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Investigation on diesel engine with biodiesel – gasoline fuel blends at a distinguished injection pressure

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Due to the design challenges and low performance of engines in green fuels, the researchers started to investigate fuel blends. The inlet parameters also will influence the performance and, emission characteristics of the engines. Considering the effect of injection pressure, the current study revealed the clarity of distinct feedstocks that may be used effectively with esterified petrol blends at different injection pressure. This study has considered the various non-edible vegetable oil-based fuels such as Pongamia methyl ester-Gasoline blend [PME-5G], Jatropha methyl ester- petrol blend [JME-5G], Neem methyl ester- petrol blend [NME-5G], Mahua methyl ester- petrol blend [MME-5G], Dairy scum methyl ester – petrol blend [DME-5G], and Used cooking oil methyl ester – petrol blend [UME-5G] for investigation. The entire test is carried out in the CI engine of irrigation water pumping systems under the distinct injection pressures of 210, 230, and 250 bar with respective loading conditions of 0%, 20%, 40%, 60%, 80%, and 100%. The output parameters such as Brake power, Thermal efficiency, Specific fuel consumption, heat release rate, cylinder pressure and emission stanadrds are elaborately discussed. The final results show the maximum performance at higher injection pressure which is reverse in the case of emissions that exhibited.

Keywords Diesel engine, Non-edible oil, Methyl ester, Gasoline, Injection pressure

Nomenclature & abbreviations

Cc	cubic capacity
Mm	millimetre
Rpm	revolutions per minute
Nm	Newton metre
HP	Horse power
Ppm	parts per Millenium
Kg	Kilogram
kW	Kilowatt
psi	pounds per square inch
°C	Degree Celsius
PME	Pongamia methyl ester
JME	Jatropha methyl ester
NME	Neem methyl ester
MME	Mahua methyl ester
DME	Dairy scum methyl ester
UME	Used cooking oil methyl ester
DEE	Di ethyl ester
CI	Compression ignition
CRDI	Common rail direct injection
RCCI	*reactivity controlled compression ignition engine.*
IP	*Injection pressure.*
CP	*Cylinder pressure.*
BTE	*Brake thermal efficiency.*
BSFC	*Brake specific fuel consumption.*

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BP *Brake power.*
UBHC *Unburnt hydrocarbon.*

Vegetable oils have been utilized as an alternative to petroleum diesel since the introduction of internal combustion engines[1]. Vegetable oil or its derivatives mixed with diesel, on the other hand, can cause several long-term problems with internal combustion engines. Fatty acid methyl ester has grown in popularity in recent years as researchers investigate the use of vegetable oils and animal fat derivatives for biodiesel, a liquid fuel. Non-edible oils such as linseed, neem, Mahua, Jatropha curcas, Kusum, Pongamia pinnata, Karanja oil, and, castor can be gathered and converted into biodiesel, positioning India as a potential leader in biodiesel production[2–5]. Even, unused non-edibles such as industrial leather waste and waste pork fatty oil are utilized for biofuel extraction, and ignition enhancers are used in CRDI engines[6,7]. The aluminium nitrate (Al $(NO_3)_3$) nanoparticles and graphene oxide nanoplates ($GONP_S$) are mixed with waste leather oil in the proportion of 50 ppm as catalysts to enhance the ignition process. A new attempt at dual fuel blend mode which runs by hydrogen gas-sapota seed biodiesel and, Ammonia (NH_3)-Cashew nut shell oil was investigated on diesel engines and better performance was obtained[8,9]. The cashew nut shell oil is also tried for reactivity-controlled compression ignition engine (RCCI) along with Al_2O_3nanoparticles to improve the performance and reduce the emission[10]. Clean vegetable oils or diesel blends, can produce a variety of long-term issues with compression ignition engines, such as lubricating oil dilution due to injector deposits, crankcase polymerization, injector pump failure, poor atomization, ring sticking, and injector coking. Vegetable oils have undesirable properties due to their inherent qualities, such as polyunsaturation, high viscosity, and poor volatility[11,12]. B20, a biodiesel/diesel blend consisting of 20% biodiesel and 80% diesel, could be used in engines without any changes[13,14]. The larger volatility range of gasoline-diesel blending may aid in meeting these aims when using fuels with prolonged Ignition delays and lower injection pressure to improve combustion stability and significantly reduce HC and CO emissions while not affect NOx or smoke emissions[15–17]. The exhaust emission analysis of different non-edible oils such as Simarouba, jojoba, linseed, and nagchampa with conventional diesel in a diesel engine under different loading conditions was performed[18,19]. The emission characteristics of Jatropha curcas with waste wood producer gas and coconut shell imitative producer gas for dual fuel engine mode are discussed and better specific fuel consumption is obtained compared to conventional fuel[20]. Similarly, linseed oil with rice husk producer gas is investigated and oxides of nitrogen and smoke have diminished[21]. The performance, combustion, and emission characteristics of a diesel engine were investigated in this context with Pongamia methyl ester-Gasoline blend [PME-5G], Jatropha Methyl ester blend with petrol [JME-5G], Neem Methyl ester blend with petrol [NME-5G], Mahua Methyl ester blend with petrol [MME-5G], Dairy scum Methyl ester blend with petrol [DME-5G], and Used cooking oil Methyl ester blend with petrol [UME-5G] as biodiesel fuel. This study looks at how injection pressure affects diesel engine performance, combustion, and emissions. The test used three injection pressures (210 bar, 230 bar, and 250 bar) with a constant compression ratio (16:1). Low-carbon alcohols, such as methanol and ethanol, have sparked widespread attention as diesel fuel additives due to their simple production techniques and high oxygen content, which improves combustion characteristics while cutting emissions[2]. Biodiesel is a clean energy source that may be used in diesel engines, boilers, and other combustion equipment[22]. Biodiesel offers some advantages over fossil diesel fuel in terms of combustion[23,24]. These alternative biodiesel combinations provide superior results and address existing difficulties with standard biodiesels. When utilizing biodiesel to fuel an engine, a greater compression ratio and injection pressure are suggested[23]. Biodiesel includes oxygen, which allows the fuel in the engine to burn entirely[25]. Even though all biodiesels and their blends have a greater flash point than diesel, transesterification reduces it[26,27]. The addition of a small amount of biodiesel to diesel raises its flash point[28]. In terms of efficiency and emissions, biodiesel with a 15% DEE (Di ethyl ether) blend outperformed biodiesel without a 15% DEE blend[29]. Biodiesel is gaining popularity among the various types of biofuels due to its features and chemical makeup, which allow it to be blended with diesel[30]. Although biodiesel has some benefits over conventional diesel fuel, there is lot of challenges still alive in achieving greater efficiency than diesel fuel. Design parameters and operating conditions of the engine are playing important role in outcomes. On the other hand, modifying the engine's geometry involves technical difficulty in compromising scientific standard and implementation. However, controlling the engine operating parameters are one of the possible ways of improving engine performance where injection pressure is a key factor, considered in this study. Instead of testing and revealing the performance of a single blends, the current study has included familiar non edible fuel blends and compared the performance under the selected pressure & load. This provides a detailed knowledge for compatibility of biodiesel blends in compression ignition engine.

Materials and methods

The Pongamia methyl ester-Gasoline blend [PME-5G] and the Jatropha methyl ester blend with petrol [JME-5G], Neem NME-5G, MME-5G, and DME-5G are methyl ester blends with petrol. Used cooking oil Methyl ester blended with petrol [UME-5G] as a biodiesel fuel used to test combustion elements engine performance such as brake power, brake specific fuel consumption, and brake thermal efficiency, as well as emission parameters such as CO (Carbon Monoxide), UBHC (Unburnt hydro carbon), and NOx (Nitrogen oxides) of CI engines. Each experimental trial was conducted with a constant compression ratio of 16:1, a constant engine speed of 1500 rpm, and varying injection pressures of 210 bar baseline, 230 bar, and 250 bar at sequential engine loads of 0%, 20%, 40%, 60%, 80%, and 100%.

