The HCCI engine mode shows enhanced combustion with higher intake temperatures, promoting more homogeneous fuel vaporization and thus increasing BTE. However, when running the engine on biodiesel, BTE is reduced due to the properties of UCO biodiesel at different blend rates. The study also observed that lambda significantly affects BTE. The fuel-air mixture is leaner at higher lambda values, leading to a reduced fuel supply. Conversely, a lower lambda value results in a richer mixture and an increased fuel supply to the chamber, facilitating better contact with air and enhancing the energy of combustion (Cinar et al., 2015; How et al., 2018; Krishnamoorthy et al., 2018; Satyanarayana et al., 2018; Singh et al., 2014; Sundararajan et al., 2016).

The Emissions Levels

This study examines emission levels in both Compression Ignition (CI) and Homogeneous Charge Compression Ignition (HCCI) engines using different Used Cooking Oil (UCO) biodiesel blends and intake temperatures. HCCI engines are characterized by significant emissions of Unburned Hydrocarbons (UHC) and Carbon Monoxide (CO), but they emit lower levels of Nitrogen Oxides (NOx). Therefore, CI engine emissions were compared with HCCI engines operating at 2700 rpm.

The emission levels of CO and Carbon Dioxide (CO_2), indicative of combustion efficiency, are discussed. Figure 8 shows that the CO emission levels vary depending on the biodiesel ratio and the engine mode, either HCCI or Direct Injection (DI). In HCCI mode, CO emissions tend to increase. An increase in intake temperature, however, reduces CO emissions. At an intake temperature of 90°C, CO emissions are low but rise with further temperature increases. In DI mode, CO emissions are at their lowest, 0.12%, but increase to 1.25% in HCCI mode when running on B20 biodiesel at 70°C. This increase is attributed to incomplete combustion due to the lower intake temperature.

Oxygen in UCO biodiesel also aids in lowering CO emissions by improving combustion (Ali et al., 2021; Khayum et al., 2021; Rajesh et al., 2020). Higher oxygen content in the fuel-air mixture reduces CO emissions as more oxidizers contact the fuel, facilitating in-cylinder combustion. The intake temperature significantly influences CO emissions in HCCI engines; higher inlet temperatures promote auto-ignition in the chamber, resulting in increased mixture fraction and easier ignition. This process leads to higher CO_2 emissions but lower CO emissions. These conditions influence the chemical reactions in

