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Boost pressure influence on combustion, emission characteristics, and performance of diesel engines with various fuel types

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A R T I C L E I N F O

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A B S T R A C T

This study investigates the effects of varying boost pressure levels on engine performance, combustion characteristics, and emissions using different fuel types (diesel, B50, B100) under various engine loads. The results show that increasing boost pressure generally enhances engine performance by raising in-cylinder pressure and heat release rates. For instance, at 75 % engine load, the cylinder pressure increased by 18.7 % for diesel and 15.9 % for B100 when the boost pressure was raised from −20 % to + 20 %. Similarly, combustion efficiency improved, with ignition delay reduced by approximately 4.1 % for diesel and 6.5 % for B100 under the same conditions. However, higher boost pressure also led to increased Brake Specific Fuel Consumption (BSFC), particularly for biodiesel fuels; for B100, BSFC increased from 297.1 g/kWh to 304.95 g/kWh at 50 % engine load. In terms of emissions, higher boost pressure significantly decreased CO and HC emissions by up to 7.5 % and 15.3 %, respectively, for B100. Nevertheless, NOx emissions increased by 5.3 % due to the oxygen content of biodiesel. Soot emissions were notably reduced, with a maximum reduction of 58.4 % observed at 75 % engine load and + 20 % boost pressure for diesel fuel. These findings underscore the need for additional strategies to control NOx emissions, especially for biodiesel applications. In conclusion, optimizing boost pressure is critical for improving engine performance and emissions. Biodiesel and its blends, despite their higher NOx emissions, provide significant environmental benefits due to their cleaner combustion characteristics. This study contributes valuable insights for designing more efficient and sustainable internal combustion engines.

1. Introduction

The world's demand for energy is increasing day by day. This increase makes it essential to use all types of energy together and effectively. Transportation has evolved significantly over the last 25 years and the number of vehicles has increased incredibly. Although electric vehicles are becoming more and more popular worldwide, combustion engines are still widely used. It is therefore very important that vehicles currently powered by fossil fuels become more environmentally friendly. It's about reducing energy consumption for the same amount of work so that a vehicle has less impact on the environment. Additionally, growth in the transportation sector is directly related to global warming [1,2].

In this context, alternative fuels like biodiesel have gained attention as a viable solution to reduce the environmental footprint of internal combustion engines. Biodiesel offers an opportunity to bridge the gap between sustainability and the continued reliance on combustion engines, making it a key candidate for greener transportation. Biodiesel, derived from vegetable oils and animal fats, offers numerous environmental advantages over fossil fuels [3]. It significantly reduces emissions of particulate matter, hydrocarbons, and carbon monoxide in diesel engines [4]. Biodiesel yields 93 % more energy than invested in its production and reduces greenhouse gas emissions by 41 % compared to fossil fuels. Its benefits include higher combustion efficiency, biodegradability, and lower sulfur content. However, challenges persist, such as higher viscosity, lower energy density, and potential impacts on food supplies [5,6]. Despite these drawbacks, biodiesel's environmental advantages make it a promising alternative fuel. To realize its full potential, issues like feedstock availability, price stability, and policy support need to be addressed [4].

Abbreviations: B100, %100 biodiesel; B50, %50 biodiesel blend; BSFC, Brake Specific Fuel Consumption; BTDC, Before Top Dead Center; BTE, Brake Thermal Efficiency; CA, Crank Angle; CO, Carbon Monoxide; CO_2, Carbon Dioxide; DI, Direct Injection; DPF, Diesel Particulate Filter; EGR, Exhaust Gas Recirculation; EGT, Exhaust Gas Temperature; HC, Hydrocarbons; HCCI, Homogeneous Charge Compression Ignition; HRR, Heat Release Rate; MFB50, Mass Fraction Burned at 50%; NO_x, Nitrogen Oxides; O_2, Oxygen; PM, Particulate Matter; RH, Relative Humidity.

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Despite growing efforts to optimize internal combustion engines for stricter environmental standards, significant gaps remain in understanding how boost pressures influence biodiesel and its blends, particularly regarding their unique combustion characteristics and emissions. Existing studies primarily focus on diesel engines operating with conventional fuels, leaving significant gaps in understanding biodiesel's unique properties and their influence on combustion characteristics, emissions, and performance under different operating conditions.

While significant attention has been paid to fuel composition and boost pressure in improving combustion and emission characteristics, piston geometry and its impact on internal dynamics also play a crucial role in overall engine performance. Studies in recent literature provide insights into how modifications to piston surfaces affect volumetric efficiency and fluid dynamics, offering an indirect perspective on the influence of in-cylinder modifications. This highlights the interconnected nature of combustion dynamics and the need for comprehensive approaches in assessing the effects of boost pressure on biodiesel blends [7]. There are only a limited number of studies on charge air pressure in the literature. Some of these studies were summarized and compared.

Despite the growing interest in optimizing internal combustion engines to meet stricter environmental standards, the effects of varying boost pressures on biodiesel and its blends remain insufficiently explored. Current studies focus primarily on diesel engines operating under conventional fuels, leaving significant gaps in understanding the nuanced impacts of biodiesel's distinct properties on combustion characteristics, emissions, and performance under varying operating conditions. This study aims to address these gaps by systematically investigating the effects of boost pressure on engine performance and emissions when using biodiesel and its blends. By doing so, it provides valuable insights into optimizing biodiesel usage and contributes to the development of more efficient and sustainable engine technologies.

There are only a limited number of studies on charge air pressure in the literature. Some of these studies were summarized and compared.

In their study, Wang et al. changed the intake air pressure (100–400 kPa) at three different engine loads. The combustion and emission characteristics of the intake air pressure were investigated. The results show that increasing the intake pressure reduces the air consumption rate. Accordingly, the air–fuel mixture in the cylinder must be improved. This indicates that the injection pressure must be optimized. An increase in intake pressure leads to an increase in soot emissions. If the intake pressure is reduced, soot emissions decrease as the oxygen concentration increases. In addition, NO_x emissions increase with increasing intake pressure [8].

Sechul et al. investigated the impact of varying lambda values and boost pressures on the combustion characteristics of a dual-fuel engine. Their study found that the brake thermal efficiency (BTE) deteriorated as the lambda value increased while maintaining a constant boost pressure. This decline in BTE was primarily attributed to increased combustion inefficiency under leaner mixture conditions. As a result of the reduced BTE, the amount of CO_2 emissions decreased with higher lambda values in both dual-fuel combustion modes [9].

CHALA et al. investigated the effects of boost pressure and injection timing on the performance and combustion characteristics of a compressed natural gas (CNG) direct injection engine. The experimental tests were conducted using a 4-stroke direct injection (DI) spark ignition engine with a compression ratio of 14. The boost pressure was varied from 2.5 to 10 kPa following the closure of the intake valves. A narrow angle injector was employed to increase the mixture ratio at engine speeds ranging from 2000 to 5000 rpm. To assess the combined effects of boost pressure and injection timing, similar tests were performed on a naturally aspirated engine, and the results were compared with those of the boosted system. The study found that the CNG direct injection engine exhibited improved performance and combustion efficiency at all operating speeds when the boost pressure exceeded 7.5 kPa. This was evidenced by faster heat release rates and a higher percentage of burned mass, indicating enhanced combustion efficiency of the charging system due to increased boost pressure. Compared to the naturally aspirated engine, an increase in cylinder pressure and temperature was observed with boost pressure, along with a reduction in combustion time [10].

In a related study, the Miller cycle and turbocharging techniques were experimentally applied to a single-cylinder, four-stroke direct injection (DI) diesel engine. Two different versions of the Miller cycle were implemented using two distinct camshafts, which provided delays of 5 and 10 crank angle (CA) degrees compared to the standard configuration. Supercharging was achieved using a screw compressor at two different pressures: 1.1 and 1.2 bar. The results indicated that emissions of NO, hydrocarbons (HC), CO, and CO_2 were reduced by 27 %, 28 %, 55 %, and 10 %, respectively, while effective power and efficiency increased by 5.1 % and 6.3 %. These findings demonstrate that the combination of the proposed techniques can effectively reduce NO_x emissions and enhance the performance of diesel engines [11].

In another study conducted with a four-stroke single-cylinder turbocharged diesel engine, the effects of five different intake air volumes (40, 50, 60, 70 and 80 %) on the performance and emission parameters were analyzed. The engine load varied between 0.5 and 3 kW. Initially, the experiments were carried out with a conventional diesel engine. Later, the experiments were conducted with an engine equipped with a turbocharger. In addition, performance analyzes such as BSFC and BTE were evaluated and emissions such as CO, HC, NO_x and soot opacity were measured and the conventional diesel engine and the engine with turbocharger were compared. The experimental results showed that BTE, CO and HC emissions increased significantly, while BSFC, NO_x and soot emissions decreased with increasing relative humidity at certain loads compared to a conventional diesel engine. At the maximum operating load with 80 % relative humidity, a maximum reduction in BSFC, NO_x and soot emissions of 4.9 %, 30.6 % and 58.4 % respectively was achieved, while BTE increased by 4.7 % [12].

In this study, the researchers conducted a numerical investigation using a 1D simulation with the GT-Power platform, complementing their experimental studies. The GT-Power model of the 1.6-liter E.torQ turbo engine, validated by previous research, was employed in parametric displacement tests. Simulations were performed on turbocharged engines with displacements of 1.0, 1.2, 1.4, and 1.6 L, as well as a 1.6-liter naturally aspirated engine. Comparative analyses were conducted based on the results, focusing on torque, power, and emission curves for CO_2, CO, hydrocarbons (HC), and NO_x. The findings demonstrated that throttled engines can compensate for reduced displacement in terms of power at medium and high speeds. Generally, reducing engine displacement leads to improvements in specific fuel consumption across the entire speed range analyzed. At speeds above 3000 rpm, a decrease in displacement results in lower specific emissions of CO_2, HC, and CO compared to the 1.6-liter naturally aspirated engine. However, the scenario differs for NOx emissions, which increase as displacement decreases, although they remain lower than those of the 1.6-liter naturally aspirated engine [13].

This study investigates the effects of biodiesel derived from waste cooking oil on engine performance. Using response surface methodology (RSM), the impacts of biodiesel ratio, engine speed, and engine load on parameters such as brake power, brake torque, and brake-specific fuel consumption (BSFC) were analyzed. Experiments were conducted on a four-cylinder, direct-injection diesel engine. The findings revealed that an increase in the biodiesel ratio led to reductions in brake power (by 4 % to 18 %) and brake torque (by 5 % to 17 %), while BSFC increased by 18 % to 24 % due to biodiesel's lower calorific value. Higher engine loads improved brake power and torque by 68 % and 69 %, respectively, whereas low-load conditions resulted in a 15 % rise in BSFC. This study highlights biodiesel's potential as a sustainable alternative fuel, despite its impact on performance metrics, and offers significant insights for optimizing engine performance and sustainabilit [14].

The environmental benefits and effects of biodiesel on engine performance have been attracting increasing attention. As a renewable energy source, biodiesel offers lower carbon emissions compared to fossil fuels, positioning itself as a sustainable alternative fuel. This study examines the effects of compression ratio and biodiesel-diesel blends containing waste cooking oil methyl ester on the combustion and emission characteristics of a diesel engine in detail. Using a zero-dimensional thermodynamic model, engine performance was analyzed under various compression ratios (14, 15, 16, 17, and 18) and biodiesel blend ratios (B0, B20, B50, B80, B100). The results demonstrated that as the compression ratio increased, cylinder pressure and heat release rate rose for all fuel blends. When the biodiesel ratio increased up to 50 %, an increase in cylinder pressure and heat release rate was observed; however, a decrease occurred when the biodiesel ratio exceeded 50 % due to its lower calorific value. Additionally, as the biodiesel ratio increased, carbon monoxide (CO) emissions decreased, while nitrogen oxide (NOx) emissions increased. According to the study's findings, the B50 blend provided the highest thermal efficiency and heat release rate among all fuel blends [15].

However, biodiesel's higher NOx emissions remain a significant challenge, limiting its widespread adoption despite its environmental benefits [16]. Addressing this issue requires innovative strategies that enhance biodiesel's performance while mitigating its emissions. Recent studies have highlighted the potential of combining biodiesel with nanotechnology to overcome these limitations [17]. To address these issues, researchers have particularly focused on alcohol-based fuel additives and exhaust gas recirculation (EGR) technology. These methods have emerged as effective solutions for reducing NOx emissions. Such studies offer promising approaches to resolving emission problems while preserving the environmental benefits of biodiesel usage [18–20].

In this context, this study aims to investigate the effects of biodiesel and optimized combustion conditions on engine performance and emissions, providing new insights into sustainable fuel solutions.