Experimental setup

An experimental setup consists of computer-based multi-fuel engine test equipment and a gas analyzer for measuring engine emissions. Emissions of oxygen, hydrocarbons, carbon dioxide, carbon monoxide, nitrogen oxides, and other components are all measured. A gas analyzer (supplied by Indus Scientific Pvt Ltd.) measures

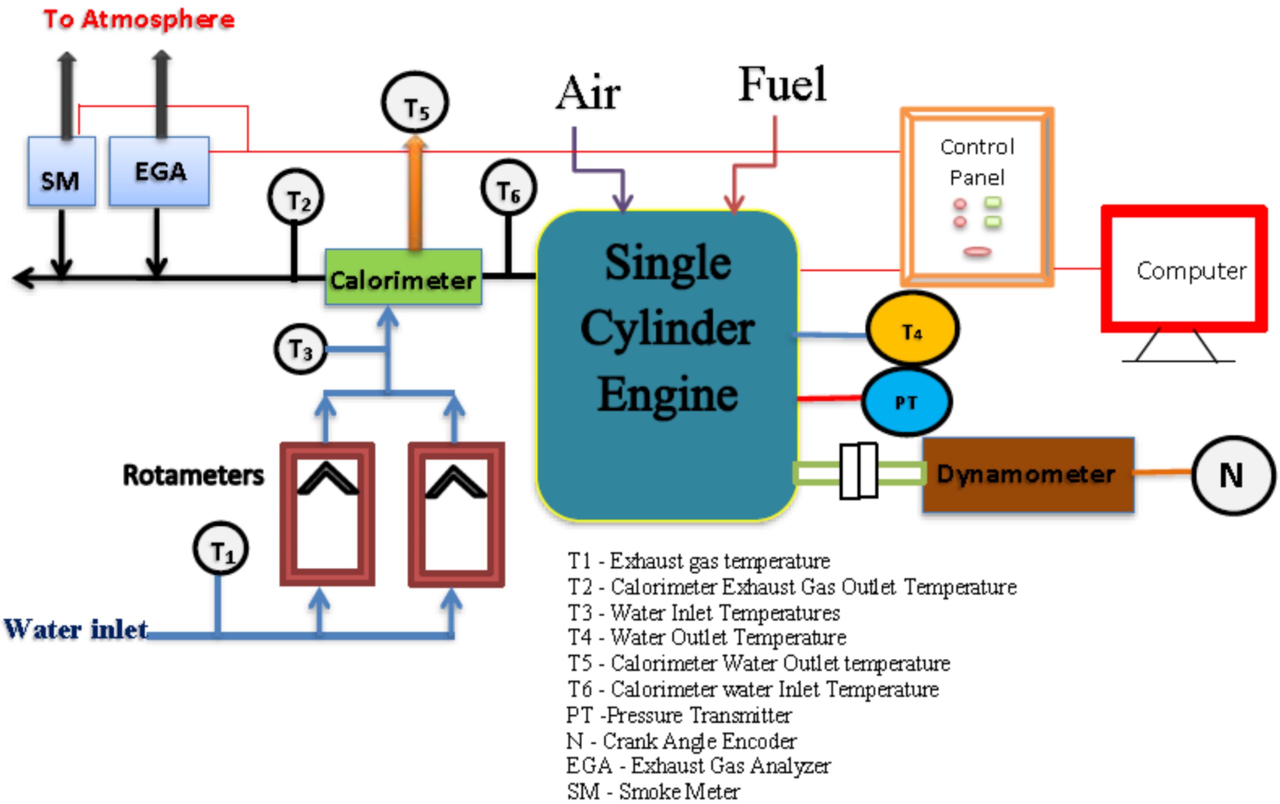

Fig. 1. Layout of Test Engine setup used for experimentation.

Engine	4 stroke single cylinder water cooled multi fuel Engine
Company	Kirloskar
Model	AV1
Rated Power	Up to 5 HP (Diesel)
Bore diameter	80 mm
Length of Stroke	110 mm
Length of Connecting rod	234 mm
Swept volume	552 cc
Rated speed	1500 rpm-3000 rpm
Compression ratio	12:1 to 20:1
Dynamometer	Eddy Current Dynamometer
Rated torque	24 N-m

Table 1. Technical specifications of diesel engine test rig.

carbon monoxide (%), carbon dioxide (%), and oxygen levels in the exhaust gas (%). Sonicators are used to agitate various materials using ultrasonic pulses. A medium is used to carry sound waves. The device converts sound energy into mechanical energy. A mechanical stirrer is a laboratory magnetic device with a spinning magnetic field that quickly spins a stir bar immersed in a liquid, churning it. The water-cooled reflux condenser consisted of a vertical tube-side condenser through which vapour flowed upward. It's also known as a knockback or vent condenser. Figure 1 depicts the research engine test layout. Table 1 lists the technical specifications of the diesel engine, whereas Table 2 lists the accuracy and uncertainty measures, as well as the engine's predicted parameters.

Parameters evaluated

To validate the biodiesel, mix in a compression ignition engine, the following parameters were investigated. Performance characteristics include brake-specific fuel consumption, brake power, and brake thermal efficiency. Combustion parameters such as cylinder pressure and heat release are related to engine crank angle. Emission criteria include carbon dioxide, carbon monoxide, nitrogen oxides, and unburned hydrocarbons.

Parameter	Accuracy	Uncertainty (%)
Time	± 0.2 s	± 0.5
Temperature	± 1° C	± 0.4
CO	0.0001% Vol	± 0.02
CO_2	0.1% Vol	± 0.8
NOx	± 1 ppm	± 0.05
HC	± 1 ppmVol	± 1.4
Flow	± 0.2 CC	± 0.76
Load	± 0.1 kg	± 0.5
Smoke Opacity	± 1% of a full scale	± 0.5
Speed	± 30 rpm	± 1.8
Calculated parameters	--	Uncertainty (%)
BTE	--	± 1.6
BSFC	--	± 1.6
HRR	--	± 0.14

Table 2. Accuracy and uncertainty measures and estimated parameters of engine.

Result & discussions

Engine performance was evaluated for all of the aforementioned petrol-mixed samples separately at various injection pressures (IP), constant speed, and compression ratios at different engine loads. To solve the challenges related to fuel replacement in unmodified C I engines, an investigation of performance measures is necessary. The measures include braking power (BP), brake thermal efficiency (BTE), and brake-specific fuel consumption (BSFC).

Engine performance parameters

Brake specific fuel consumption (BSFC)

Figure 2a depicts the relationship between brake-specific fuel consumption and engine load for PME-5G, NME-5G, MME-5G, JME-5G, UME-5G, DME-5G biodiesel blend, and diesel with calorific values of 39,400 KJ/kg, 40,063 KJ/kg, 40,095 KJ/kg, 39,994 KJ/kg, 39,585 KJ/kg, 37,955 KJ/kg, and 44,800 KJ/kg, respectively. Because the DME-5G biodiesel blend has the lowest calorific value of all other samples and diesel, the engine consumes more fuel at higher engine loads (60%, 80%, and 100%) at all three injection pressures of 210 bar, 230 bar, and 250 bar, as shown in Fig. 2a and b, and 2c.

At 210 bar injection pressure (Fig. 2a), BSFC values for MME-5G, PME-5G, and NME-5G engines at 80% engine load are 0.32 kg/KWh, 0.33 kg/KWh, and 0.34 kg/KWh, respectively, compared to 0.28 kg/KWh for diesel. At 230 bar injection pressure (Fig. 2b), fueling MME-5G, PME-5G, NME-5G, and JME-5G at 80% engine load yields very similar values of 0.29 kg/KWh, 0.34 kg/KWh, 0.35 kg/KWh, and 0.36 kg/KWh, respectively, when compared to Diesel at 0.32 kg. Similarly, at a higher injection pressure of 250 bar (Fig. 2c), fueling MME-5G, PME-5G, NME-5G, and JME-5G at 80% engine load yields extremely similar values of 0.19 kg/KWh, 0.201 kg/KWh, 0.22 kg/KWh, and 0.24 kg/KWh, respectively, when compared to diesel at 0.16 kg/KWh. At a greater injection pressure of 250 bar, the PME-5G, NME-5G, MME-5G, and JME-5G showed similar results to diesel fuel at higher engine loads (60%, 80%, and 100%), as shown in Fig. 2c. Previous studies have demonstrated that as engine load increases from zero to 100%, brake-specific energy and fuel consumption decrease[2,15].

As the engine's load increases, the mean effective cylinder pressure and mechanical efficiency rise, resulting in lower specific fuel consumption[31,32]. At 60% and 80% engine load, the BSFC of the DME-5G blend is 0.46 and 0.38 kg/KWh, respectively. At 60% and 80% engine load, diesel produces 0.37 Kg/KWh and 0.28 Kg/KWh, respectively. At 60% and 80% engine load, the remaining samples range between 0.38 Kg/KWh and 0.42 Kg/KWh. DME-5G blend appears to be the ideal sample because to its extremely near BSFC of 19% and 26% higher than diesel for the specified engine load.

Brake thermal efficiency (BTE)

Figure 3a depicts the distribution of brake thermal efficiency versus engine load at 210 bar of injection pressure. Figure 3a shows that when the engine load increases, the braking thermal efficiency for PME-5G, NME-5G, MME-5G, JME-5G, UME-5G, DME-5G biodiesel blends, and diesel steadily increases. Diesel has BTE values of 26%, 30%, and 29% for engine loads of 60%, 80%, and 100%, respectively, at 210 bar injection pressure. At 210 bar injection pressure and 80% engine load, the BTE values for PME-5G, NME-5G, and MME-5G engines are 27.94%, 26.45%, and 25.85%, respectively, compared to 30.3% for diesel. NME-5G, JME-5G, UME-5G, and PME-5G all have a close association with BTE for Diesel. DME-5G has the lowest brake thermal efficiency across all engine loads due to its lower Calorific value.

Diesel has BTE values of 28%, 29%, and 31% for engine loads of 60%, 80%, and 100%, respectively, at an injection pressure of 230 bar. At this injection pressure, MME-5G, NME-5G, and JME-5G show extremely similar results of 27.68%, 25.17%, and 24.74%, respectively, when compared to Diesel at 28.69%. At higher engine loads, the MME-5G and Diesel bear a remarkable likeness. Figure 3b shows that NME-5G, JME-5G, UME-5G, and PME-5G have a close association with the BTE of Diesel.

