Energy Conversion and Management: X 22 (2024) 100557

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

Impact of RON on a heavily downsized boosted SI engine using **2nd** generation biofuel – A comprehensive experimental analysis

Mohamed Mohamed [a,*], Abinash Biswal [a], Xinyan Wang [a], Hua Zhao [a,*], Anthony Harrington [b], Jonathan Hall [b]

[a] *College of Engineering, Design and Physical Science, Brunel University, London, UK*
[b] *MAHLE Powertrain Ltd., UK*

ABSTRACT

Sustainable energy solutions are paramount in the urgent global drive against climate change, especially in transportation. This research focuses on second-generation biogasolines and their potential in the context of decarbonisation. Two biogasolines, 99 RON E20 and 95 RON E20, were rigorously tested in a downsized single-cylinder engine. Their performance, combustion, and emissions were compared against the conventional fossil fuel, 95 RON E10, under varying engine loads. Additionally, a comprehensive injection parameter sweep was conducted for both biofuels at low and high loads, shedding light on their unique operational characteristics and operational regimes. This research significantly enhances our knowledge about the potential of these new biofuels and their implications for a more sustainable energy future. The findings of the experiments demonstrate no substantial difference between the tested biofuels and fossil fuels. Biofuel with a higher octane number provides more knock resistance than fossil fuel, resulting in increased thermal efficiency due to spark advance ability. However, more significant hydrocarbon emissions were detected for biofuels than fossil fuels due to more extensive aromatic content. Both biofuels have stable combustion in low and high-load operations under varying injection pressures and injection start times. 99 Bio E20 has a wider operational range than 95 Bio E20. However, due to very high HC emissions, especially at high-load operations, an early injection start with more significant injection pressure is not recommended for biofuel. From a broader perspective, both biofuels exhibit the promising potential to serve as drop-in replacements in spark ignition engines.

Introduction

Decarbonisation pathways are riddled with complex obstacles requiring comprehensive solutions. Addressing these challenges requires interdisciplinary research, policy coordination, technological innovation, and global cooperation to effectively transition towards a low-carbon and sustainable future [1–4]. Despite rapid electric vehicle sales, a large chunk of the transportation sector will still use liquid fuels by the middle of the century. While biofuels are attractive as low-carbon alternatives, those derived from food crops may conflict with petroleum production. Investigating the expansion of biofuels while addressing food crop rivalry with second-generation biomass biofuels [5–7]. Also analyses how biotechnology could transform the global agricultural industry, improving crop productivity and balancing biofuel and food production. Analysis shows that legislative frameworks, technological advances, and institutional support are crucial for increasing food and biofuel production [8–11].

Internal combustion engines can substantially contribute to carbon–neutral transportation by replacing conventional fuels with zero-carbon alternatives such as hydrogen and ammonia. However, the widespread adoption of these eco-friendly fuels necessitates significant financial expenditures, the development of appropriate infrastructure, and strong support from regulatory bodies and political authorities [12–15].

Ethanol and methanol offer a pathway to a sustainable and low-carbon energy future, addressing intricate issues tied to fossil fuel usage. Their renewability, compatibility with existing combustion technologies, and emissions reduction potential position them as significant contributors to global climate action and energy security. Nevertheless, challenges like energy-efficient production, feedstock

Abbreviations: 95 Fossil E10, Fossil fuel with 95 RON and 10 % Ethanol; 95 Bio E20, Bio-fuel with 95 RON and 20 % Ethanol; 99 Bio E20, Bio-fuel with 99 RON and 20 % Ethanol; ATDC, After Top Dead Centre; AFR, Air Fuel Ratio; BTDC, Before Top Dead Centre; CA, Crank Angle; CA50, 50 % burn duration; CO, Carbon Monoxide; CO2, Carbon Dioxide; ECU, Engine Control Unit; EMOP, Exhaust Valve Maximum Opening Point; EVC, Exhaust Valve Closing; FID, Flame Ionisation Detector; HC, Hydrocarbons; ICE, Internal Combustion Engine; IMEP, Indicated Mean Effective Pressure; IMOP, Inlet Valve Maximum Opening Point; ISCO, Indicated Specific Carbon Monoxide; ISFC, Indicated Specific Fuel Consumption; ITE, Indicated Thermal Efficiency; IVC, Inlet Valve Closing; MFB, Mass Fraction Burned; MON, Motored Octane Number; PMI, Particle Matter Index; RON, Research Octane Number; SOI, Start Of Injection; VLI, Vapor Lock Index.

* Corresponding authors.
E-mail addresses: mohamed.mohamed@brunel.ac.uk (M. Mohamed), hua.zhao@brunel.ac.uk (H. Zhao).

https://doi.org/10.1016/j.ecmx.2024.100557
Received 2 January 2024; Received in revised form 21 February 2024; Accepted 3 March 2024
Available online 4 March 2024

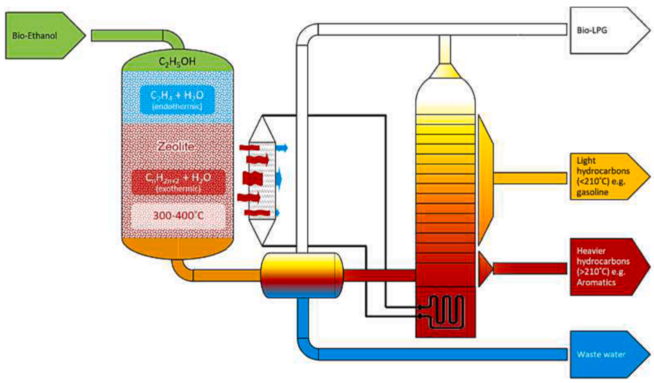

Fig. 1. Schematic of Bio-gasoline production[34].