In the literature, studies examining the effects of boost pressure on biodiesel blends are quite limited. This gap has resulted in insufficient understanding of the interactions between biodiesel's unique properties such as its oxygen content and lower calorific value and boost pressure, as well as their influence on combustion and emission characteristics. This study aims to fill this gap by systematically analyzing the combustion and emission characteristics of biodiesel blends (B50 and B100) under varying engine loads and boost pressures. Unlike previous studies that primarily focus on conventional diesel, this research uniquely investigates the interactions between boost pressure and biodiesel properties, including their effects on combustion efficiency, heat release rate, and emission characteristics. By addressing these aspects, the study provides valuable insights into the potential of biodiesel blends to reduce particulate emissions and improve combustion stability while identifying challenges such as increased NOx emissions. This approach not only addresses a critical gap in the literature but also contributes valuable knowledge to ongoing efforts to enhance the sustainability of engine performance and emissions control for future research and practical applications.

2. Material and methods

2.1. Test fuels

The diesel fuel used in the tests was supplied by an international company and complies with the EN95 standard. The biodiesel used in this study was purchased from a national company that complies with TS14214 standards and holds ISCC certification, specializing in biodiesel production using advanced technologies. The company processes waste vegetable oils and locally cultivated oilseed crops, such as canola and safflower, grown under contract farming models in various regions, ensuring high-quality biodiesel production while supporting agricultural sustainability. The physical and chemical properties of the fuels used are given in Table 1. The engine tests were carried out first with diesel, then with B50 and finally with B100.

Table 1
Some properties of test fuels.

Property	Units	EN 14214	Diesel	Biodiesel
Density (at 15 °c)	kg m^{-3}	860–900	832.2	883.7
Kinematic viscosity (at 40 °c)	mm^2 s^{-1}	3.5–5.0	3.54	4.485
Water content	(m/m)%	max. 0.050	0.020	0.020
Iodine value	g I.100 g^{-1}	max. 120	–	81.47
Flash point	°C	min. 101	>55	110
Sulphur	mg/kg	max. 10	10	6.2
Total contamination	mg/kg	max. 24	24	10.7
Oxidation stability	mg/kg	min. 8	22	13.1
Cetane number	–	min. 51	51	51.3
Cold filter plugging point	°C	–	−15	−2

2.2. Test system and engine

The engine under study is a 4-stroke, single-cylinder type with a cylinder diameter and stroke of 106.5 x 127 mm, resulting in an engine displacement of 1120 cm^3. It features a compression ratio of 16.4:1. The engine can deliver a maximum power of 18 kW and a maximum torque of 120 Nm, with a maximum no-load speed of 2500 rpm. The fuel system is a direct injection type, utilizing a common rail at 1800 bar, supported by a Bosch 1.050 bar high-pressure mechanical fuel pump. The cooling system is water-cooled using mains water. The engine is equipped with two intake valves and one exhaust valve.

2.3. Engine test setup and conditions

The system used is fully computerized and all variables are set by the computer. In this experimental study, engine performances were performed as described in ISO 14369. Additionally, measurement of exhaust emissions was carried out in accordance with ISO 8178. In this study, the tests were carried out at a constant engine speed of 1600 rpm and at 50 % and 75 % engine load conditions to represent a range of partial operating scenarios commonly encountered in real-world applications. The 50 % load condition represents a moderate operating state, simulating scenarios where the engine operates under relatively low load, such as during cruising or low-speed driving. This load point provides valuable insights into fuel consumption and emissions in a balanced state without imposing excessive strain on the engine. Conversely, the 75 % load condition corresponds to a higher partial load, simulating situations where the engine operates closer to its optimal performance range, such as during highway driving or moderate acceleration. This load point is critical for assessing the effects of fuel type and boost pressure on engine efficiency, emissions, and combustion characteristics under more demanding conditions. By selecting these specific load points and maintaining a constant engine speed, the study ensures the representation of a wide range of practical engine operating conditions. This approach makes the findings highly relevant to real-world applications and provides comprehensive insights into the engine's performance and emission behavior.

Four different boost pressures were determined as operating parameters. The boost pressure applied directly by the engine control unit was monitored so that the effects of the boost pressure on the engine could be tracked directly. The test cell utilized in this study is equipped with an AVL 515X Supercharger – Boost Air Pressure System, which is integrated into the experimental setup to supply compressed and conditioned air to the engine. This system allows precise and consistent regulation of intake air pressures, a critical factor for evaluating the effects of boost pressure on engine performance and emissions. The AVL 515X Supercharger enables controlled air delivery at various boost pressure levels, simulating specific engine operating conditions under well-defined parameters. The boost pressure was meticulously controlled and adjusted via a computer interface, allowing precise and automated regulation throughout the experiments. The supercharger system ensures an accuracy of ± 10 mbar, providing highly reliable and consistent boost pressure application. To maintain this level of accuracy, the device was subjected to regular calibration at defined intervals, ensuring the reliability of measurements and consistency of experimental results. This advanced setup allowed for flexible testing across a wide range of operating conditions, including different engine loads and fuel types. By providing precise control over boost pressure levels, the system facilitated a comprehensive investigation into the interactions between air intake dynamics and the combustion characteristics of various fuels, contributing significantly to the robustness of the study's findings. The air inlet pressure was set to 240 mbar gage pressure (approximately 1240 mbar absolute pressure) as part of the standardized conditions determined by the AVL software integrated into the test setup. This value was specifically selected to simulate controlled and repeatable engine operating scenarios, ensuring consistency and accuracy in experimental measurements. The standardized pressure setting aligns with the study's objectives to evaluate engine performance and emissions under well-defined conditions. This configuration enables a reliable analysis of the effects of varying operating parameters, contributing to the robustness of the experimental results. Table 2 shows the experimental design of the engine under two load conditions with varying reinforcement pressure levels (% Reinforcement Pressure: −20 %, −10 %, 0 %, +10 %, +20 %).

These conditions were selected to investigate the effects of boost pressure variations and load levels on engine performance and emissions. The gage pressure values represent the pressures measured at the engine, while the absolute pressures include atmospheric pressure to provide a complete representation of the operating conditions. These pressure values are critical for analyzing the influence of boost pressure and load conditions on the engine's performance metrics.

The emission measurements during the tests were carried out in accordance with ISO EN 14396. During the tests, the oil temperature was set to 90 °C and the water temperature to 70 °C. In addition, the air intake temperature was set at 25 °C and the fuel temperature at 20C. The general schematic view of the used test system is given in Fig. 1.

The engine operating conditions are given in Table 3 and the accuracy values of the measuring devices used in the test system are given in Table 4.

3. Result and discussion

3.1. Brake fuel specific consumption (BFSC)

In this section, the effect of changing the charge air pressure on the BFSC was investigated. In Fig. 2, the change of BFSC at different engine loads and boost air pressures is shown. The graph examines the effects of different fuel types (Diesel, B50, and B100) on **Brake Specific Fuel Consumption (BSFC − g/kWh)** under 50 % and 75 % engine load conditions. At 50 % load, BSFC values for diesel fuel decreased with increasing boost pressure (from 269.28 g/kWh to 260.76 g/kWh), with a slight increase at the final boost level. This decrease can be attributed to the high energy density of diesel fuel and the improved combustion efficiency resulting from increased air intake at higher boost pressures. In contrast, BSFC values for B50 increased (from 284.44 g/kWh to 291.26 g/kWh) under the same conditions. This increase is due to the lower energy density of biodiesel compared to diesel, requiring more fuel injection to maintain the same engine output. For B100, BSFC values were the highest at 50 % load (increasing from 297.10 g/kWh to 304.95 g/kWh) due to the lower energy density and higher viscosity of pure biodiesel, which led to higher fuel consumption. At 75 % load, BSFC values for diesel fuel significantly decreased with increasing boost pressure, reaching the lowest value of 225.22 g/kWh. This decrease is explained by improved air–fuel mixture and enhanced combustion efficiency at higher engine loads. BSFC values for B50 at 75 % load exhibited a more stable trend (from 260.38 g/kWh to 254.84 g/kWh), while B100 showed consistently higher BSFC values (from 260.54 g/kWh to 256.57 g/kWh) due to its lower energy content, which necessitates higher fuel consumption.

Overall, diesel fuel demonstrated the lowest BSFC values under all load and boost conditions, while biodiesel blends showed higher BSFC values due to their lower energy density and higher viscosity. This analysis highlights that while biodiesel offers environmental advantages, it requires careful consideration of energy efficiency in its applications. This situation is similar to many studies in the literature [21–24]. However, it is noteworthy here that the BSFC values of B100 and B50 increase more under high load conditions than under low load conditions. The high viscosity and density of biodiesel and the low calorific value lead to an increase in the BFSC value with the use of biodiesel. This could indicate that increased boost pressure has a negative impact on engine efficiency, especially for biodiesel and biodiesel blends.

Table 2
Gage and Absolute Pressure Values for Different Boost Pressure Levels and Load Conditions.

Boost Pressure (%)	Load 50 % Gage presure (mbar)	Load 50 % Absolute pressure (mbar)	Load 75 % Gage presure (mbar)	Load 75 % Absolute pressure (mbar)
−10 %	192	1192	660	1660
−20 %	216	1216	742.5	1742.5
0	240	1240	825	1825
10 %	264	1264	907.5	1907.5
20 %	288	1288	990	1990

3.2. Exhaust gas temperatures

Exhaust gas temperature (EGT) is critically important for evaluating engine performance, efficiency, and emissions. To manage EGT, especially in situations where temperatures may be insufficient for effective aftertreatment at low loads, various strategies can be implemented [25]. Additionally, adjusting engine parameters such as coolant temperature, injection timing, and engine speed can significantly impact EGT [26]. These strategies and models are essential for optimizing engine performance and reducing emissions. Fig. 3 shows the exhaust gas temperatures ($T_{exhaust}$) for three fuel types (Diesel, B50, and B100) under 50 % and 75 % engine loads at varying boost pressures.

At 50 % load, the exhaust gas temperature for diesel fuel increases from 302.80 °C to 317.57 °C as boost pressure rises. This increase is due to higher combustion chamber temperatures caused by the additional air provided by the boost. B50 follows a similar increasing trend, with temperatures rising from 281.98 °C to 295.08 °C. B100 exhibits the highest temperatures at 50 % load, increasing from 295.61 °C to 305.59 °C, primarily due to its higher viscosity and slower combustion, which prolong the combustion phase and generate more heat. At 75 % load, exhaust gas temperatures are generally higher due to increased engine load. Diesel fuel temperatures start at 299.95 °C, decrease slightly to 290.48 °C at moderate boost pressure, and rise to 320.39 °C at the highest boost level. This pattern reflects improved combustion efficiency at moderate boost and higher heat generation at maximum boost. B50 exhibits a consistent increase from 282.11 °C to 315.25 °C as boost pressure rises, reflecting the greater fuel requirements and heat generation of biodiesel blends under higher loads. B100 records the highest exhaust gas temperatures at 75 % load, increasing from 295.78 °C to 333.15 °C, driven by its prolonged combustion and higher fuel consumption. In summary, exhaust gas temperature increases with both boost pressure and engine load across all fuel types. Diesel fuel maintains the lowest temperatures due to its efficient combustion, while B50 and B100 show progressively higher values, with B100 consistently reaching the highest temperatures due to its combustion characteristics. These findings highlight the impact of biodiesel on exhaust gas temperatures, which may influence engine durability and emissions control. This situation is similar to many studies in the literature [24,27–29].