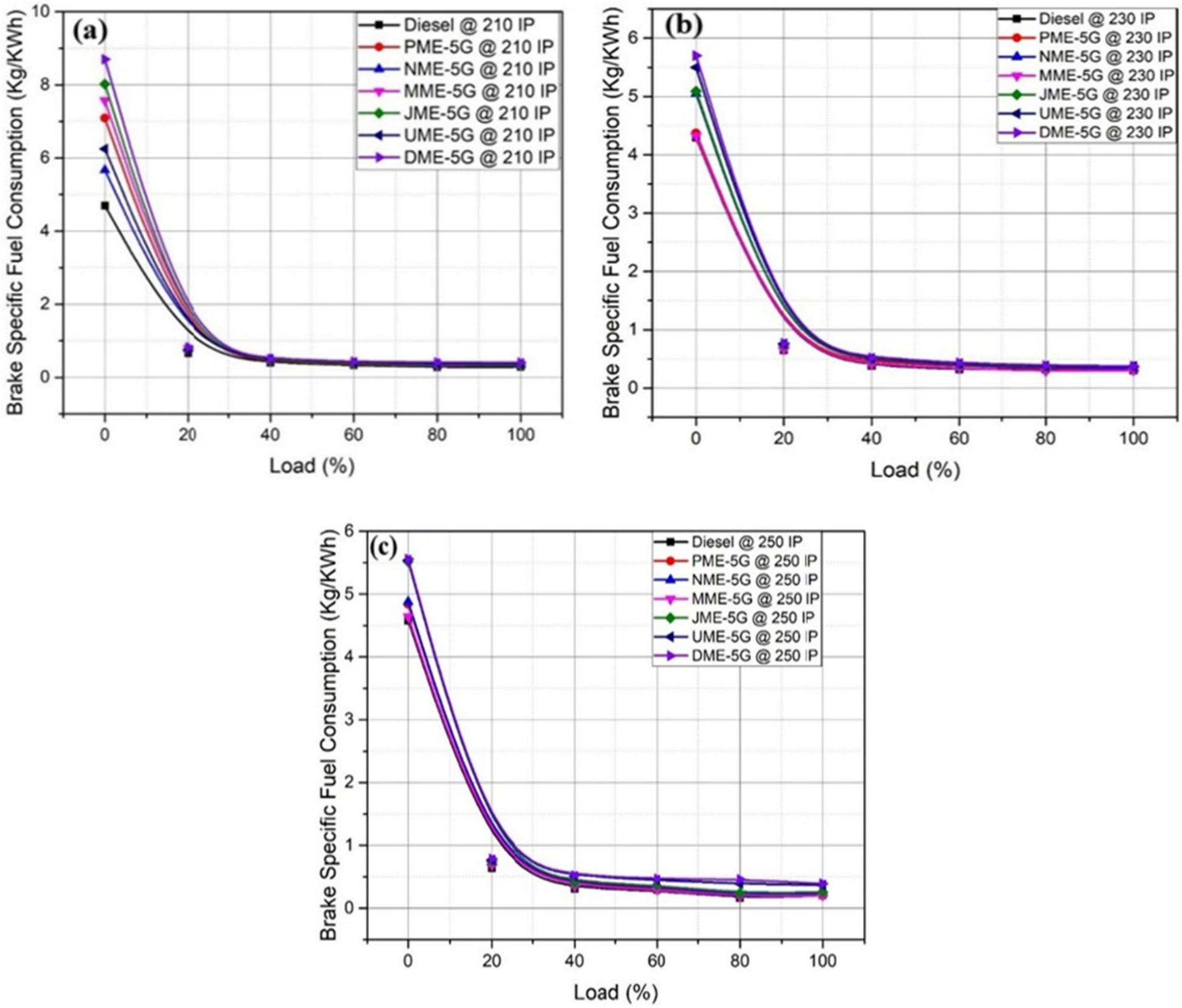

Fig. 2. BSFC vs. Load at IP (**a**) 210 bar, (**b**) 230 bar, (**c**) 250 bar.

Diesel has BTE values of 25%, 26%, and 28% for engine loads of 60%, 80%, and 100%, respectively, at 250 bar injection pressure. At this injection pressure, fueling MME-5G, NME-5G, and JME-5G at 80% engine load yields extremely similar values of 23.89%, 23.73%, and 22.65%, respectively, compared to Diesel at 25.68%. NME-5G, JME-5G, UME-5G, and PME-5G all have a close association with diesel BTE, as seen in Fig. 3c. At higher injection pressures of 250 bar, brake thermal efficiency declines by 5% on average. At a standard injection pressure of 200 bar, methyl ester neem oil has lower braking thermal efficiency than diesel fuel at all loads due to its high viscosity and poor mixture formation[33].

Brake power (BP)
Figure 4a displays the brake power produced at all prescribed engine loads when the engine is fuelled with PME-5G, NME-5G, MME-5G, JME-5G, UME-5G, DME-5G biodiesel, or diesel. The profiles produced for PME-5G, NME-5G, MME-5G, JME-5G, UME-5G, DME-5G biodiesel blend, and Diesel indicate a direct link between braking power and engine load. At 210 bar injection pressure, brake power of UME-5G, DME-5G and PME-5G for 80% engine load shows very closer values of 3.19 KW, 3.16 KW and 3.15 KW respectively while compared to Diesel with 3.22 K. At this stage, diesel produces 3.22 KW of brake power, while the UME-5G produces 3.19 KW of brake power, which is 0.93% less than diesel. At higher injection pressure of 230 bar, UME-5G, JME-5G and PME-5G for 80% engine load shows very closer values of 3.23 KW, 3.21 KW and 3.15 KW respectively while compared to Diesel with 3.2 KW. At this stage, the brake power produced by Diesel is 3.2 KW, whereas the UME-5G produced 3.23 KW, which is 0.92% more than Diesel. Figure 4b shows that the PME-5G, NME-5G, MME-5G, JME-5G, and DME-5G biodiesel blends had remarkably similar results at 230 bar injection pressure. Similarly at higher injection pressure of 250 bar, UME-5G, JME-5G and PME-5G for 80% engine load shows very closer values of 3.18 KW, 3.14 KW and 3.13 respectively while compared with Diesel with 2.98 KW. Here,

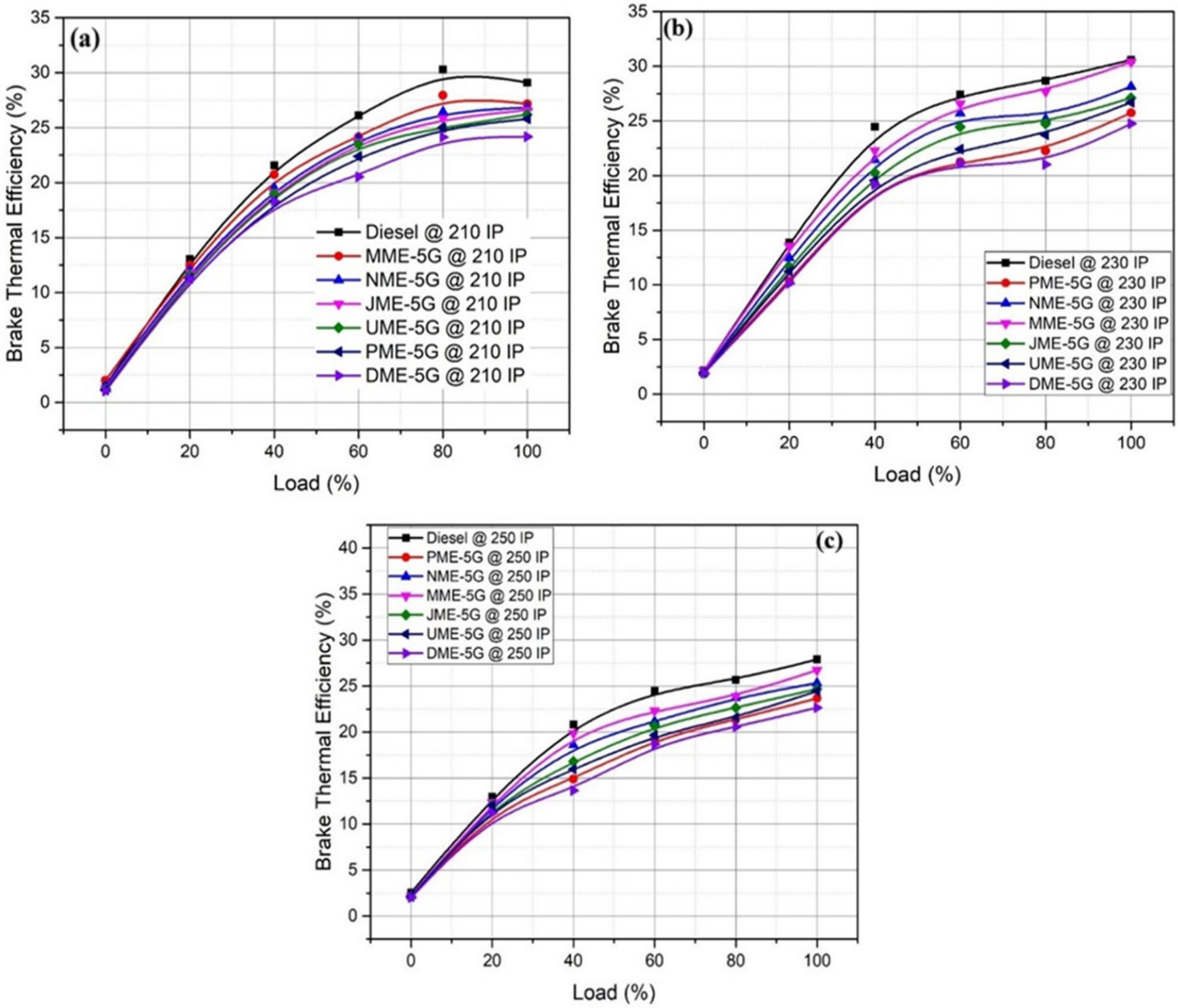

Fig. 3. BTE vs. load at IP (**a**) 210 bar, (**b**) 230 bar, (**c**) 250 bar.

the brake power produced for Diesel is 2.98 KW, whereas the UME-5G produced 3.18 KW of brake power, which is 6% greater than Diesel.