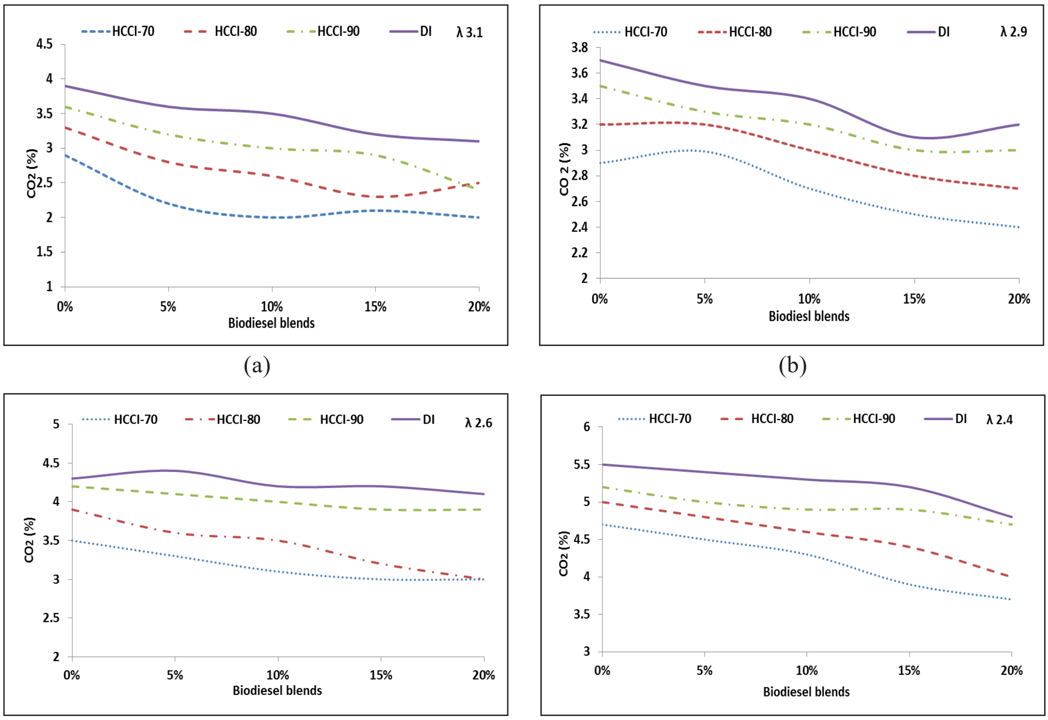


(c) (d)

Figure 8. CO emissions in HCCI and CI modes at 2700 rpm with varying biodiesel blends and intake temperatures with lambda: (a) λ = 3.1; (b) λ = 2.9; (c) λ = 2.6; and (d) λ = 2.4

the combustion chamber, such as $CO + OH = CO_2 + H$ and $CO + O_2 = CO_2 + O$. Higher intake temperatures reduce the engine's volumetric efficiency and the concentration of oxygen molecules in the chamber, resulting in a greater quantity of OH radicals, which in turn lowers CO emission levels (Singh et al., 2014).

The levels of CO_2 emissions are influenced by varying biodiesel blend ratios and intake temperatures in Direct Injection (DI) and Homogeneous Charge Compression Ignition (HCCI) modes. Generally, CO_2 emissions decrease when operating in HCCI mode and diminish with increased biodiesel content. The highest and lowest CO_2 emission levels recorded were 3.78% with diesel fuel in DI mode and 2.15% with B20 biodiesel at HCCI-70°C, respectively. Running the engine in HCCI mode reduces CO_2 emissions, which decrease with rising biodiesel rates and varying intake temperatures (Gad & Ismail, 2021). Figure 9 shows the impact of biodiesel blend rates on CO_2 emission levels. It shows that CO_2 emissions increased from 2.6% to 4% with increased intake temperature, whereas CO_2 emissions decreased with increasing biodiesel ratios of B0, B5, B10, B15, and B20. Specifically, CO_2 emissions decreased to 1.95% but then increased to 2.55% when the intake temperature was raised to 90°C. These variations are attributed to different operating conditions, including lambda settings, intake temperatures, and biodiesel blend ratios. The



(a) (b)

(c) (d)

Figure 9. CO_2 emissions in HCCI and CI modes at 2700 rpm for varying biodiesel mix ratios and intake temperatures with lambda: (a) λ = 3.1; (b) λ = 2.9; (c) λ = 2.6; and (d) λ = 2.4

lambda influences the fuel-air mixture, shifting it from leaner to richer with a decrease in lambda value. This change also depends on the fuel supplied to the combustion chamber.

Furthermore, higher intake temperatures enhance air movement, facilitating easier contact and mixing between air and fuel. Consequently, these results indicate that using UCO biodiesel in HCCI mode reduces CO_2 emissions further due to the higher oxygen content in the biodiesel, which improves combustion efficiency. These findings are consistent with those reported in previous studies (Gowthaman & Sathiyagnanam, 2016; Li et al., 2021; Etaiw et al., 2022).

Hydrocarbon (HC) emissions are released from unburned engine fuel mixtures. Figure 10 illustrates the effects of fuel mix ratios and intake temperatures on engine HC emissions in Direct Injection (DI) and Homogeneous Charge Compression Ignition (HCCI) modes. In DI mode, HC emissions were reduced from 31 ppm to 26 ppm when the biodiesel rate was increased from B0 to B20. The HC emission level initially was 83 ppm but dropped to 76 ppm as the temperature increased. Conversely, in HCCI mode, at an intake temperature of 70°C, HC emission levels increased as the biodiesel blend rate decreased. With an increase in the biodiesel ratio, HC emissions were reduced to 81 ppm at λ = 2.4 and decreased to 62 ppm with B20 biodiesel. Specifically, when the engine was operated with B20 biodiesel