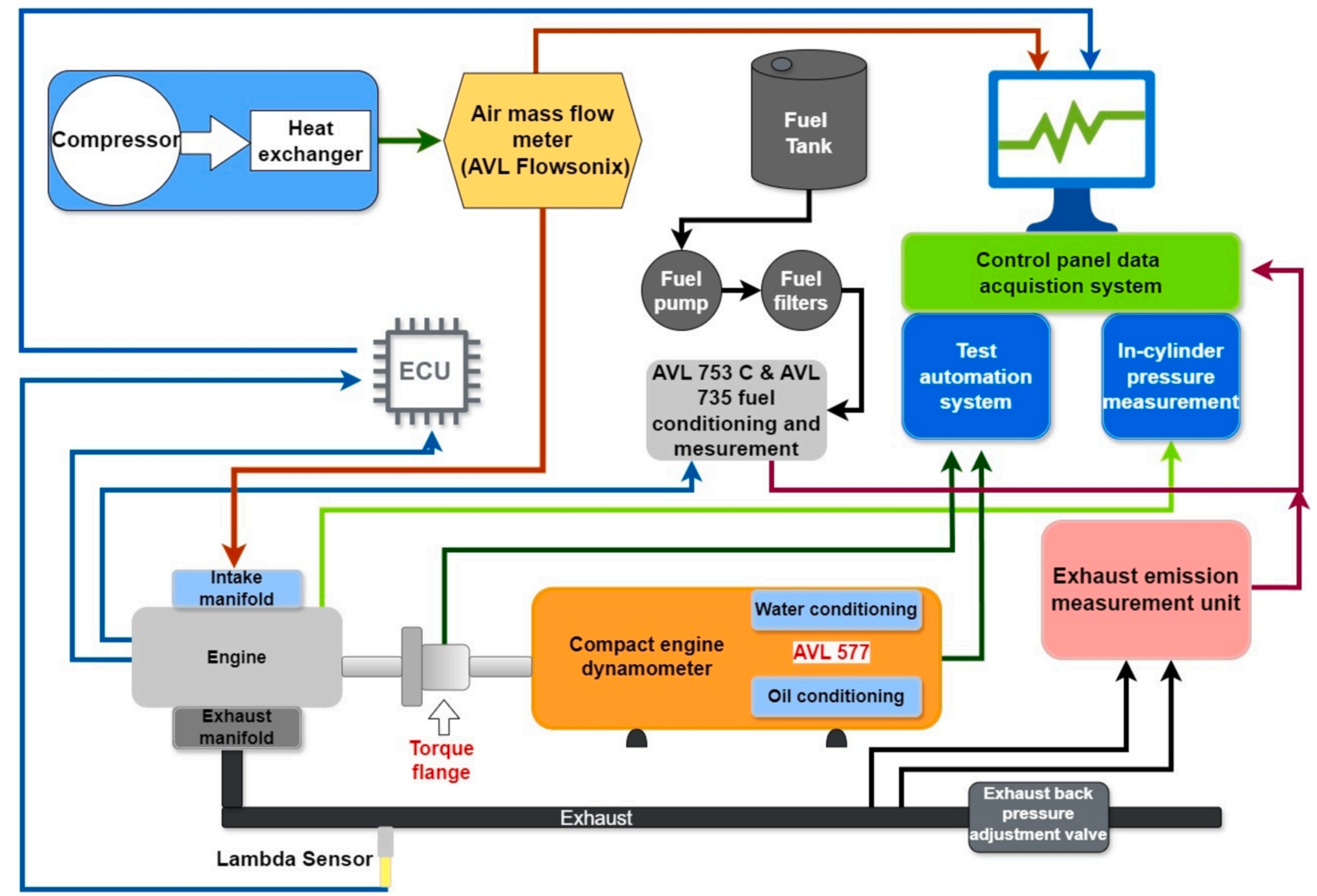

Fig. 1. Schematic view of the engine test system.

Table 3
Fixed engine input parameters.

Input parameters	Unit	50 % Engine load value	75 % Engine load value
Engine speed	rpm	1600	1600
Engine oil tempature	°C	90	90
Engine coolant tempature	°C	70	70
Air intake pressure	kPa	24	24
Air temparure	°C	25	25
Main injection timing	BTDC °CA	11.5	11.8
Plot injection timing	BTDC °CA	19.5	19
Pilot injenciton duration	ms	0.2961	0.2767
Main injenciton duration	ms	1.1150	1.5453
Total injenciton duration	ms	1.411	1.822
Injection presure	bar	900	1300

Table 4
The accuracy values of the test systems.

Measurement	Device	Accuracy
Torque	HBM Torque Flange	±0.1 %
Engine Speed	AVL Encoder	≤±0.1CA
Test Cell Humidity	Vaisala – HMT 330	±1% RH
Test Cell Temperature	Vaisala – HMT 330	±0.2 °C
In-cylinder Pressure	AVL Xion	0.05CA
Injection timing	Angle Encoder	±0.1CA
Supercharger – Boost Air Temperature	AVL 515X	±5°C
Supercharger – Boost Air Pressure	AVL 515X	±10 mbar
Engine Coolant & Oil Conditioning	AVL-577	±1K
Fuel Consumption	AVL-735	<0.15 %
Temperature Sensors	PT100 (K Type)	≤±1%

3.3. CO emissions

CO emissions are colorless, poisonous and toxic gasses that are produced during the combustion of fuels at low temperatures or incomplete combustion [30,31]. Carbon monoxide (CO) is a toxic pollutant produced during the combustion process in internal combustion engines, particularly when fuel is not completely burned [32]. CO emissions from vehicles significantly contribute to air pollution and pose serious environmental and health risks. Factors such as engine operating conditions, fuel type, and air–fuel ratio directly affect CO emission levels [33]. These measures help to enhance engine efficiency while minimizing environmental impacts. However, CO poisoning remains one of the leading causes of fatal poisonings worldwide, necessitating continued efforts to reduce emissions [33,34]. Fig. 4 shows the change in carbon monoxide (CO) emissions at different loads, boost pressures and fuels.

Fig. 4 shows the variation in carbon monoxide (CO) emissions under different engine loads, boost pressures, and fuel types. At 50 % engine load, CO emissions for B100 fuel at −20 % boost pressure are 0.01921 %, decreasing to 0.01778 % at + 20 % boost pressure. This demonstrates that increasing boost pressure enhances combustion efficiency by improving the air–fuel mixture, leading to reduced CO emissions. A similar pattern is evident for B50 and diesel fuels. Notably, diesel fuel

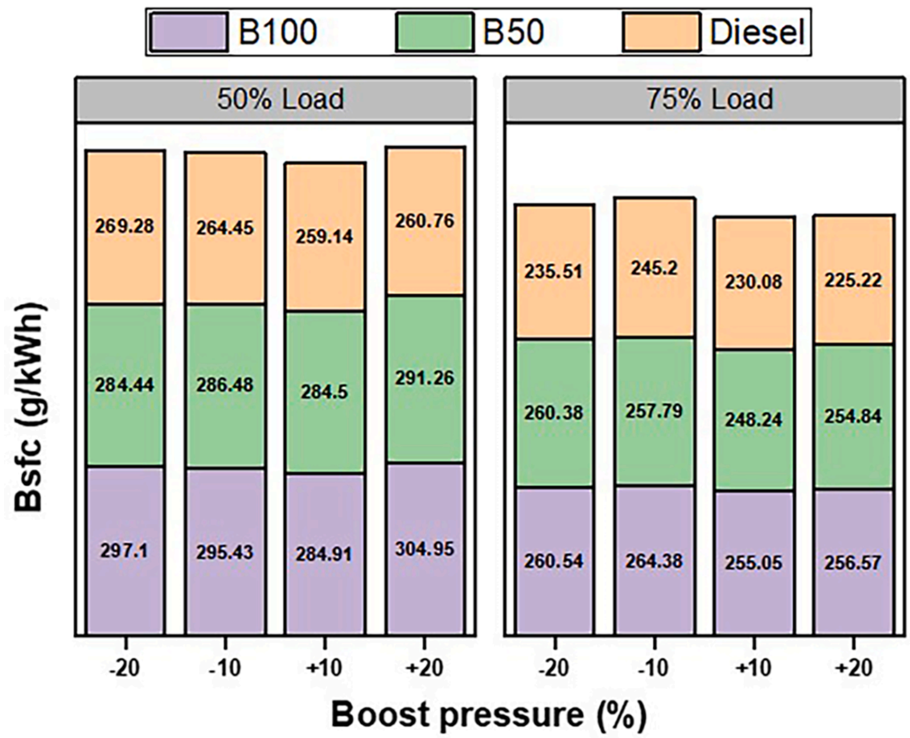

Fig. 2. Variation of BSFC with boost pressure.

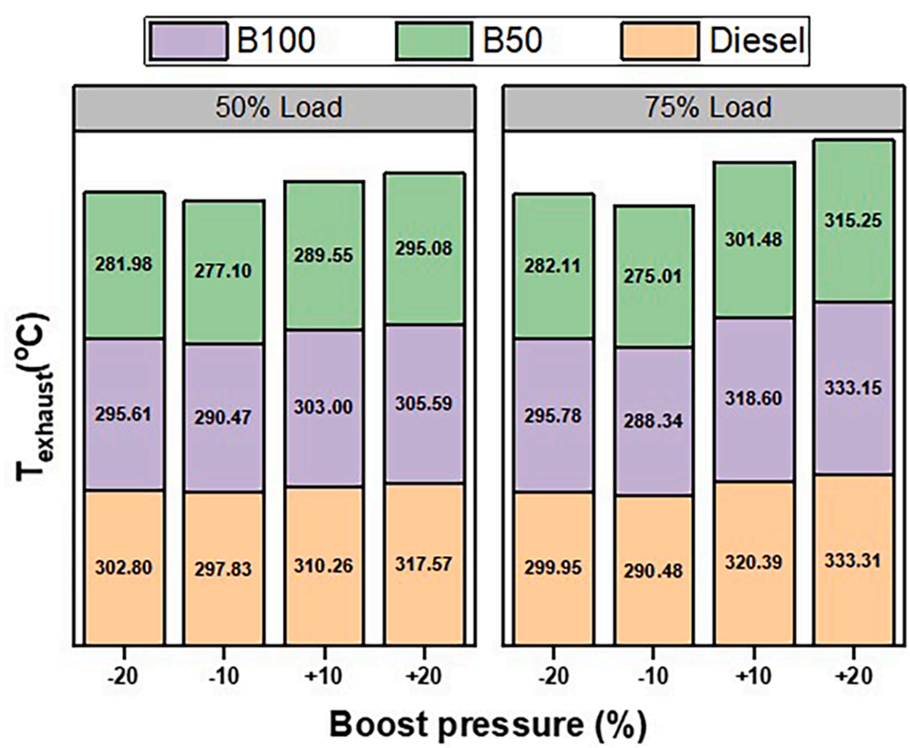

Fig. 3. Change of exhaust gas temperatures with boost pressure.

shows a substantial reduction in CO emissions with increased boost pressure, where values drop from 0.02127 % at −20 % boost pressure to 0.01989 % at + 20 % boost pressure. This decrease is due to better combustion conditions facilitated by increased air availability at higher boost pressures. CO emissions also decrease as engine load increases, showcasing improved combustion efficiency at higher loads. For instance, at 75 % engine load, CO emissions for B100 drop from 0.01181 % at −20 % boost pressure to 0.0108 % at + 20 % boost pressure. Similar reductions are observed for B50 and diesel fuels, with diesel consistently exhibiting the highest CO emissions. These findings highlight the cleaner combustion characteristics of biodiesel fuels, particularly B100, which has the lowest CO emissions under all load and boost pressure

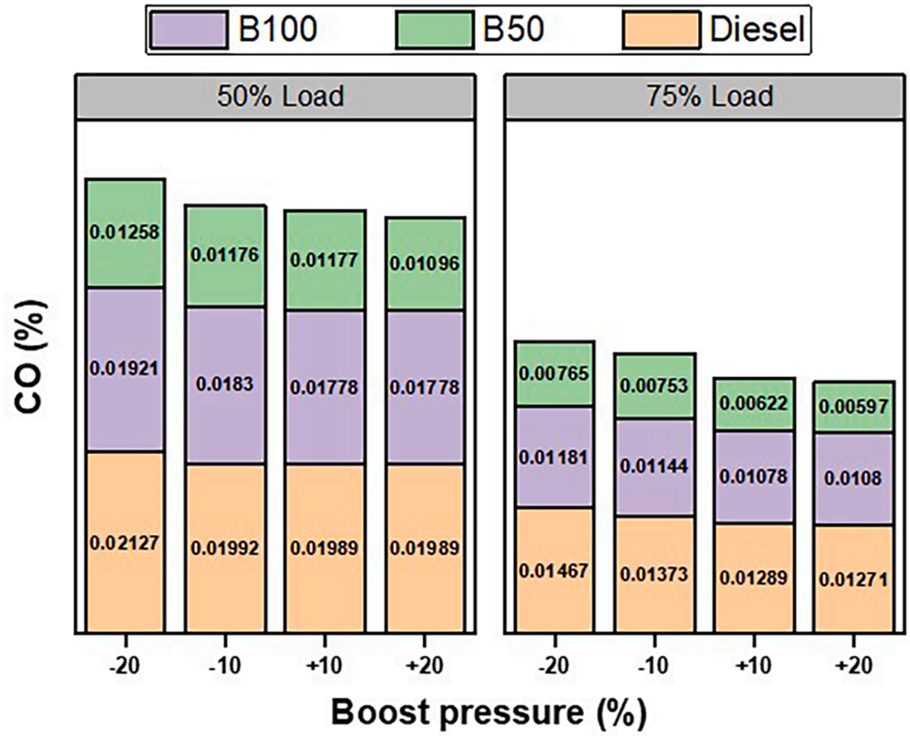

Fig. 4. Change of CO according to boost pressure.

conditions. The presence of oxygen in biodiesel's molecular structure supports more complete combustion compared to diesel. The graph also emphasizes the critical role of boost pressure in reducing CO formation across all fuel types. Higher boost pressures increase the amount of air entering the engine, thereby improving combustion efficiency and reducing incomplete combustion by-products like CO. Overall, the differences between biodiesel and diesel are clear, with biodiesel offering a more sustainable and environmentally friendly option due to its lower CO emissions and cleaner burning properties.