At a higher injection pressure of 250 bar, the brake power of the PME-5G, NME-5G, MME-5G, JME-5G, and DME-5G biodiesel blends exceeds that of diesel, as illustrated in Fig. 4c. As the engine load grows, so does the brake power provided by the fuel sample. When compared to diesel, the castor oil blend sample had significantly lower brake power under varying engine load conditions[34].

Engine combustion characteristics

Cylinder pressure (CP)

Figure 5a displays the cylinder pressure developed within an engine cylinder versus crank angle at 80% engine load when the engine was running at 210 bar of injection pressure and fuelled with PME-5G, NME-5G, MME-5G, JME-5G, UME-5G, DME-5G biodiesel and diesel. The cylinder pressure distribution curve displayed by all blended samples is comparable to the Diesel. At 210 psi of injection pressure and 80% engine loading, the UME-5G produces 61.93 bar of cylinder pressure, while the Diesel exerts 59.26 bar. UME-5G has 4.3% higher cylinder pressure than diesel. The sample blends, such as NME-5G, MME-5G, JME-5G, and DME-5G, provide very close cylinder pressure to that of diesel.

Similarly, with 230 bar of injection pressure and 80% engine loading, MME-5G produces 62.63 bar and Diesel exerts 62.47 bar of cylinder pressure. MME-5G has 0.25% higher cylinder pressure than diesel. Figure 5b shows sample blends such as PME-5G, NME-5G, JME-5G, and UME-5G yield cylinder pressures that are extremely near to those of diesel. Similarly, at 250 bar of injection pressure and 80% engine loading, JME-5G produces 61.17 bar and Diesel exerts 61.19 bar of cylinder pressure, respectively. JME-5G has 0.03% lower

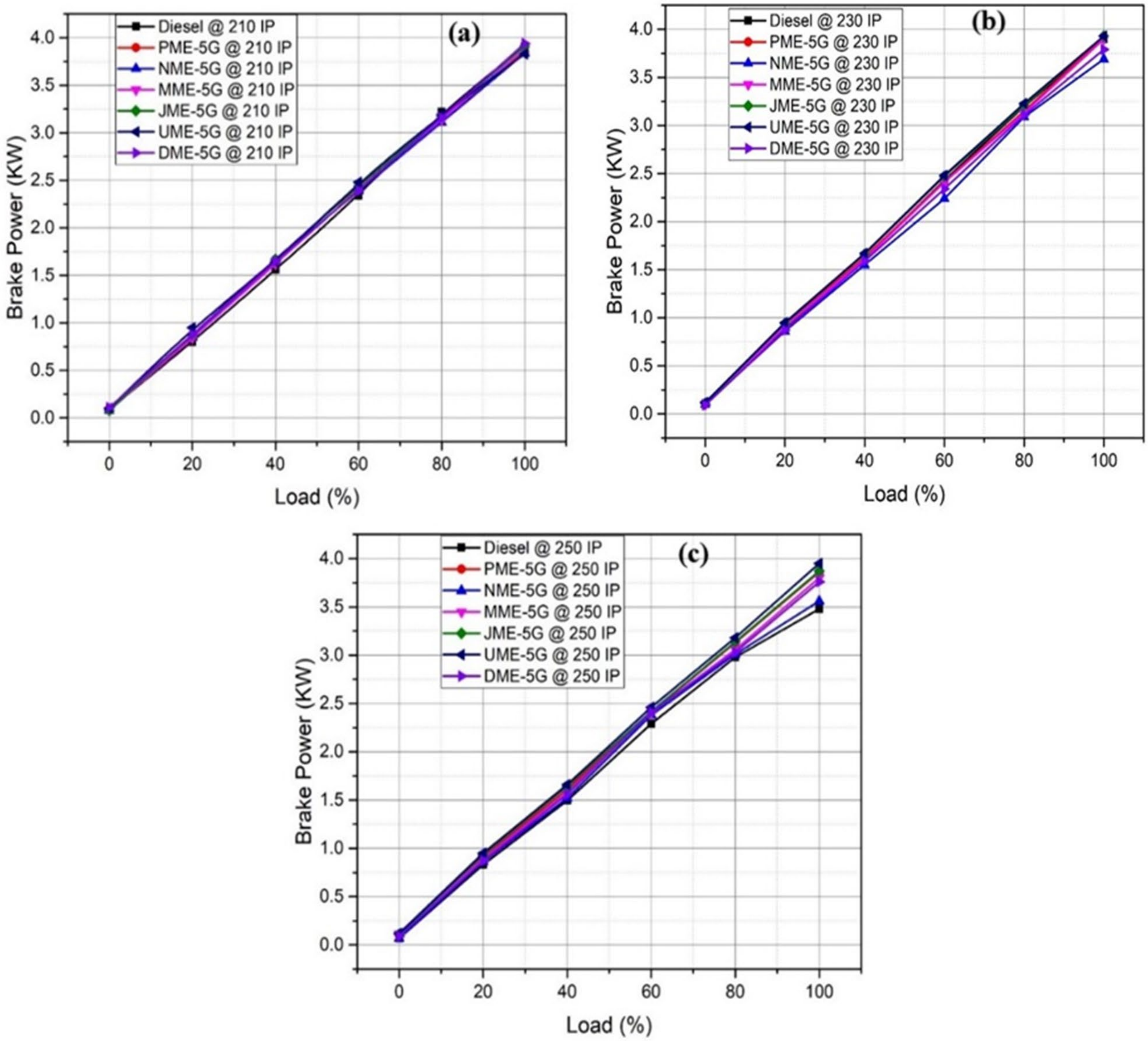

Fig. 4. Brake Power vs. Load at IP (**a**) 210 bar, (**b**) 230 bar, (**c**) 250 bar.

cylinder pressure than diesel. Figure 5c shows that sample blends such as MME-5G and UME-5G create cylinder pressures comparable to diesel.

The cylinder peak pressure is determined by the biodiesel's early combustion rate, which is controlled by the uncontrolled heat release phase. Biodiesel has a lower cylinder peak pressure than conventional diesel because of its high viscosity and low volatility. According to studies, the cylinder peak pressure of biodiesel increases as the engine load increases due to the volume of biodiesel injected into the cylinder[2,35]. When utilizing biodiesel and similar mixes, the early peaking features require extra attention to guarantee that the peak pressure occurs after TDC for safe and efficient operation. Otherwise, a peak pressure around or before TDC results in significant engine knock, reducing engine durability[28]. When DEE (diethyl ether) is added to neat biodiesel, the peak pressure rises relative to neat biodiesel. This is because DEE has a greater cetane number and is more flammable, resulting in a better-premixed combustion phase and a higher peak pressure[29]. At 100% engine load, the average cylinder pressure for PME-5 G and diesel is similar[36]. If a fuel ignites slower than diesel fuel and combustion happens after the fuel and air have had more time to mix, both pollutants could be lowered simultaneously, eliminating the well-known soot-NOx trade-off[17].