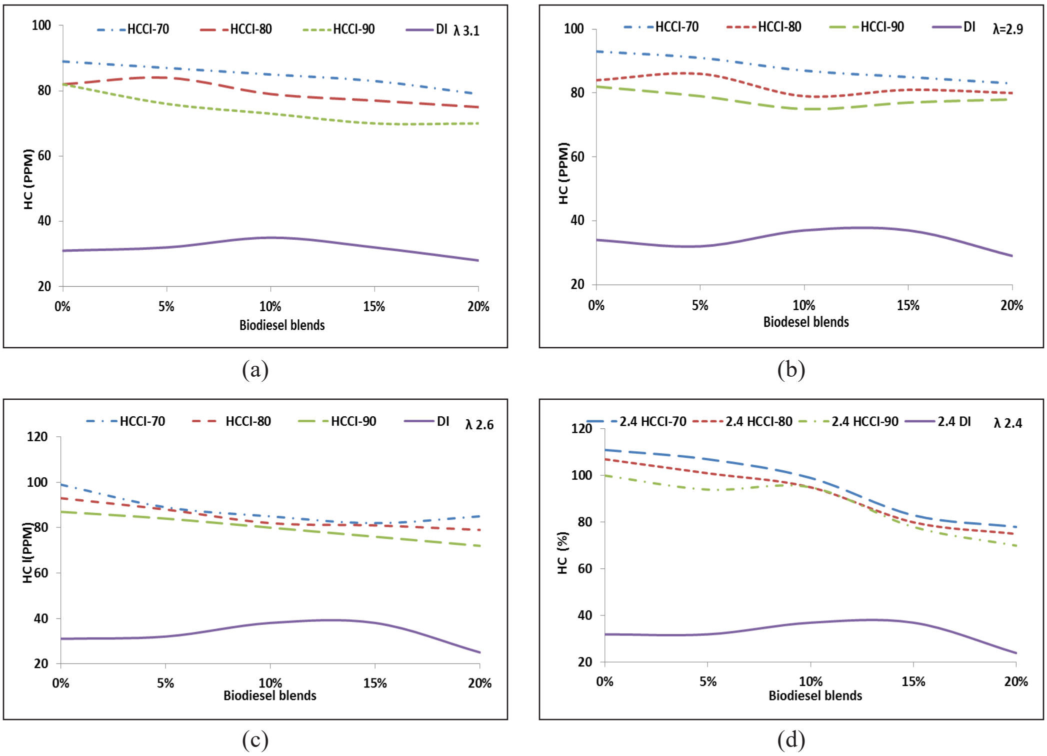


Figure 10. HC emission values in HCCI and CI modes at 2700 rpm for different biodiesel mixes and intake temperatures at lambda: (a) λ = 3.1; (b) λ = 2.9; (c) λ = 2.6; and (d) λ = 2.4

at 70°C, the HC emission level was 69 ppm, which then decreased to 65 ppm at an intake temperature of 90°C.

The reason for these variations is primarily the mode of operation. Running the engine in HCCI mode, coupled with the slow mixing velocity, typically resulted in higher HC emission levels. The reduction in HC emissions is attributed to a leaner air-fuel mixture, which creates a more homogeneous mix, thus facilitating better combustion. Additionally, using biodiesel reveals that higher blend ratios, which have a greater oxygen content, can lead to incomplete combustion. Other studies have reported similar findings when operating HCCI engines with biodiesel (Kumar & Rehman, 2016; Satyanarayana et al., 2018).

NOx emission production is a critical aspect frequently addressed in engine standards regulations. NOx is primarily produced in high-temperature combustion chamber reactions, where air nitrogen combines with oxygen to form nitric oxide (NO). In HCCI mode, low-temperature combustion effectively reduces NOx emissions. As depicted in Figure 11, different biodiesel mix ratios (B0, B5, B10, B15, and B20) affect the engine's NOx emissions in HCCI mode at 70°C. Reducing the biodiesel blend rate and intake temperature in HCCI mode leads to lower NOx emissions. For example, increasing the input air temperature from 70°C to 90°C decreased NOx emissions from 8 ppm to 6 ppm.