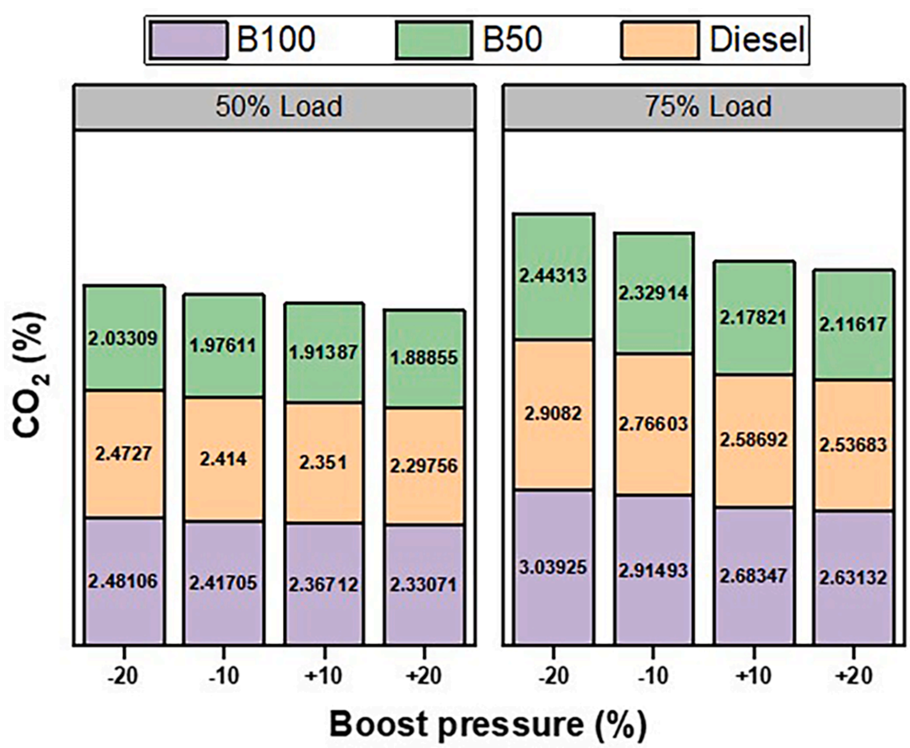

Fig. 5. Change of CO_2 according to boost pressure.

3.4. CO_2 emissions

Climate change driven by CO_2 emissions from sources such as internal combustion engines poses significant threats to human health. Proposed solutions include the gradual phasing out of internal combustion engines, transitioning to renewable energy sources, and restricting vehicle use in urban areas [35]. Fig. 5 shows the change in CO_2 emissions at different loading pressures. At 50 % load, CO_2 emissions are higher at 20 % and −10 % boost pressure.

In the graph, emission values for different fuel types (B100, B50, and Diesel) are compared under 50 % and 75 % load conditions as a function of boost pressure. At 50 % load, Diesel fuel exhibited the highest emission value of 0.02127 under −10 boost pressure. For other boost pressures, Diesel's emission values were 0.01992 at −20 boost pressure, 0.01989 at + 10 boost pressure, and 0.01989 at + 20 boost pressure. Compared to Diesel, B50 showed approximately 20 % lower emissions, with a value of 0.01258 under −10 boost pressure, which is about 40 % lower than Diesel. B100, on the other hand, recorded a value of 0.01921 under −10 boost pressure, which is about 10 % lower than Diesel. Similarly, at 75 % load, as the boost pressure increased, Diesel's emission values decreased: 0.01467 under −10 boost pressure, 0.01271 under −20 boost pressure, 0.01289 at + 10 boost pressure, and 0.01271 at + 20 boost pressure. Both B100 and B50 showed 25 % and 40 % lower emissions, respectively, compared to Diesel, due to the lower carbon intensity and cleaner combustion properties of biodiesel. The increase in boost pressure improved combustion efficiency across all fuels, leading to a general reduction in emissions. However, Diesel consistently maintained higher emission levels compared to biodiesel blends. These results highlight the significant impact of boost pressure and load conditions on emission performance.

3.5. HC emissions

Hydrocarbon (HC) emissions from internal combustion engines are significant pollutants that result from incomplete fuel combustion [36]. Along with other pollutants such as CO, NOx, and particulate matter, HC emissions contribute to air pollution and have adverse health effects [32]. To mitigate HC emissions, various strategies have been developed, including advanced fuel injection systems, catalytic converters, and engine control technologies [36]. Fig. 6 shows the variation in hydrocarbon (HC) emissions at 50 % and 75 % engine loads under different boost pressures (−20 %, −10 %, +10 %, and + 20 %). At 50 % engine load, HC emissions are higher at −20 % and −10 % boost pressures, particularly for diesel fuel, which records the highest values. When the boost pressure is reduced by 20 %, HC emissions for diesel fuel are 70.97 ppmC, while they are 57.96 ppmC for B50 and 41.73 ppmC for B100. At −10 % boost pressure, HC emissions decrease slightly to 58.98 ppmC for diesel, 57.25 ppmC for B50, and 40.68 ppmC for B100. This decrease is due to the partial improvement in air–fuel mixing as boost pressure increases, although it remains insufficient for complete combustion. At positive boost pressures (+10 % and + 20 %), HC emissions decrease significantly across all fuel types. For instance, at + 10 % boost pressure, HC emissions drop to 66.70 ppmC for diesel, 53.44 ppmC for B100, and 37.88 ppmC for B50. Further increasing the boost pressure to + 20 % reduces HC emissions to 64.55 ppmC for diesel, 53.96 ppmC for B100, and 37.32 ppmC for B50. This reduction is attributed to the improved combustion efficiency enabled by the enhanced air intake at higher boost pressures, which reduces unburned hydrocarbons in the exhaust. Biodiesel fuels, particularly B100, consistently exhibit the lowest HC emissions due to their oxygen content, which supports more complete combustion.

At 75 % engine load, HC emissions are generally lower for all fuels compared to 50 % load, demonstrating that higher loads promote more efficient combustion. At −20 % boost pressure, HC emissions are 40.82 ppmC for diesel, 32.67 ppmC for B100, and 24.47 ppmC for B50. When the boost pressure is increased to −10 %, emissions decrease to 40.28 ppmC for diesel, 31.81 ppmC for B100, and 23.16 ppmC for B50. Positive boost pressures further reduce HC emissions, with values of 37.44 ppmC for diesel, 31.28 ppmC for B100, and 21.90 ppmC for B50 at + 10 % boost pressure. At + 20 % boost pressure, the lowest emissions are recorded as 36.84 ppmC for diesel, 29.93 ppmC for B100, and 20.97 ppmC for B50. Overall, the data clearly shows that HC emissions are highest at lower boost pressures and decrease with increasing boost pressure for all fuel types. Biodiesel fuels consistently outperform diesel in reducing HC emissions due to their cleaner burning properties and oxygen content, which enhances combustion. Additionally, higher engine loads further decrease HC emissions by improving combustion efficiency. This highlights the environmental benefits of biodiesel and the

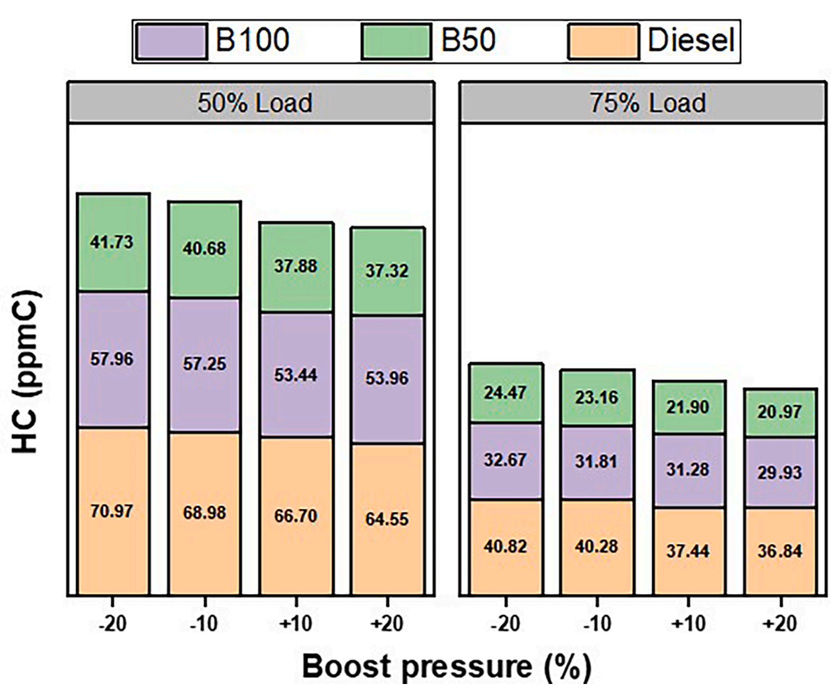

Fig. 6. Change of HC according to boost pressure.

importance of optimizing boost pressure to minimize unburned hydrocarbons in engine exhaust.

3.6. NO_x emissions

Nitrogen oxides (NO_x) are significant atmospheric pollutants with detrimental effects on both human health and the environment [37]. These compounds contribute to respiratory issues, mental health problems, and environmental degradation through mechanisms such as acid rain and ozone layer depletion [37,38].

NOx emissions primarily originate from the combustion of fossil fuels across various sectors, including energy production and transportation [37]. Although the direct impact of NO_x on the greenhouse effect is subject to debate, these compounds indirectly contribute to climate change by participating in ozone formation [39,40]. Ozone pollution, which is significantly influenced by NO_x emissions, poses a major global health hazard, leading to numerous premature deaths and asthma-related emergencies each year [40]. To mitigate these issues, various abatement technologies are under exploration, including biological treatment methods and the implementation of more stringent emissions regulations [37,39]. High temperature and pressure in the cylinder are the main reasons for NO_x formation. In addition, the physical and chemical properties of the fuel used are another important factor in NO_x formation [41–43].

Fig. 7 shows the change in NO_x emissions as a function of boost pressure. As the engine load increased, NO_x emissions peaked for all fuels. NO_x emissions are high when the engine load is 50 % and the boost pressure is negative. When the boost pressure was reduced by 20 %, NO_x emissions from engines running on diesel fuel were observed to be about 427.14 ppm, 422.8 ppm for B100 fuel and 352.54 ppm for B50 fuel. A slight decrease in NO_x emissions was observed when boost pressure was reduced by 10 %. With positive boost pressure, NO_x emissions decrease or remain stable. When boost pressure is increased by 10 %, NO_x emissions are 340.69 ppm for B50, 407.43 ppm for diesel and 416.45 ppm for B100. Similarly, when boost pressure is increased by 20 %, NO_x emissions were found to be 336.32 ppm for B50 fuel, 404 ppm for Diesel and 409.46 ppm for B100. NO_x emissions generally increase at a load of 75 and are even higher when the boost pressure is negative. NO_x emissions decrease when the boost pressure is positive. If the boost pressure is increased by 10 %, the NO_x emissions are 722.2 ppm for B100, 668.47 ppm for diesel and 587.82 ppm for B50. When the boost pressure is increased by 20 %, NO_x emissions of 715.42 ppm for B100, 658.24 ppm for diesel and 580.19 ppm for B50 were observed. In general, the data in the graph shows that NO_x emissions decrease with increasing boost pressure, while negative boost pressure increases emissions. At 75 % engine load, the highest NO_x amount was obtained with B100 fuel. Due to the oxygen in the structure of biodiesel, NO_x emission formation is higher [42,44].

3.7. Oxygen

Oxygen emissions in engines are critical for influencing combustion efficiency, performance, and environmental impact. Oxygen-enriched combustion can enhance engine performance and reduce harmful emissions such as carbon monoxide (CO) and hydrocarbons (HC); however, it may also lead to increased nitrogen oxides (NO_x) emissions [45,46]. To address the rise in NO_x emissions associated with oxygen-enriched engines, exhaust gas recirculation (EGR) is often employed as a mitigation strategy [46]. Lambda sensors play a vital role by monitoring oxygen levels in exhaust gases, thereby optimizing the air–fuel ratio and controlling emissions. The ideal air–fuel ratio, known as the stoichiometric ratio, is 14.7:1, which balances performance and emissions [47]. Deviations from this ratio can result in increased pollutants and reduced engine efficiency. As emission regulations become increasingly stringent, various control technologies have been developed to reduce air pollutants and greenhouse gases from both diesel and gasoline engines [48]. Therefore, monitoring and managing oxygen emissions are essential for optimizing engine performance and minimizing environmental impact.