Heat release rate

Figure 6a displays the heat released rate during combustion within an engine cylinder vs. crank angle at 80% engine load, with the engine operating at 210 bar injection pressure and fuelled by PME-5G, NME-5G, MME-5G, JME-5G, UME-5G, DME-5G biodiesel and diesel. The heat release rate distribution curves of all blended samples are comparable to the Diesel. At 210 bar of injection pressure and 80% engine loading, UME-5G

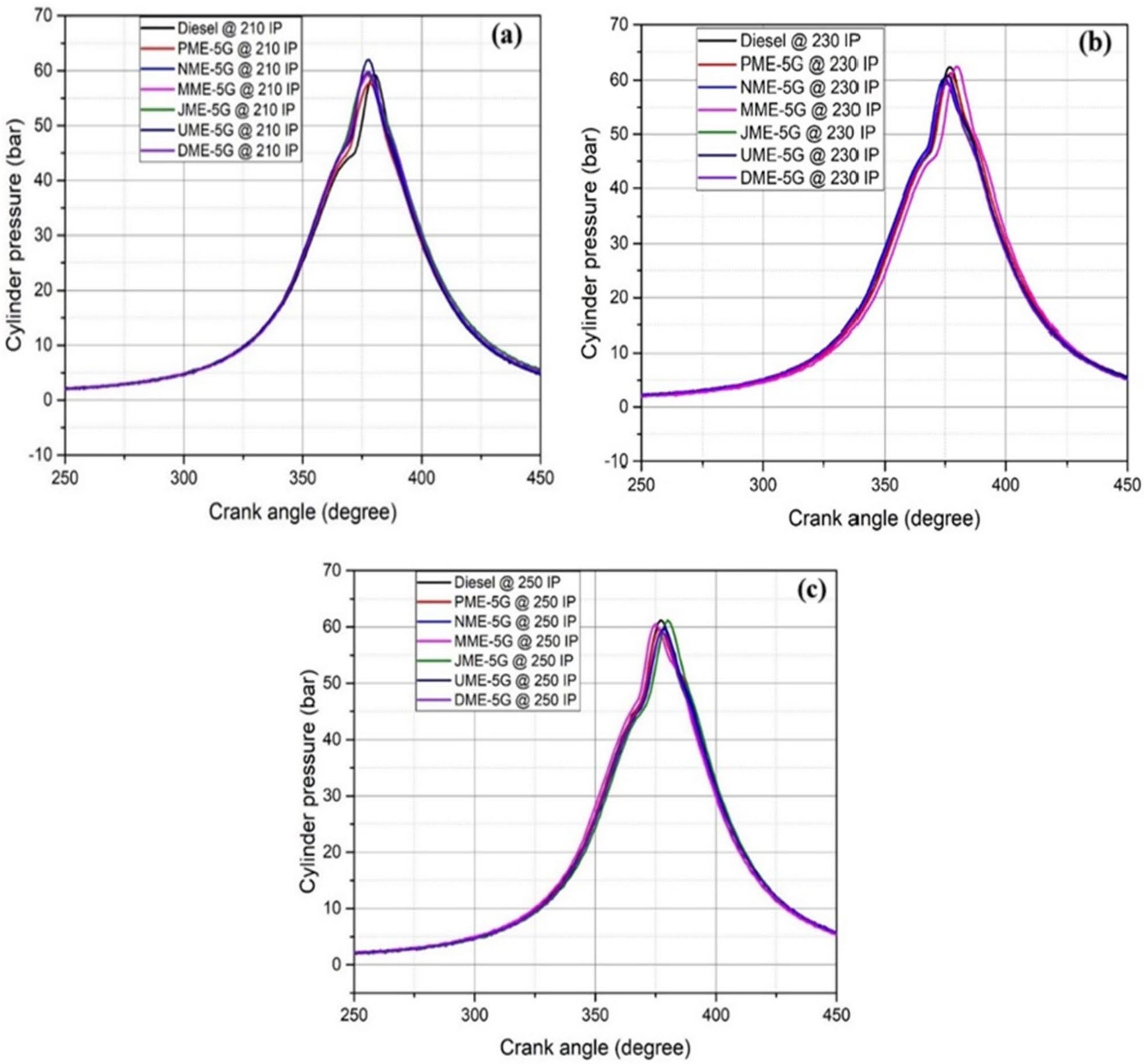

Fig. 5. Cylinder Pressure vs. Crank angle at (**a**) IP = 210 bar, (**b**) IP = 230 bar, (**c**) IP = 250 bar.

produces 35.15 J/degree CA, while Diesel releases 37.61 J/degree CA of heat release rate. UME-5G has a 6.5% lower heat release rate than diesel. Sample blends such as DME-5G and NME-5G produce results similar to diesel, as illustrated in Fig. 6a. Similarly, at 230 bar of injection pressure and 80% engine loading, MME-5G produces 40.9 J/degree CA of heat release rate, while Diesel releases 38.62 J/degree CA. MME-5G has a 5.5% higher heat release rate than diesel. Sample blends such as NME-5G and PME-5G produce values similar to diesel, as illustrated in Fig. 6b.

Similarly, at 250 bar of injection pressure and 80% engine loading, the JME-5G produces 35.27 J/degree CA of heat release rate, whereas the Diesel releases 31.51 J/degree CA. JME-5G has a 10.6% higher heat release rate than diesel. The sample blends NME-5G, MME-5G, and PME-5G generate values similar to Diesel, as shown in Fig. 6c. Biodiesel has a lower calorific value than diesel, therefore it requires more fuel to maintain the engine operating at a steady speed under varying loads[2]. According to the heat release rate, biodiesel and its mixes had a shorter igniting delay than diesel. Biodiesel and comparable mixes have a less intense premix combustion phase due to the shorter ignition delay.

When utilising diesel, however, increased fuel accumulation over a somewhat longer delay time resulted in a faster rate of heat release. Because of the shorter delay, biodiesel and equivalent mixtures reach their maximal heat release rate earlier than neat diesel. Biodiesel and biodiesel blends, on the other hand, emit slightly less heat in the late combustion phase than diesel.

This is because elements with a higher oxygen concentration can complete the combustion of any remaining fuel after the main combustion period and continue to burn in the late combustion phase[28]. The net heat release

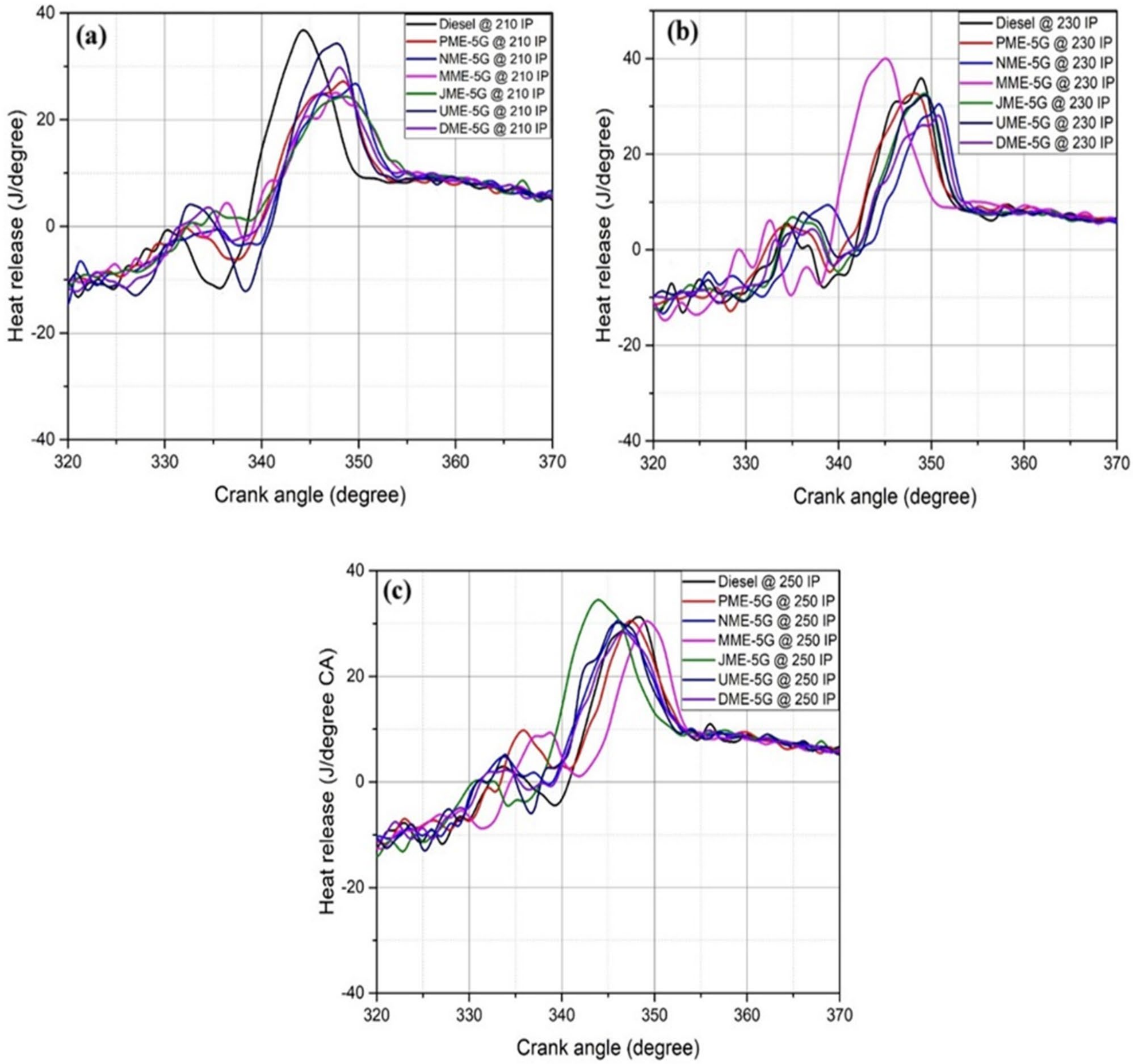

Fig. 6. Heat release vs. Crank angle at IP (**a**) 210 bar, (**b**) 230 bar, (**c**) 250 bar.

rate (NHRR) increased as IP increased due to higher cylinder pressure and combustion temperature[37]. The vaporization of the fuel stored during the ignition delay at the start has a negative heat release rate. This becomes positive as the combustion process begins. The premixed fuel-air combination burns swiftly following the ignition delay phase, followed by diffusion combustion, which is governed by the fuel-air mixing velocity[38]. As the load rose, the heat emitted in the premixed combustion phase stayed roughly constant, whereas the heat released in the regulated combustion phase increased[39].