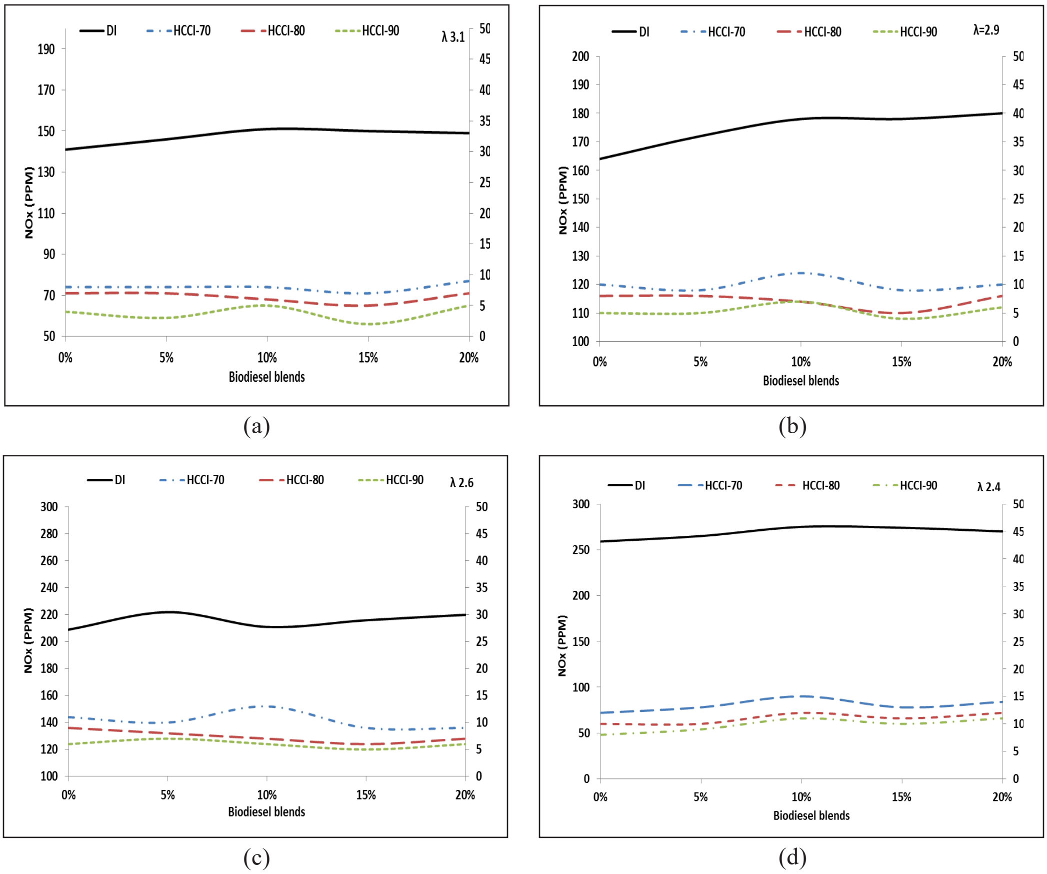


Figure 11. Different biodiesel mixes and intake temperature at lambda affect NOx emission levels in HCCI and CI modes at 2700 rpm: (a) λ = 3.1; (b) λ = 2.9; (c) λ = 2.6; and (d) λ = 2.4

When comparing diesel fuel and biodiesel fuel in HCCI mode, diesel fuel exhibits lower NOx emission levels: 4 ppm at 70°C and 3 ppm at 90°C. The lambda setting also plays a role in NOx emissions; a low lambda results in a richer blend with more fuel, thereby increasing NOx emissions. Higher combustion temperatures are known to increase NOx emissions, as temperature is a key factor in forming NOx. The increase in NOx emissions is correlated with combustion temperature and biodiesel concentration, which contains oxygen molecules. Nitrogen reacts with oxygen to form NO, further oxidizing to NO2. As the inlet air temperature rises, NOx emissions decrease. HCCI mode is effective in reducing NOx emissions, and this reduction is further enhanced with increased biodiesel blend rates. Conversely, NOx emissions tend to increase with a higher biodiesel blend ratio due to the high oxygen content in biodiesel. Moreover, the decrease in NOx emission levels when operating in HCCI mode has been corroborated by several studies (How et al., 2018; Khandal et al., 2019; Kumar & Rehman, 2016; Puškár & Kopas, 2018; Wei et al., 2017).