Fig. 8 shows the oxygen (O_2) content in the exhaust gas at different

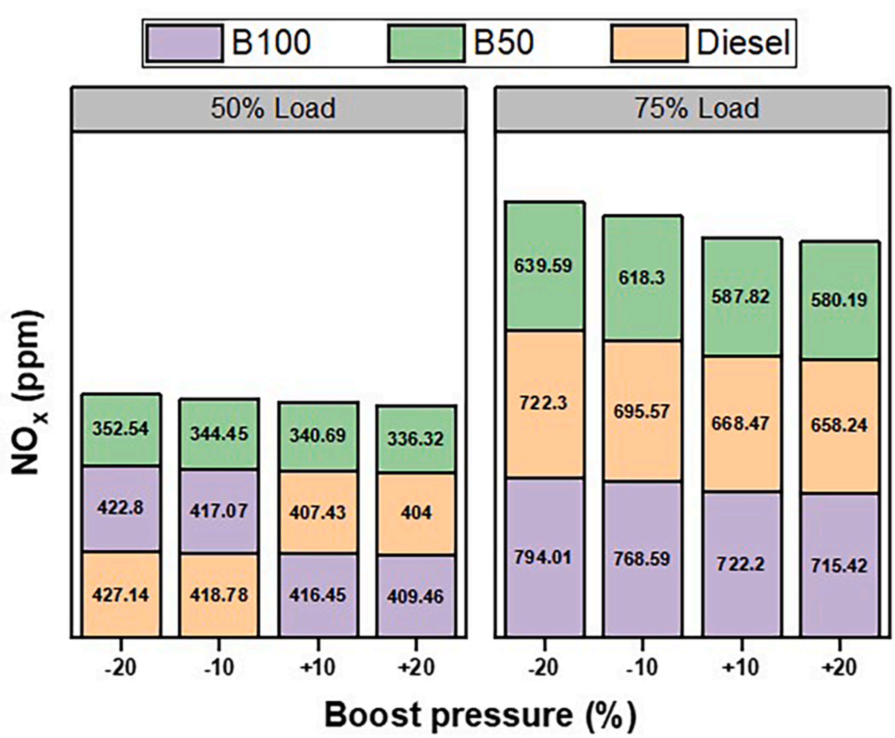

Fig. 7. Change of NO_x according to boost pressure.

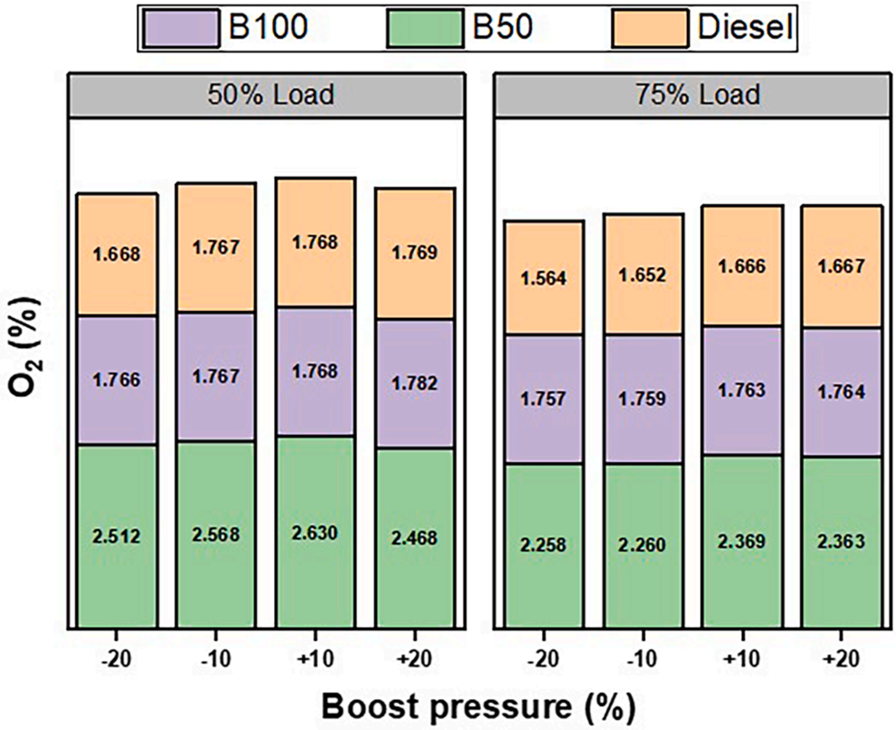

Fig. 8. Change of O_2 according to boost pressure.

boost pressures, 50 % and 75 % engine load. While the O_2 emission for biodiesel (B100) at 50 % engine load is 1.76646 % at −20 % boost pressure, this value is 1.78225 % at + 20 % boost pressure. This shows that O_2 emissions increase with increasing boost pressure. A similar trend is observed for B50 and diesel fuels. For example, while the O_2 emissions of diesel fuel are 1.66778 % at −20 % boost pressure, this value increases to 1.76876 % at + 20 % boost pressure. At an engine load of 75 %, O_2 emissions are generally lower than at 50 % load. It is clear that the engine produces more power at high load and therefore a more complete combustion takes place. For example, with biodiesel (B100), the O_2 emission at −20 boost pressure is 1.75737 %, while at + 20 % boost pressure this value is 1.76398 %. Similarly, it is observed that high boost pressures increase O_2 emissions for B50 and diesel fuels. For example, while the O_2 emissions of B50 fuel are 2.25796 % at −20 % boost pressure, this value increases to 2.36330 % at + 20 % boost pressure. The differences between biodiesel and diesel fuel can also be clearly seen in the graph. Biodiesel (B100) generally has the lowest O_2 emissions under both load conditions, while B50 fuel has the highest O_2 emissions. Increasing boost pressure seems to have an increasing effect on O_2 emissions, especially under high load conditions.

3.8. Soot

Soot formation in combustion processes is influenced by various factors, including temperature, pressure, and local stoichiometry. Fuel-rich regions with insufficient oxygen promote soot formation under atmospheric conditions [49]. Increasing ambient temperature enhances soot formation, particularly in low-oxygen environments. The process involves fuel pyrolysis, nucleation, coalescence, surface growth, aggregation, and oxidation [50]. Oxygen concentration plays a crucial role, with higher levels potentially increasing soot formation due to elevated temperatures and altered mixing dynamics. However, oxygenated fuel additives can reduce overall soot emissions, though they may increase the number of small soot particles. Factors such as fuel properties, combustion conditions, and environmental oxygen concentration significantly impact soot formation in automobile engines [49–51].

Soot emissions from diesel engines pose significant environmental and health risks, necessitating the implementation of effective reduction strategies [52]. Modern approaches involve structured catalysts designed to enhance soot-catalyst contact and combustion efficiency, utilizing various active species and supports for soot abatement [53]. Advances in soot formation modeling have incorporated empirical, semi-empirical, and detailed models to better understand and predict soot generation under different fuels and engine conditions [54]. Catalytic diesel particulate filters (DPFs) have emerged as a promising technology for soot reduction [55]. Fig. 9 shows the change in the amount of soot as a function of the different charging pressures. The left half of the diagram contains the data determined at a load of 50 % and the right half contains the data at a load of 75 %. At 50 % load, a general decrease in the amount of soot can be observed as the boost pressure increases. The highest amount of soot (7.81 mg/m^3) is observed with diesel fuel at −20 % pressure, followed by B100 (6.43 mg/m^3) and B50 (4.26 mg/m^3). When the pressure increases to −10 %, the amount of soot decreases with diesel (6.62 mg/m^3), while a similar decrease is observed with B50 and B100. At + 20 % pressure, the lowest soot levels are achieved: for diesel (8.88 mg/m^3), B50 (3.19 mg/m^3) and B100 (5.06 mg/m^3). At 75 % load, the decrease in the amount of soot becomes more evident with the increase in pressure. While the highest soot amount of diesel fuel (2.98 mg/m^3) is observed at −20 % pressure, these values for B50 and B100 are 2.86 mg/m^3 and 1.92 mg/m^3, respectively. When the pressure is increased to + 20 %, the lowest amount of soot (5.05 mg/m^3) is obtained with diesel fuel, and these values for B50 and B100 are 0.71 mg/m^3 and 1.11 mg/m^3, respectively. Overall, the data seen in the graph shows that increasing turbo pressure is effective in reducing soot, and biodiesel blends (B50 and B100) generally produce less soot than diesel fuel. Moreover, with the increase in load (from 50 % to 75 %), the decreasing trend in soot production becomes more evident. As a result, soot emissions are reduced with the use of biodiesel. This situation is similar to the studies in the literature [56,57].

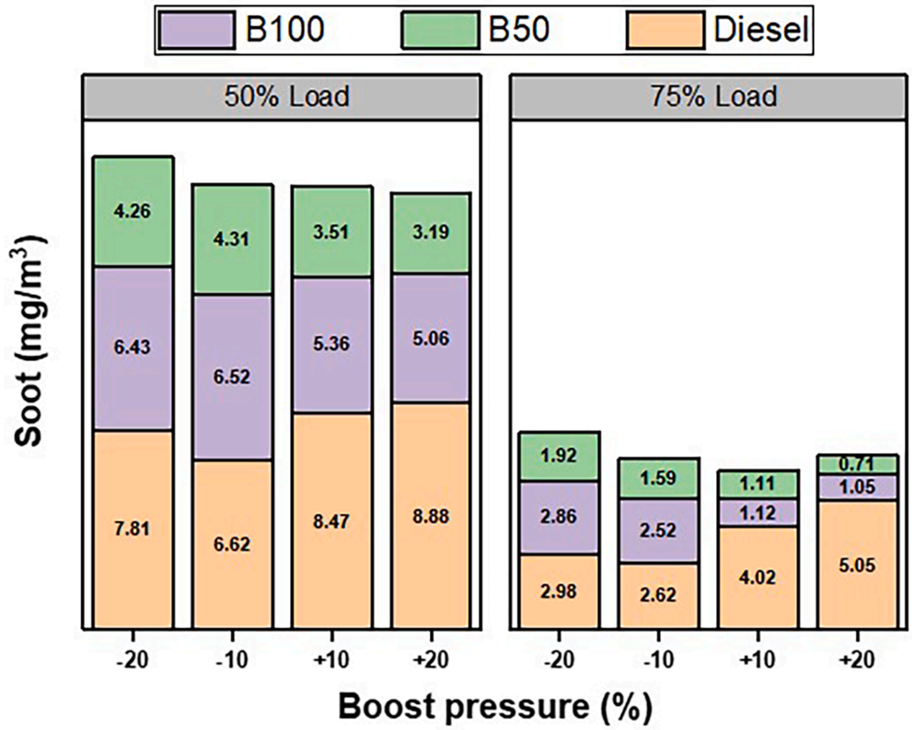

Fig. 9. Change of soot according to boost pressure.

3.9. Opacity

In the context of engine emissions, "opacity" is a crucial measure that indicates how much light is blocked or transmitted by exhaust gases, and it is particularly relevant for diesel engines. Opacity serves as a key indicator of the density of smoke emitted from the exhaust, which correlates with the amount of particulate matter present. High opacity values suggest incomplete combustion, indicating the presence of significant levels of soot and other particulates, which can have detrimental environmental and health impacts. Opacity measurements are used to assess compliance with emission standards and to determine maintenance needs. Additionally, maintaining low opacity levels can enhance engine efficiency and optimize fuel consumption. Therefore, opacity is an important parameter for monitoring engine performance and its

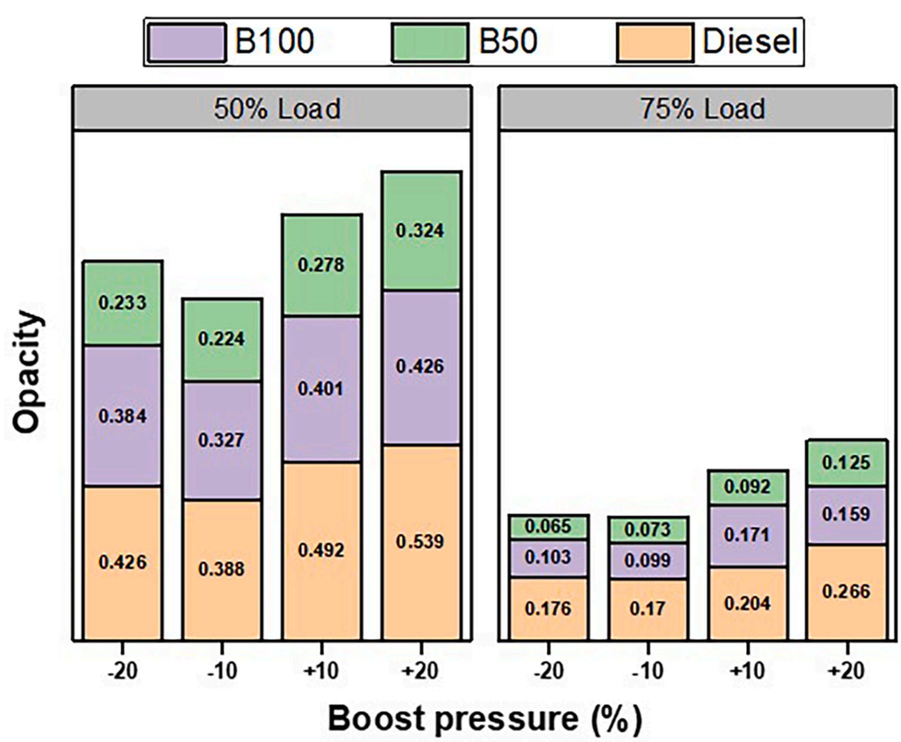

Fig. 10. Change of opacity according to boost pressure.

environmental impact. Fig. 10 shows the changes in the opacity of the soot quantity at different loading pressures.