Engine emission characteristics

Carbon monoxide (CO)

Figure 7a displays the percentage of carbon monoxide emitted during engine exhaust versus engine load when the engine is run at 210 bar injection pressure and fuelled with PME-5G, NME-5G, MME-5G, JME-5G, UME-5G, DME-5G biodiesel and diesel. Figure 7a shows that the percentage of carbon monoxide emitted with each successive increment in engine load steadily increases for diesel and all sample mixes. At 80% engine load, CO emission by Diesel is 0.915%, whereas NME-5G produced the least content of all samples, 0.604% of CO percentage. The NME-5G emitted 33.9% less CO than the diesel. The sample blends such as PME-5G, MME-5G, JME-5G, UME-5G, and DME-5G emitted lower CO emissions compared to diesel emissions. As shown in Fig. 7b, the sample blends PME-5G, MME-5G, JME-5G, UME-5G, and DME-5G had lower CO emissions compared to Diesel emissions. At 230 bar of injection pressure and 80% engine load, CO emissions by Diesel were 0.983%, while CO emissions by NME-5G were in the range of 0.821%.

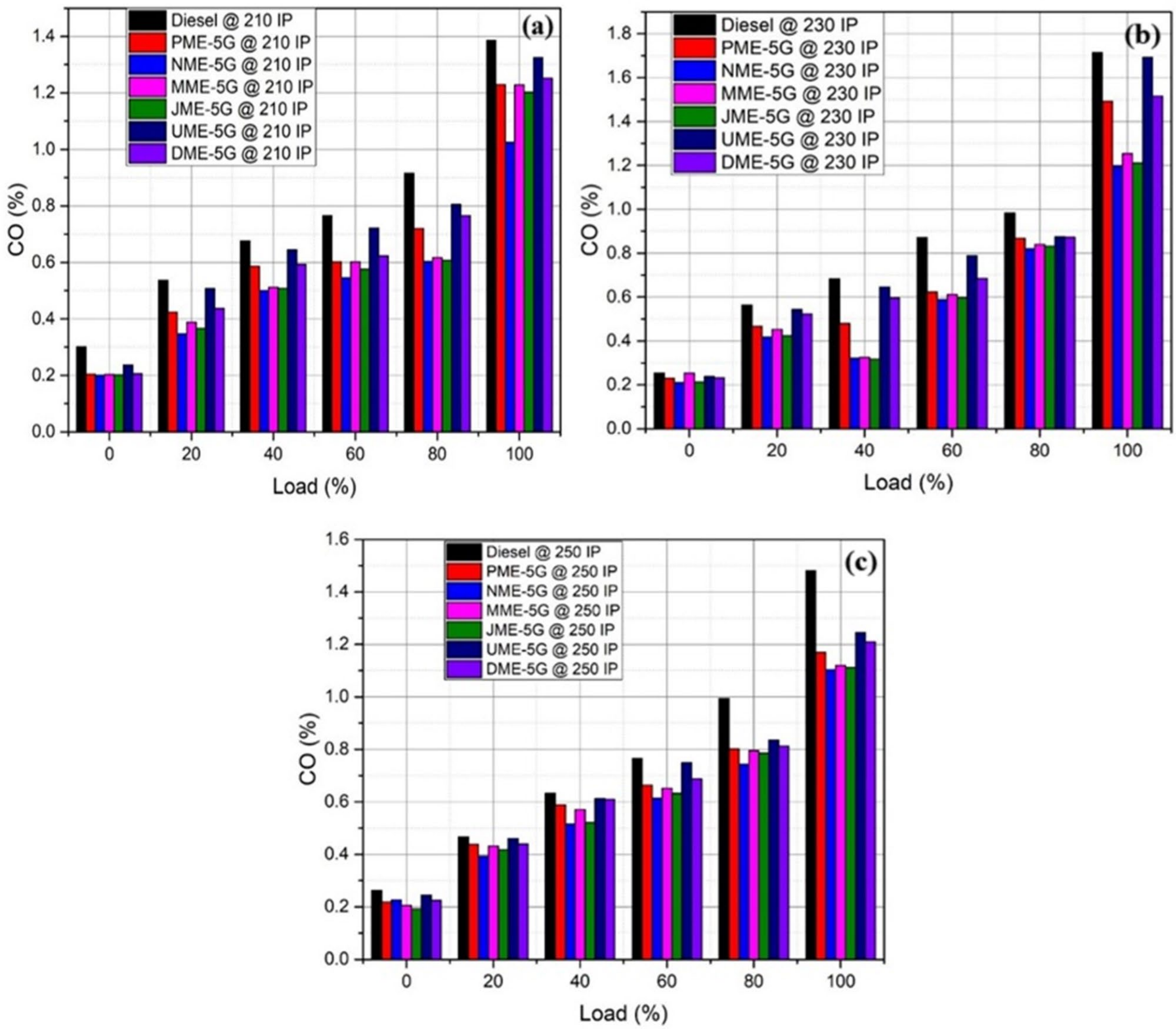

Fig. 7. Carbon monoxide vs. Load at IP (**a**) 210 bar, (**b**) 230 bar, (**c**) 250 bar.

Similarly, at 250 bar of injection pressure and 80% engine load, diesel emits 0.994% of CO, while NME-5G emits the least amount of CO, around 0.744%. The NME-5G emitted 25.1% less CO than the diesel. Figure 7c shows that sample mixes such as PME-5G, MME-5G, JME-5G, UME-5G, and DME-5G emit less CO than diesel emissions. When the injection pressure is increased to 200 bar, CO emissions are minimized.

Increased injection pressure reduces CO emissions by improving fuel-air mixing and full combustion[40]. Increased injection pressure reduces smoke density and CO emissions while increasing NOx emissions in a diesel engine powered by an ethanol-diesel fuel combination[41].

Carbon dioxide

Figure 8a displays the percentage of carbon dioxide emitted during engine exhaust versus engine load while the engine is operated at 210 bar injection pressure and fuelled with PME-5G, NME-5G, MME-5G, JME-5G, UME-5G, DME-5G biodiesel and diesel. Figure 8a shows that the percentage of carbon dioxide released with each successive increment in engine load steadily increases for diesel and all sample mixes. At 80% engine load, diesel emits 8.62% CO_2, while PME-5G emits only 7.24% CO_2. PME-5G released 16% less CO_2 emissions than the diesel. Sample mixes such as NME-5G, MME-5G, JME-5G, UME-5G, and DME-5G emitted less CO_2 than diesel emissions. Similarly, at 230 bar of injection pressure and 80% engine load, CO_2 emissions by diesel are 8.65%, while UME-5G emits the least CO_2 content, at 7.587%. UME-5G emitted 12% less CO_2 than the Diesel.

Figure 8b shows that sample mixes such as NME-5G, MME-5G, JME-5G, PME-5G, and DME-5G emitted less CO_2 than diesel. Similarly, at 250 bar of injection pressure and 80% engine load, CO_2 emissions from diesel are 8.92%, whereas UME-5G emits the least amount of CO_2 emissions, at 8.06%. UME-5G released 9.6% less CO_2 emissions than the diesel. Figure 8c shows that sample blends such as NME-5G, MME-5G, JME-5G, PME-