CONCLUSION

This study evaluated the performance of Used Cooking Oil (UCO)-based biodiesel in a Homogeneous Charge Compression Ignition (HCCI) engine mode. The margin of error for each measured parameter was as follows: power (± 0.04), HC (0.05%), NOx (0.2%), CO (0.06%), CO_2 (0.1%), and Brake Specific Fuel Consumption (BSFC) (+3%). In HCCI mode, diesel and UCO-based biodiesel have resulted in lower emissions compared to Direct Injection (DI) mode, suggesting that UCO-based biodiesel in HCCI engines could further reduce pollutants. HCCI mode led to lower in-cylinder pressures, decreased intake temperatures, and higher UCO biodiesel blend ratios. For instance, when operating with B20 biodiesel, the in-cylinder pressure dropped from 81 to 73 bar at 90°C.

The highest Heat Release Rate (HRR) recorded was 28 J/°CA in HCCI mode at an intake temperature of 70°C using diesel fuel. Engine power decreased when the intake temperature was raised from 2.5 kW to 2.3 kW in DI mode and dropped to 0.9 kW in HCCI mode using B20 biodiesel at 70°C. The Brake Mean Effective Pressure (BMEP) for the HCCI engine was lower due to its operation under low-load conditions. A higher BMEP was observed at full load with diesel fuel, reaching 3.32 bar. However, BMEP decreased with increasing engine speed and the introduction of UCO. The lowest BMEP, 1.5 bar, was noted at 3600 rpm using B20, likely due to UCO's lower energy content than diesel fuel.

Additionally, BSFC increased in HCCI mode, peaking at 90°C. At a lambda setting 2.4, the BSFC reached 340 g.kw/h in HCCI mode at 70°C using diesel fuel, marking the highest point. Brake thermal efficiency (BTE) declines when using biodiesel, which is attributed to the properties of UCO biodiesel (high viscosity and low calorific value). BTE decreased from 29% to 15% when operating the HCCI engine at an intake temperature of 90°C, primarily because HCCI engines run at low-load conditions.

CO emissions decreased with biodiesel fuel, while CO_2 and NOx emissions increased due to the accelerated combustion rate. CO emissions increased when switching from DI to HCCI mode but decreased with UCO biodiesel. CO emissions also declined with increased intake temperature and lambda for all fuels. Conversely, CO_2 production showed an opposite trend to CO. The HCCI engine yielded lower CO_2 emissions than the DI engine. The higher oxygen content in UCO-based biodiesel improved combustion, reducing CO and CO_2 emissions. However, the same high oxygen content increased NOx formation during combustion.

Regarding NOx emissions, the HCCI engine significantly reduced them, aligning with findings from numerous studies. Yet, increasing the blend ratio of UCO-based biodiesel only modestly improved NOx emissions. The higher oxygen content in higher biodiesel blends facilitated more rapid combustion, reducing Unburned Hydrocarbon (UHC) emissions. HC emissions were higher in HCCI engines compared to DI mode. A decrease in lambda resulted in higher HC emissions due to the richer fuel mixture and increased fuel supply to the engine. Finally, UHC and CO_2 emissions decreased with an increased UCO content in the blend.

ACKNOWLEDGEMENTS

Research grants and facilities from Universiti Putra Malaysia are appreciated. GP-IPS from UPM funds the study with project code GP-IPS 9706000 and is partly funded by the Malaysia Fundamental Research Grant Scheme (FRGS) under grant 5524734.

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