In the case of 50 % load, a general downward trend in the opacity values can be observed with the increase in turbo pressure. At −20 % turbo pressure, the opacity value of diesel fuel is 0.426, while B100 is 0.384 and B50 is 0.233. This shows that biodiesel offers cleaner combustion. At a pressure of −10 %, the opacity for diesel fuel was found to be 0.388, for B100 0.327 and for B50 0.224. At + 10 % pressure, the turbidity value of diesel fuel increases to 0.492, while it is 0.401 for B100 and 0.278 for B50. At a pressure of + 20 %, the turbidity of diesel fuel was 0.539, of B100 0.426 and of B50 0.324. At a load of 75 %, a significant decrease in turbidity values is observed with increasing pressure. While the opacity value of diesel fuel at −20 % pressure was 0.176, it was given as 0.103 for B100 and 0.065 for B50. At a pressure of −10 %, the opacity value of diesel fuel was 0.17, of B1000.099 and of B50 0.073. At a pressure of + 10 %, the opacity value of diesel fuel was 0.204, of B100 0.171 and of B50 0.092. At a pressure of + 20 %, the opacity of diesel fuel was 0.266, of B100 0.159 and of B50 0.125. Overall, this graph shows that increasing the turbo pressure effectively reduces exhaust opacity and that biodiesel blends (B50 and B100) generally have lower opacity values than diesel fuel.

3.10. Cylinder gas pressure

Fig. 11 illustrates the changes in cylinder gas pressure for diesel, B50, and B100 fuels at different boost pressure levels under 50 % load conditions.

Initially, examining the results for diesel fuel reveals that the maximum in-cylinder pressure significantly increases with rising boost pressure. The cylinder pressure is at its lowest at −20 % boost pressure

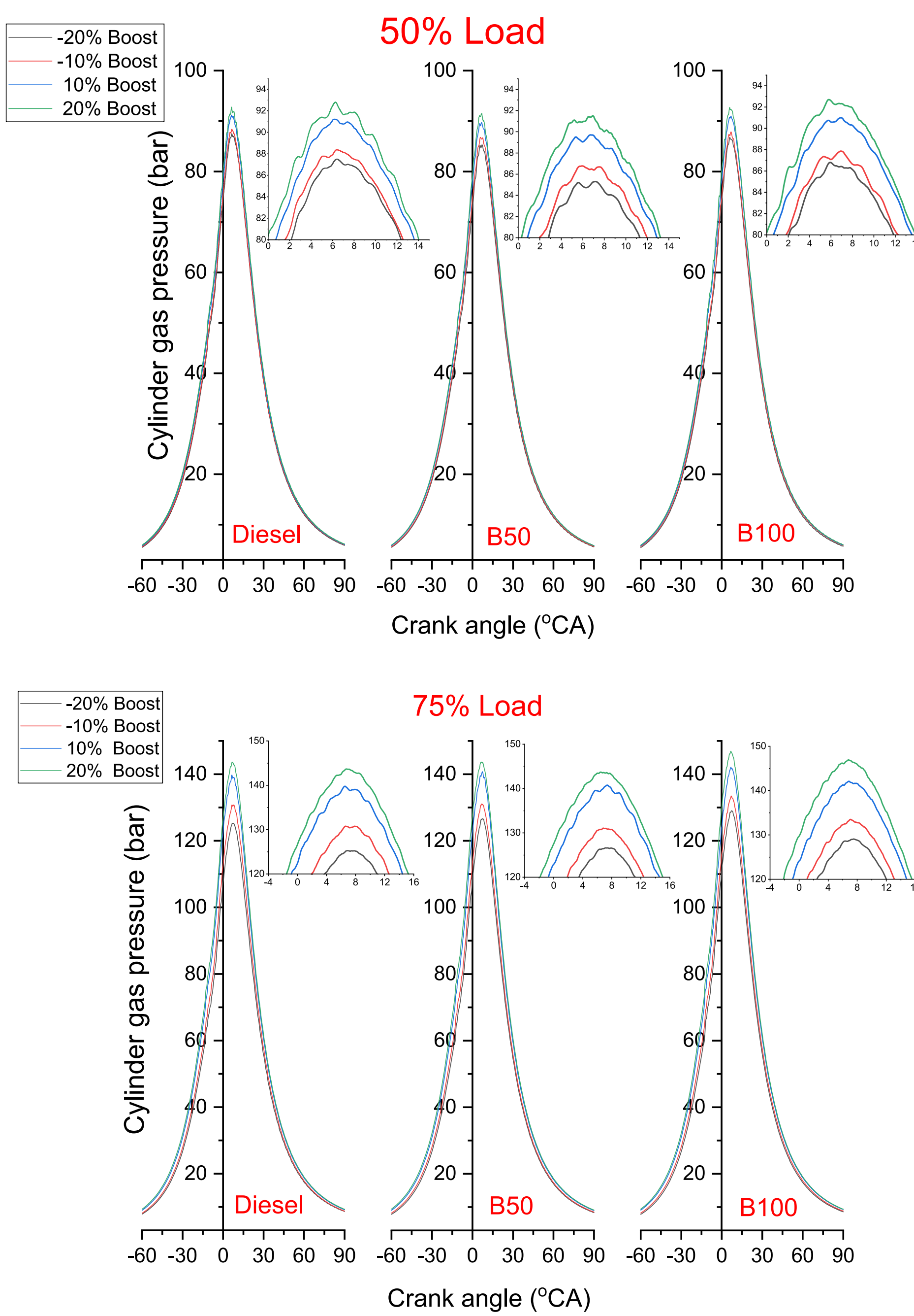

Fig. 11. Change of cylinder gas pressure according to boost pressure.

and reaches its highest value at + 20 % boost pressure. Increasing boost pressure enhances cylinder pressure and advances combustion timing, thereby improving thermal efficiency [58]. This indicates that the engine can draw in more air with increased boost pressure, leading to more efficient combustion. High boost pressure allows for the use of more fuel, thereby increasing combustion efficiency and achieving higher cylinder gas pressure. A similar trend is observed with B50 fuel. As boost pressure increases, the cylinder pressure values rise. However, the maximum pressure values for B50 fuel appear slightly lower compared to diesel fuel. Biodiesel and alcohol fuels generally result in lower maximum cylinder pressures compared to conventional diesel due to their lower energy densities [59,60]. This may be attributed to the slightly lower calorific value of B50 fuel compared to diesel. Nevertheless, as boost pressure increases, B50 fuel also facilitates more efficient combustion, resulting in higher cylinder pressure. For B100 (pure biodiesel), the results show a similar increase in cylinder pressure with rising boost pressure.

However, B100 fuel exhibits the lowest maximum pressure values compared to B50 and diesel fuels. This can be explained by the lower energy density of biodiesel, which produces less energy during the combustion process. Yet, as boost pressure increases, the combustion efficiency of B100 fuel improves, achieving higher pressure values. Another important aspect in the diagram is the effect of boost pressure on the timing of the combustion process. It is observed that combustion starts earlier at high boost pressure and reaches higher pressure values more quickly. This underscores the need for careful adjustment of boost pressure to enhance engine performance. While correct combustion timing increases engine efficiency, excessively high pressure can

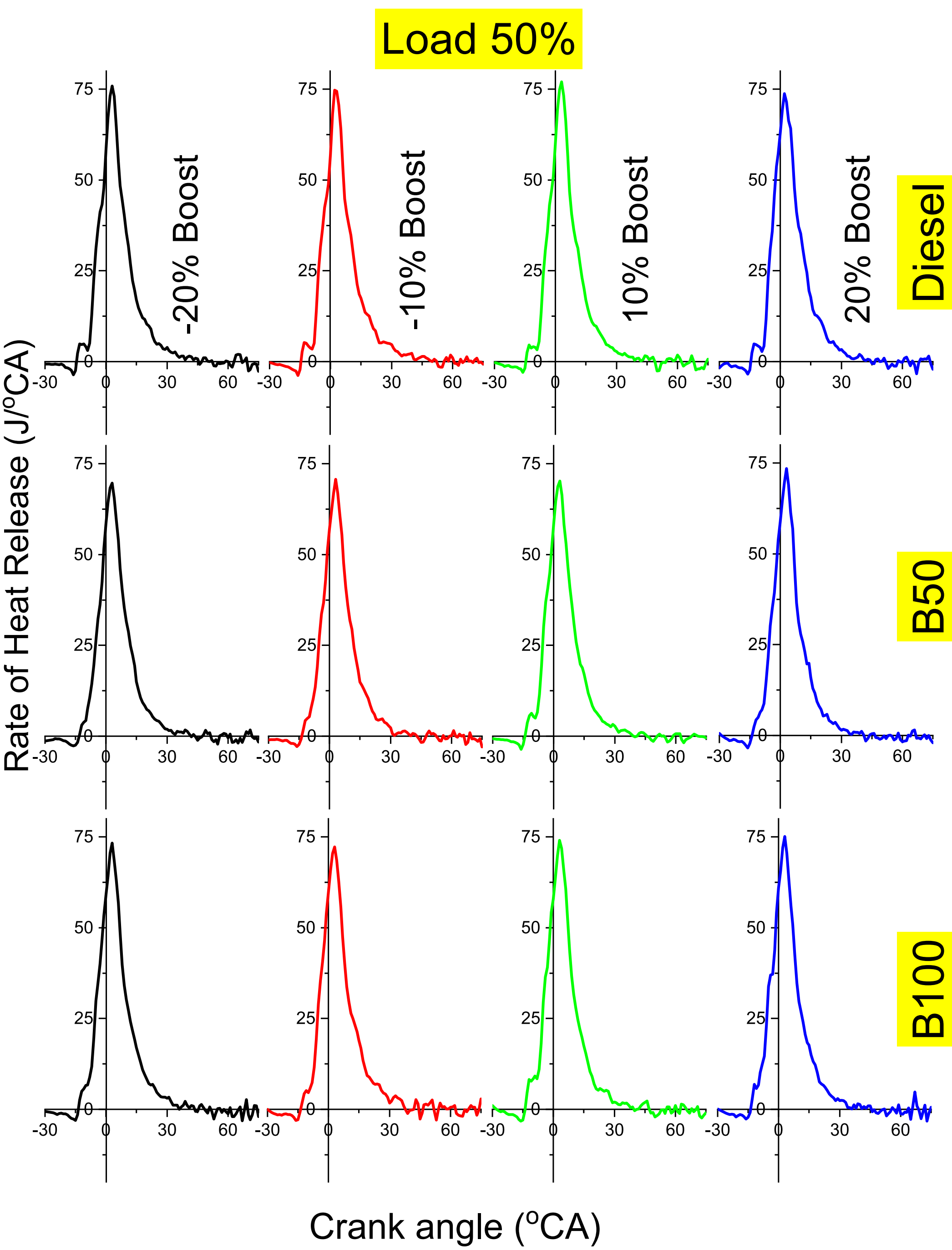

Fig. 12. Change of rate of heat release according to boost pressure (Load 50%).

damage the engine. In summary, the data in the graph clearly demonstrates the effects of boost pressure on engine performance and combustion efficiency.

An increase in boost pressure for diesel, B50, and B100 leads to higher cylinder pressure and thus a more efficient combustion process. However, biodiesel fuels have lower energy density than diesel, resulting in lower maximum pressure values. These findings provide crucial insights for optimizing engine performance and selecting the appropriate fuel type.