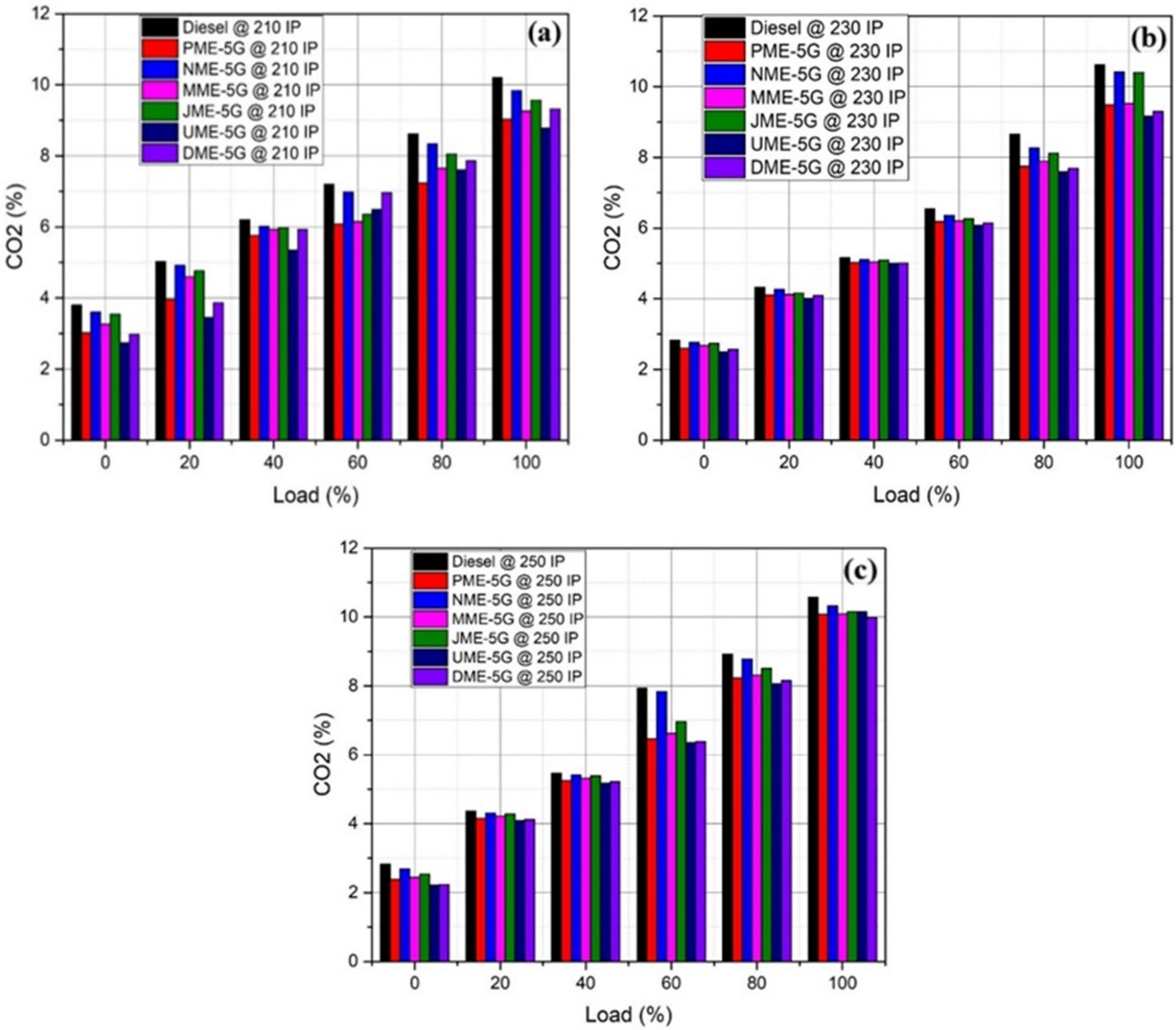

Fig. 8. Carbon dioxide vs. load at IP (**a**) 210 bar, (**b**) 230 bar, (**c**) 250 bar.

5G, and DME-5G emitted less CO_2than diesel. The increased injection pressure lowers HC, NOx, and smoke emissions while increasing CO and exhaust temperature[23]. Increased injection pressure and methyl ester content in diesel cause higher CO_2emissions. This is because higher injection pressure produces finer fuel spray, which properly blends fuel and air, completing the combustion process[42]. The CO_2percentage emission pattern for PME-5 G biodiesel blends is nearly identical to that of diesel fuel for all engine load settings (0%, 20%, 40%, 60%, 80%, and 100%)[36].

Unburned hydrocarbons

Figure 9a displays the ppm of unburned hydrocarbons emitted during engine exhaust versus engine load while the engine was running at 210 bar of injection pressure and fuelled with PME-5G, NME-5G, MME-5G, JME-5G, UME-5G, DME-5G biodiesel and diesel. Figure 9a shows that the ppm of unburned hydrocarbons released as engine load increases progressively for diesel and all sample mixes. At 80% engine load, diesel emits 226 ppm of unburned hydrocarbons, while JME-5G emits the least amount, around 126 ppm of unburned hydrocarbons. JME-5G produced 44% less unburned hydrocarbon emissions than diesel.

The sample blends NME-5G, MME-5G, PME-5G, UME-5G, and DME-5G produced fewer unburned hydrocarbons than diesel emissions. Similarly, at 230 bar of injection pressure and 80% engine load, diesel emits 280 ppm of unburned hydrocarbons, while JME-5G emits the least amount, around 219 ppm of unburned hydrocarbons. JME-5G emitted 21% less unburned hydrocarbons than diesel. Figure 9b shows that sample blends such as NME-5G, MME-5G, PME-5G, UME-5G, and DME-5G emitted fewer unburned hydrocarbons than diesel.

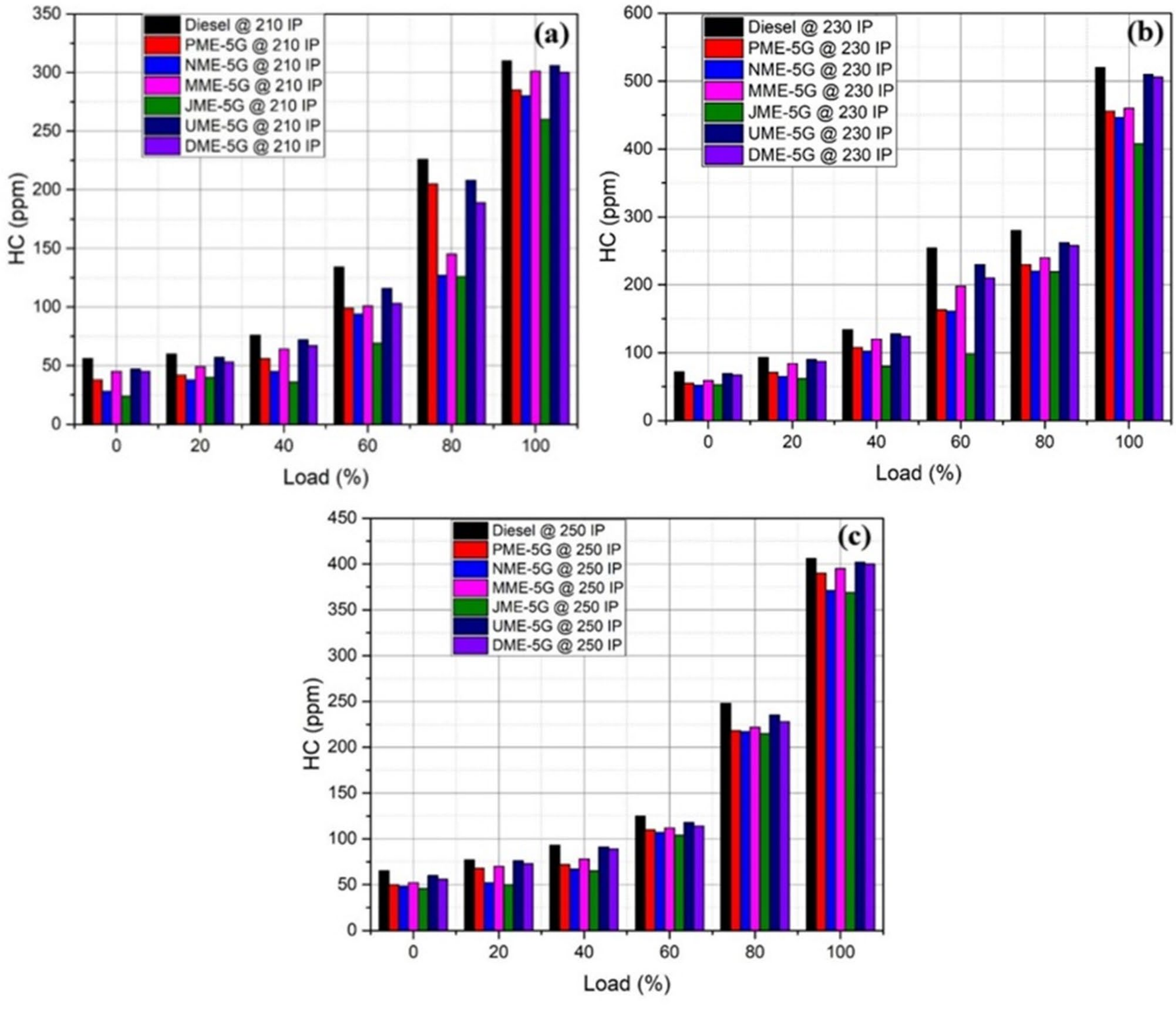

Fig. 9. Unburned Hydrocarbons vs. load at IP (**a**) 210 bar, (**b**) 230 bar, (**c**) 250 bar.

Similarly, at 250 bar of injection pressure and 80% engine load, diesel emits 248 ppm of unburned hydrocarbons, while JME-5G emits the least amount, around 215 ppm of unburned hydrocarbons. JME-5G emitted 13% less unburned hydrocarbons than diesel.

Figure 9c shows that sample mixes such as NME-5G, MME-5G, PME-5G, UME-5G, and DME-5G emitted fewer unburned hydrocarbons than diesel. Because of increased fuel burning at higher Injection Pressure, HC decreases considerably as Indicated Power increases. The decrease in HC emissions as the blend proportion increases could be attributed to full combustion due to the increased oxygen concentration[43,44]. High-pressure injection was used to significantly reduce particle emissions while having little effect on hydrocarbon emissions and slightly raising NOx emissions[45,46].