3.11. Heat release rates

Figs. 12 and 13 shows the heat release rates of fuels at different boost pressures. Heat Release Rate (HRR) analysis is crucial for understanding combustion behavior in diesel engines. Recent research has focused on improving HRR models to enhance accuracy and applicability [61]. The heat release rate shows the distribution of heat generated during the combustion process as a function of the crank angle and is a critical parameter for engine performance and emissions. The heat release rate is a critical parameter for engine performance and emissions, affecting factors such as NOx and particulate matter emissions, fuel economy, and combustion efficiency [62]. The diagram consists of three main parts: The top section shows the results for diesel fuel, the middle section shows the results for the B50 biodiesel blend, and the bottom section shows the results for B100 biodiesel. Each section contains four diagrams corresponding to four different boost pressure levels. The

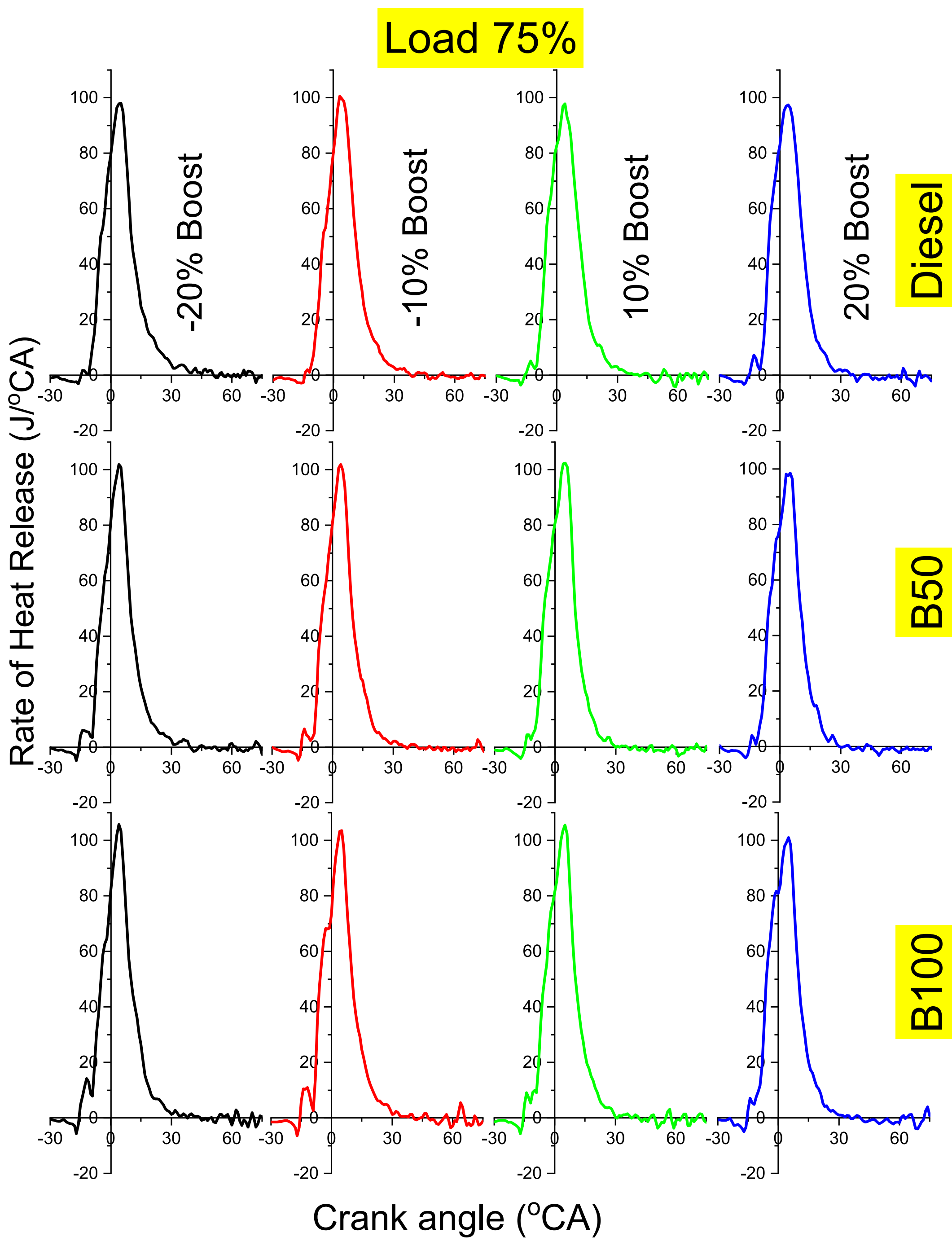

Fig. 13. Change of rate of heat release according to boost pressure (Load 75%).

horizontal axis shows the crank angle (°CA), and the vertical axis shows the heat release rate (J/°CA).

The analysis of HRR (Heat Release Rate) for different fuels (Diesel, B50, and B100) at 50 % engine load under various boost pressures reveals significant findings. For Diesel fuel, the maximum HRR values are observed as 75.92 J/°CA at −20 % boost, 74.79 J/°CA at −10 % boost, 77.07 J/°CA at + 10 % boost, and 73.82 J/°CA at + 20 % boost. Diesel achieves its highest HRR at + 10 % boost, reflecting the impact of moderate positive boost pressures on enhancing air–fuel mixing and combustion efficiency. However, at + 20 % boost, the HRR decreases slightly, likely due to increased thermal losses or combustion instabilities. At negative boost pressures (−20 % and −10 %), the HRR values are lower due to reduced air density, which limits combustion efficiency.

For B50 fuel, the maximum HRR values are recorded as 69.65 J/°CA at −20 % boost, 68.90 J/°CA at −10 % boost, 70.85 J/°CA at + 10 % boost, and 69.85 J/°CA at + 20 % boost. Similar to Diesel, B50 achieves its highest HRR at + 10 % boost, indicating that moderate boost pressures improve combustion efficiency even for biodiesel blends. The increase in air density at + 10 % boost compensates for the lower energy density of B50, resulting in a significant increase in HRR. At negative boost pressures, HRR values are lower, with 68.90 J/°CA at −10 % boost being the lowest value, reflecting suboptimal air–fuel mixing. At + 20 % boost, HRR shows a slight reduction compared to + 10 %, suggesting diminishing returns at higher boost pressures.

For B100 fuel, the maximum HRR values are 66.73 J/°CA at −20 % boost, 67.85 J/°CA at −10 % boost, 68.47 J/°CA at + 10 % boost, and 67.22 J/°CA at + 20 % boost. B100 reaches its peak HRR at + 10 % boost, showcasing the positive effect of moderate boost pressures on combustion efficiency. The oxygen-rich nature of biodiesel contributes to stable and prolonged combustion, as evidenced by the relatively consistent HRR values across boost levels [63].

At negative boost pressures, HRR values are lower, with 66.73 J/°CA at −20 % boost being the minimum, due to limited air availability for combustion. At + 20 % boost, a slight decline in HRR to 67.22 J/°CA is observed, which can be attributed to the limitations of biodiesel's lower calorific value under high boost conditions. In conclusion, the results demonstrate that moderate positive boost pressures (+10 %) generally optimize HRR for all fuels by improving air–fuel mixing and enhancing combustion efficiency. Diesel consistently achieves the highest HRR values across all boost levels, highlighting its superior energy density and combustion characteristics. B50 fuel shows a balance between cleaner combustion and relatively high energy release, making it a viable alternative for reducing emissions without compromising performance significantly.

B100 fuel, while exhibiting lower HRR values, benefits from positive boost pressures, with its oxygen content supporting stable combustion. These findings emphasize the critical importance of optimizing boost pressure based on fuel type to achieve desired combustion efficiency and emission control.

Based on the provided data, the analysis of HRR (Heat Release Rate) for different fuels (Diesel, B50, B100) at 50 % and 75 % engine loads across various boost pressures reveals significant insights. For Diesel fuel, at 75 % load, the highest HRR is observed at −10 % boost pressure with a value of 100.55 J/°CA, while at 50 % load, it is 74.79 J/°CA. This indicates an increase in HRR with higher engine loads. For B50 fuel, the maximum HRR at 75 % load is 102.47 J/°CA at + 10 % boost, compared to 70.26 J/°CA at 50 % load, again showing a similar trend of increased HRR with load. B100 fuel exhibits the highest HRR at 75 % load with 105.72 J/°CA at −20 % boost, while at 50 % load, it is 73.35 J/°CA. Among all fuels, B100 at −20 % boost and 75 % load achieves the highest HRR, whereas Diesel at + 20 % boost and 75 % load records the lowest HRR of 97.40 J/°CA. Overall, the data suggests that HRR values increase with engine load, correlating with enhanced fuel combustion and energy release. This analysis is crucial for understanding the impact of different fuels and boost pressures on combustion efficiency.

These findings highlight the importance of optimizing boost pressure to enhance combustion efficiency and engine performance across different fuel types. Research on diesel engine performance and emissions under various fuels and operating conditions has yielded several key insights. Boost pressure plays a crucial role in enhancing combustion efficiency and engine performance across different fuel types [58]. Generally, higher boost pressures lead to improved thermal efficiency and advanced combustion phasing. Biodiesel blends, such as B20 and B100, demonstrate potential for enhancing engine performance and reducing emissions compared to conventional diesel, especially at higher injection pressures [64,65]. These findings underscore the importance of optimizing boost pressure and fuel selection to achieve better engine efficiency and lower emissions.

3.12. İgnition delay, combustion mass fraction (MBF) and combustion time

Fig. 14 shows the changes in parameters such as ignition delay, combustion mass fraction (MBF) and combustion time as a function of boost pressure. Ignition delay refers to the time between fuel injection and the start of combustion and is usually measured as crank angle (CA). The ignition delay varies for each fuel type depending on the boost pressure. For diesel fuel, at 50 % load and −20 % boost pressure, the ignition delay is 7.87 crank angle (CA), which decreases to 7.70 CA at 20 % boost pressure, representing an approximate reduction of 2.10 %. At 75 % load, these values are 7.82 CA at −20 % boost and 7.57 CA at 20 % boost, indicating a reduction of about 3.12 %. For B50 fuel, at 50 % load and −20 % boost pressure, the ignition delay is 7.68 CA, decreasing to 7.59 CA at 20 % boost, which is about a 1.25 % reduction. At 75 % load, the values are 7.52 CA at −20 % boost and 7.14 CA at 20 % boost, showing a reduction of approximately 4.99 %. For B100 fuel, at 50 % load and −20 % boost pressure, the ignition delay is 7.68 CA, decreasing to 7.33 CA at 20 % boost, representing a reduction of about 4.47 %. At 75 % load, these values are 7.15 CA at −20 % boost and 6.94 CA at 20 % boost, indicating a reduction of approximately 2.96 %. The data clearly demonstrates that increasing boost pressure generally leads to a reduction in ignition delay across all fuel types and load conditions. This trend suggests that higher boost pressures enhance the combustion process, likely due to increased air density and improved fuel–air mixing, which facilitates quicker ignition. Diesel fuel shows the most significant reduction in ignition delay at higher loads, while B50 and B100 fuels also exhibit notable decreases, particularly at 75 % load. These findings highlight the importance of optimizing boost pressure to improve engine efficiency and performance, especially when using alternative fuels like B50 and B100. Research on diesel and gasoline engines has explored the effects of various parameters on combustion characteristics. Increasing boost pressure in diesel engines leads to shorter ignition delays and combustion periods, with alcohol-diesel blends showing faster combustion reactions compared to pure diesel [60].

The MFB50 values also change with boost pressure for each fuel type. For diesel fuel, at 50 % load and −20 % boost pressure, the MFB50 is 4.18 CA, which decreases to 3.94 CA at 20 % boost, showing a reduction of about 5.63 %. At 75 % load, these values are 4.43 CA at −20 % boost and 4.04 CA at 20 % boost, indicating a reduction of approximately 8.64 %. For B50 fuel, at 50 % load and −20 % boost pressure, the MFB50 is 3.83 CA, decreasing to 3.66 CA at 20 % boost, which is about a 4.48 % reduction. At 75 % load, the values are 3.85 CA at −20 % boost and 3.56 CA at 20 % boost, showing a reduction of approximately 7.57 %. For B100 fuel, at 50 % load and −20 % boost pressure, the MFB50 is 4.09 CA, decreasing to 3.92 CA at 20 % boost, representing a reduction of about 4.11 %. At 75 % load, these values are 3.92 CA at −20 % boost and 3.76 CA at 20 % boost, indicating a reduction of approximately 3.94 %. The data indicates that increasing boost pressure generally results in a decrease in MFB50 values across all fuel types and load conditions. This trend suggests that higher boost pressures enhance the combustion process, likely due to improved air–fuel mixing and increased