Oxides of nitrogen

Figure 10a displays the ppm of nitrogen oxides emitted during engine exhaust versus engine load while the engine was running at 210 bar of injection pressure and fuelled with PME-5G, NME-5G, MME-5G, JME-5G, UME-5G, DME-5G biodiesel and diesel. Figure 10a shows that the ppm of nitrogen oxides emitted as engine load increases progressively for diesel and all sample blends. At 80% engine load, diesel emits 242 ppm of oxides of nitrogen, while JME-5G emits 147 ppm. JME-5G emitted 39% fewer oxides of nitrogen than diesel. The sample blends, such as NME-5G, MME-5G, PME-5G, UME-5G, and DME-5G, emitted less nitrogen oxides than diesel emissions.

Similarly, at 230 bar of injection pressure and 80% engine load, the ppm of Oxides of Nitrogen by Diesel is 161 ppm, but the JME-5G emits the least amount, in the range of 169 ppm. JME-5G emitted 4.7% higher oxides of nitrogen than diesel. Figure 10b shows that sample blends such as NME-5G, MME-5G, PME-5G, UME-5G, and DME-5G emit more nitrogen oxides than diesel emissions. Similarly, at 250 bar of injection pressure and

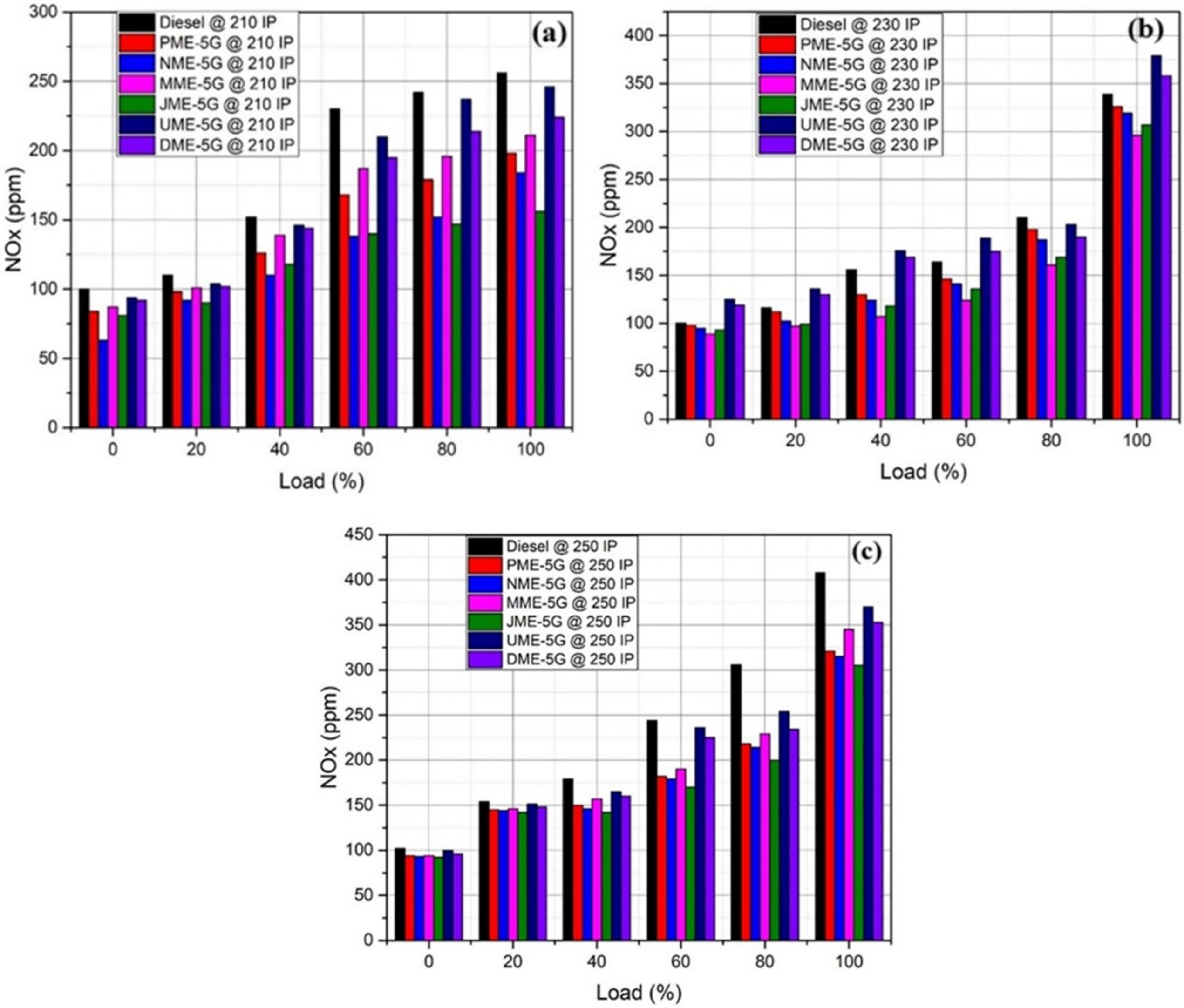

Fig. 10. Oxides of Nitrogen vs. load at IP (**a**) 210 bar, (**b**) 230 bar, (**c**) 250 bar.

80% engine load, diesel emits 306 ppm of oxides of nitrogen, whereas JME-5G emits the least amount, in the region of 200 ppm of oxides of nitrogen. JME-5G emitted 34% less oxides of nitrogen than the diesel.

Figure 10c shows that sample mixes such as NME-5G, MME-5G, PME-5G, UME-5G, and DME-5G emit fewer nitrogen oxides than diesel emissions. It was recommended that high injection pressure be employed to reduce smoke, CO, and UHC emissions, and low injection pressure to reduce NOx and CO_2emissions[37,47]. Higher injection pressures of up to 250 bar result in considerable performance improvements for all examined fuels, albeit to varied degrees. With this optimal injection pressure, the B20 was discovered to have the best performance characteristics[48].

The temperature inside the cylinder has a considerable influence on NOx creation, and as the temperature rises, so does the amount of NOx produce[44,49]. In the same way that increasing the load raises the fuel-air ratio, increasing the KOME proportion raises the oxygen content, increasing NOx emissions[50,51]. NOx and carbon dioxide emissions increased as injection pressure increased, but smoke, HC, and CO emissions decreased[52,53].

Conclusion

The performance of the engine exhibited by the compression ignition engine at three injection pressures reflects clear differences from all the distinguished synthesized samples.

- DME-5G blend appears to be the ideal sample because to its extremely near BSFC of 19% and 26% higher than diesel for the specified engine load. At a greater injection pressure of 250 bar, the PME-5G, NME-5G, MME-5G, and JME-5G showed similar results to diesel fuel at higher engine loads (60%, 80%, and 100%).
- At a higher injection pressure of 250 bar, fueling MME-5G, NME-5G, and JME-5G at 80% engine load yields extremely close BTE values of 23.89%, 23.73%, and 22.65%, respectively, compared to Diesel at 25.68%. The maximum efficiency difference lies below 11%.

- Compared to the injection pressure at 210 bar, fuelling at higher injection pressure provided the very close Brake power. Particularly, at injection pressure of 250 bar upon fuelling UME-5G, JME-5G, and PME-5G for 80% engine load shows 3.18 KW, 3.14 KW, and 3.13 respectively which is very close to Diesel with 2.98 KW.
- At 210 bar of injection pressure for 80% engine loading UME-5G exhibits 4.3% more-cylinder pressure than Diesel. At 230 bar of injection pressure for 80% engine loading MME-5G exhibits 0.25% more-cylinder pressure than Diesel. Similarly, at 250 bar of injection pressure for 80% engine loading JME-5G exhibits 0.03% less cylinder pressure than Diesel.
- Heat release rate is lower at injection pressure 210 bar and higher at 230 & 250 bar under 80% engine loading. UME-5G has lower heat release of 6.5%, MME-5G & JME-5G 6.5% have high release rate of 5.5% & 10.6% than diesel respectively.
- Carbon monoxide released by the engine at an injection pressure of 210 bar upon fuelling NME-5G, JME-5G, and MME-5G for 80% engine load shows lesser values of 0.604%, 0.607%, and 0.617% respectively while compared to Diesel with 0.915%. The rate of CO is more at higher injection pressure.
- At 210 bar injection pressure and 80% engine load, carbon dioxide emissions from PME-5G, UME-5G, and MME-5G engines are 7.24%, 7.61%, and 7.65%, respectively, compared to 8.62% for diesel. The rate of CO_2 is more at higher injection pressure.
- Unburned hydrocarbon released by the engine at an injection pressure of 210 bar upon fuelling JME-5G, NME-5G, and MME-5G for 80% engine load shows lesser values of 126 ppm, 127 ppm, and 145 ppm respectively while compared to Diesel with 226 ppm. The rate of UBHC is more at higher injection pressures.
- Nitrogen oxides emitted by JME-5G, NME-5G, and PME-5G engines at 210 bar during 80% engine load were 147, 152, and 179 ppm, respectively, compared to 242 ppm for diesel.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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G P: Experimentation & InvestigationA B: Conceptualization & MethodologyG F: Formulation & CalculationM N: Interpretation of results & Report writing.

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Declarations

Competing interests
The authors declare no competing interests.

Conflict of interest
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