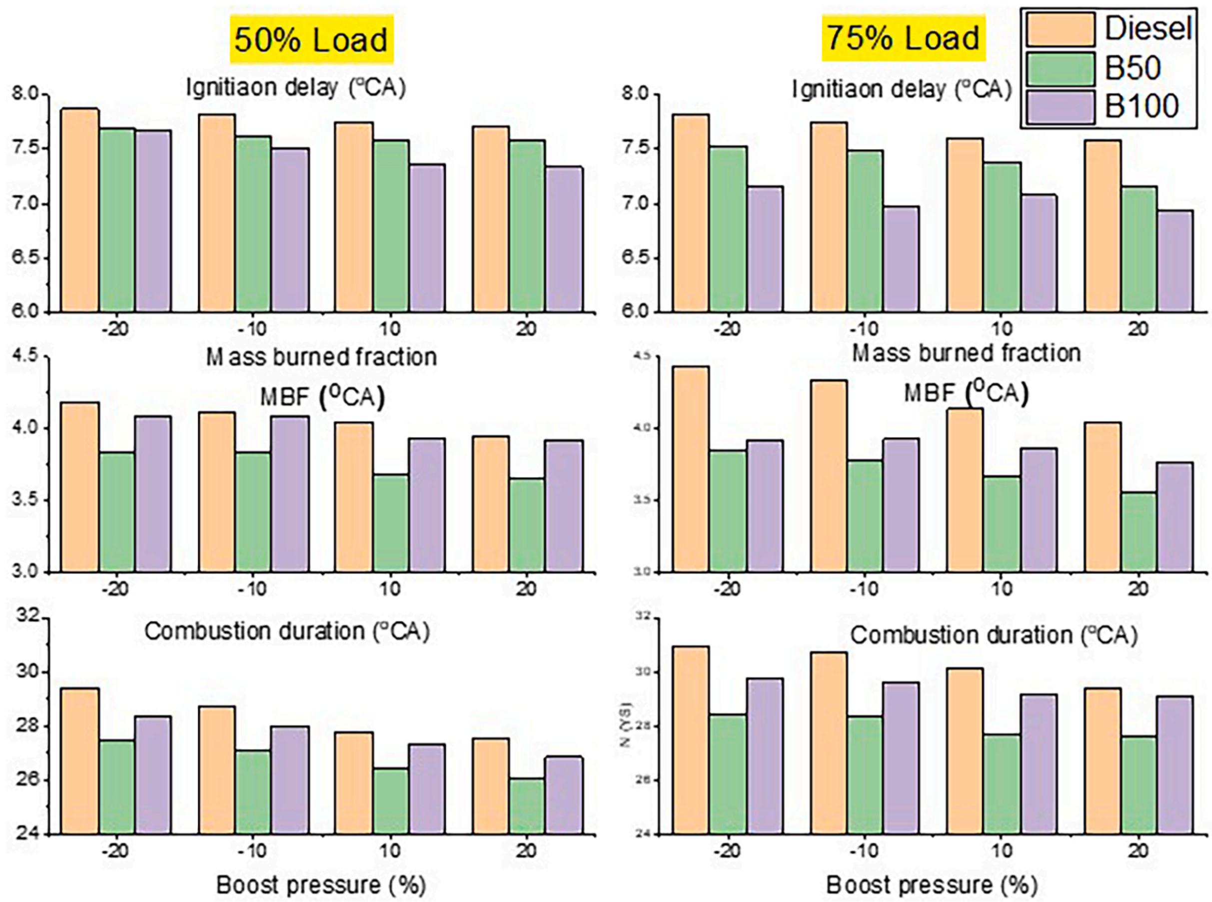

Fig. 14. Change of ignition delay, combustion mass fraction (MBF) and combustion time according to boost pressure.

combustion efficiency. Diesel fuel shows the most significant reduction in MFB50 at higher loads, while B50 and B100 fuels also exhibit notable decreases, particularly at 75 % load. These findings underscore the potential benefits of optimizing boost pressure to improve engine performance and efficiency, especially when using alternative fuels like B50 and B100.

Increasing boost pressure generally improves combustion efficiency and reduces MFB50 values across different fuel types and load conditions [266]. Biodiesel blends show higher cetane numbers and earlier auto-ignition compared to conventional diesel, with B100 igniting up to 3 degrees of crank angle earlier than B0 [66]. Optimizing biodiesel blends, EGR rates, and pilot injection timing can effectively reduce PM emissions while maintaining low NOx levels, with B30 blend and 10 % EGR rate showing promising results [67]. These findings highlight the potential for improving engine performance and reducing emissions through careful fuel selection and operating parameter optimization.

Combustion duration also varies with boost pressure for each fuel type. For diesel fuel, at 50 % load and −20 % boost pressure, the combustion duration is 30.96 CA, which decreases to 29.38 CA at 20 % boost, showing a reduction of about 5.09 %. At 75 % load, these values are 29.39 CA at −20 % boost and 27.51 CA at 20 % boost, indicating a reduction of approximately 6.40 %. For B50 fuel, at 50 % load and −20 % boost pressure, the combustion duration is 28.38 CA, decreasing to 27.63 CA at 20 % boost, which is about a 2.65 % reduction. At 75 % load, the values are 27.47 CA at −20 % boost and 26.02 CA at 20 % boost, showing a reduction of approximately 5.31 %. For B100 fuel, at 50 % load and −20 % boost pressure, the combustion duration is 29.78 CA, decreasing to 29.10 CA at 20 % boost, representing a reduction of about 2.26 %. At 75 % load, these values are 28.33 CA at −20 % boost and 26.84 CA at 20 % boost, indicating a reduction of approximately 5.24 %.

The data reveals that increasing boost pressure generally leads to a decrease in combustion duration across all fuel types and load conditions. This trend suggests that higher boost pressures enhance the combustion process by promoting more efficient and complete burning of the fuel–air mixture.

3.13. Knock index

Fig. 15 shows the variation of the engine's knock index (in bar) as a function of different boost pressure levels. The Knock Index was measured using an in-cylinder pressure sensor (AVL Xion) integrated into the test engine. This sensor, with a precision of 0.05 crank angle degrees (CA), ensured highly accurate pressure data acquisition. The measurement process was conducted through a computer-controlled system and dedicated software, enabling real-time data acquisition and processing for the reliable calculation of the Knock Index. This setup allowed for precise monitoring of knocking phenomena, ensuring that the analysis was robust and accurate, contributing to a detailed understanding of the engine's combustion behavior under various test conditions. The knock index is an important indicator of combustion quality and engine performance. The upper part of the diagram shows the data determined at an engine load of 50 and the lower part shows the data at an engine loadof 75. The boost pressure values are on the horizontal axis and the knock index values are on the vertical axis. At a load of 50 %, some changes in the knock index can be observed with the increase in turbo pressure. At a pressure level of −20, the knock index of diesel fuel was measured at 0.493 bar, of B50 at 0.428 bar and of B100 at 0.445 bar. At a pressure level of −10, the knock index of diesel fuel was 0.495 bar, of B50 0.335 bar and of B100 0.486 bar. At + 10 pressure, the knock index for diesel fuel was 0.516 bar, 0.462 bar for B50 and 0.487 bar for

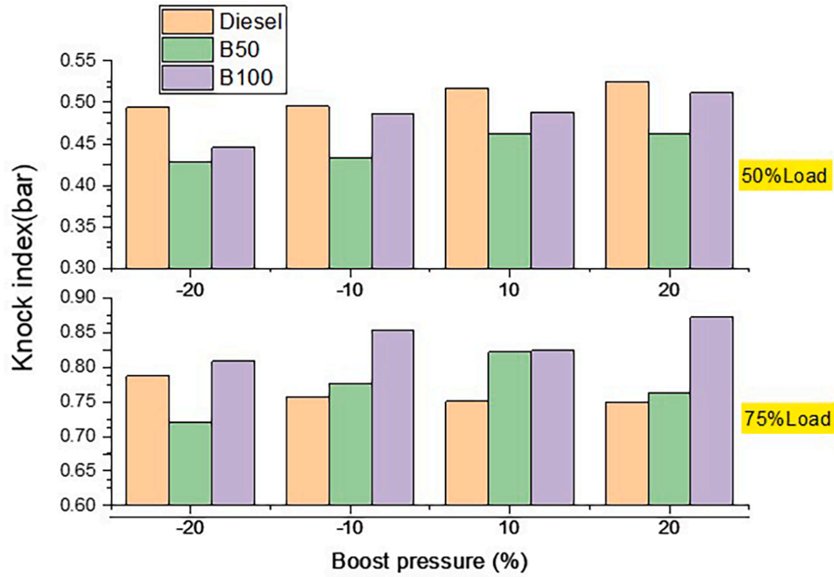

Fig. 15. Change of knock index according to injection timing.

B100. At a pressure of + 20 %, the knock index for diesel fuel was 0.525 bar, 0.462 bar for B50 and 0.511 bar for B100. At a load of 75 %, the change in the knock index becomes clearer with increasing pressure. At −20 % pressure, the knock index of diesel fuel was measured at 0.787 bar, of B50 at 0.720 bar and of B100 at 0.808 bar. At a pressure of −10 %, the knock index for diesel fuel was 0.756 bar, for B50 0.720 bar and for B100 0.808 bar. At + 10 pressure, the knock index for diesel fuel was 0.750 bar, 0.822 bar for B50 and 0.824 bar for B100. At a pressure of + 20 %, the knock index for diesel fuel was 0.748 bar, 0.763 bar for B50 and 0.8720 bar for B100.

The knock index is a critical parameter for assessing engine performance and preventing damage in internal combustion engines. It can be determined using engine block vibration and a piezoelectric knock sensor [68,69] Knock occurrence is detected by comparing the calculated knock index to a statistically determined threshold, such as the three-sigma rule [68]. Various signal processing techniques, including Empirical Mode Decomposition and Short-Time Fourier Transform, can be applied to extract knock features from vibration signals [69]. While in-cylinder pressure sensors provide the most precise knock recognition, vibration-based methods are more cost-effective for on-board applications [70].

While diesel fuel generally has a higher knock index, B50 and B100 fuels offer lower knock index values. This shows that biodiesel provides smoother and more efficient combustion. As turbo pressure increases, the knock index generally increases, indicating that the engine is exposed to more knock at higher pressure and temperature. However, the use of biodiesel blends can mitigate these effects and ensure more stable engine operation.

Our study possesses significant strengths in terms of both experimental design and contributions to the literature. Firstly, this research systematically examines the effects of boost pressure on different biodiesel blends (B50 and B100), addressing a critical gap in the existing literature. While previous studies have predominantly focused on conventional diesel fuels, this work takes an innovative approach by linking the unique properties of biodiesel such as its oxygen content, lower calorific value, and combustion characteristicsn with boost pressure. Detailed analyses of the performance of biodiesel blends under varying boost pressures in terms of emissions and combustion characteristics provide valuable contributions both scientifically and practically. From an experimental design perspective, the study evaluates various fuel types (diesel, B50, and B100) under different boost pressures and engine loads. The use of precise measurement equipment and standardized protocols ensures the reliability and reproducibility of the results. The research comprehensively discusses the effects of boost pressure on parameters such as HRR, BSFC, CO, HC, and NOx, in both physical and chemical contexts. This approach goes beyond simply presenting observational results, offering an in-depth analysis of the underlying cause-and-effect relationships. Furthermore, the findings are compared with previous studies in the literature, clearly highlighting the unique contributions of this work. The study also provides critical insights into environmental sustainability. Detailed analyses of biodiesel and its blends contribute to understanding the balance between NOx and particulate emissions. Notably, the oxygen content of biodiesel facilitates emission reductions, laying the groundwork for the development of environmentally friendly engine technologies. At the same time, challenges such as the increase in NOx emissions highlight the need for future research to develop effective mitigation strategies. In conclusion, this research explores the applicability and sustainability of biodiesel blends under various engine conditions, offering significant contributions to both academic literature and industrial applications. The findings provide valuable insights for optimizing engine performance while minimizing environmental impact, clearly demonstrating the importance and originality of this study within the field.

4. Conclusion

This study comprehensively analyzed the effects of varying boost pressures on engine performance, combustion characteristics, and emissions for diesel, B50, and B100 fuel types under different engine loads. The findings highlight the critical role of boost pressure in improving engine performance and reducing environmental impacts, although significant differences were observed depending on the type of fuel used. Higher boost pressures significantly enhanced combustion efficiency by increasing in-cylinder pressure and heat release rates, particularly for biodiesel blends (B50 and B100). However, the lower energy density of biodiesel resulted in slightly reduced peak pressures and increased brake specific fuel consumption (BSFC) compared to diesel, emphasizing the trade-off between power output and fuel economy. From an emissions perspective, higher boost pressures were found to substantially reduce CO, HC, and particulate matter emissions for all fuel types. Biodiesel blends consistently outperformed diesel due to their oxygen-rich structure. However, NOx emissions were observed to increase with higher boost pressures, particularly for biodiesel, underscoring the need for effective NOx control strategies in biodiesel applications. Combustion characteristics analysis revealed that higher boost pressures shortened ignition delay and combustion duration, leading to faster and more efficient combustion. Biodiesel blends, with their higher cetane numbers, exhibited earlier ignition and more stable combustion, reinforcing their potential as a sustainable alternative fuel. This study is one of the few that utilized the AVL 515X Supercharger system, enabling precise control of boost pressure and providing a detailed analysis of the combustion and emission performance of biodiesel blends. The use of this advanced system significantly enhanced the reliability and repeatability of the experimental results, filling a critical gap in the literature and providing a robust data foundation for future research. Future studies are recommended to investigate biodiesel blends under different injection timings and pilot injection strategies to better understand their effects on combustion dynamics. Such research could contribute to the development of new optimization strategies aimed at improving engine efficiency and reducing emissions. Additionally, exploring the effects of biodiesel produced from alternative feedstocks with varying fatty acid profiles on combustion and emissions could deepen the understanding of feedstock composition impacts. Finally, investigating the potential of multi-fuel blends, such as biodiesel combined with renewable fuels like hydrogen or alcohols, could offer innovative pathways for balancing emissions reduction and engine performance.

CRediT authorship contribution statement

Hüseyin Söyler: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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