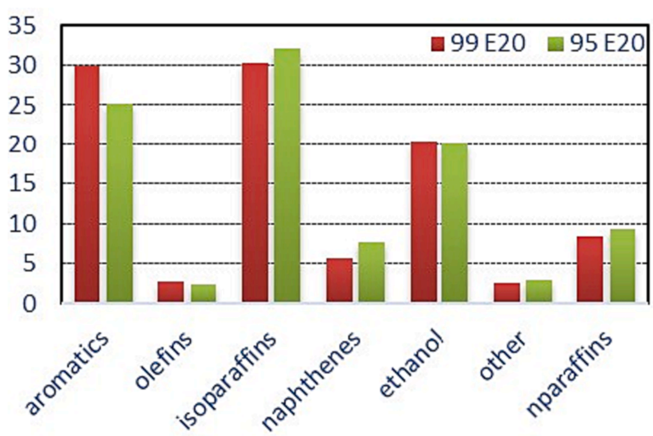

Fig. 2. Composition of Bio-gasoline.

Table 1
Fuel properties comparison.

Parameter	Unit	95 Fossil E10	99 Bio E20	95 Bio E20
Bio-Content	% v/v	10.1	100	100
Honda PMI		1.03	2.09	1.88
Simplified PMI		–	2.21	2.95
Vapor Lock Index (VLI)		–	812	763
Research Octane Number (RON)		95.50	99	96.20
Motored Ocatne Number (MON)		85.10	86.10	85.00
Carbon (C)	% (m/m)	83.06	79.43	79.02
Hydrogen (H)	% (m/m)	13.35	13.30	13.57
Density(at 15 °C)	kg/L	0.753	0.766	0.761
Initial Boiling Point (BP)	°C	34.9	28.5	34.9
H/C Ratio		1.915	1.995	2.046
O/C Ratio		0.03244	0.06880	0.07039
Air to Fuel ratio (AFR) (Stoic)	assumes	13.98	13.39	13.43
H + C + O	%	100.00	100.00	100.00
Ethanol & Higher Alcohols	% (v/v)	9.8	20.2	20.4
Net Calorific value (LHV)	MJ/kg	41.33	39.23	39.36
Gross CV	MJ/kg	44.17	42.05	42.23
Sulfur Content	mg/kg	3.2	<1	<1

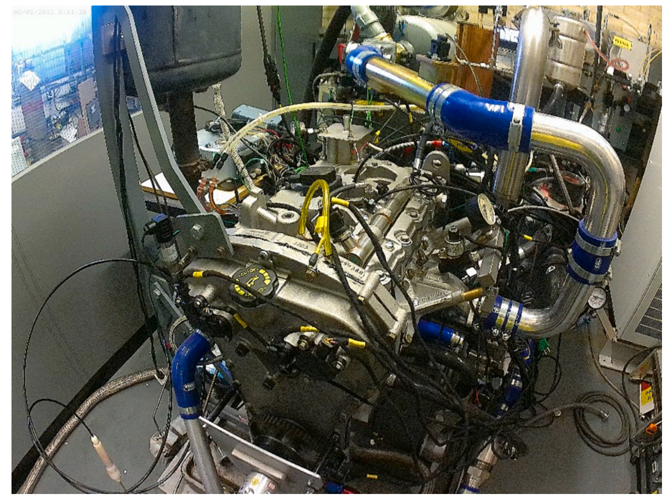

Fig. 3. Photographic view of the single-cylinder engine.

Table 2
Engine specification.

Configuration	Single Cylinder
Displaced volume	400 cc
Stroke X Bore	73.9 mm x 83 mm
Compression Ratio	11.1: 1
Number of Valves	4
Exhaust Valve Timing	EMOP (Exhaust Maximum Opening Point) 100-140°CA BTDC, 11 mm Lift, 278 °CA Duration
Inlet Valve Timing	IMOP (Intake Maximum Opening Point) 80–120 °CA ATDC, 11 mm Lift, 240°CA Duration
Injection System	Central Direct Injection outwardly opening spray ≤ 200 bar. PFI injector at 8 bar
Injection Control	MAHLE Flexible ECU (MFE)

conflicts, and distribution efficiency must be tackled to unlock their full potential. Collaborative efforts of researchers, governments, industry, and society are crucial. Alcoholic fuels require technological advancements, supportive regulations, and public awareness campaigns. Research is vital for production efficiency and feedstock diversity, while government support aids industry growth. Educating consumers on alternative fuels is essential. Alcoholic fuels promise a sustainable energy future, pivotal for reducing emissions, enhancing energy security, and diversifying energy sources. As technology advances and collaborations strengthen, alcoholic fuels could become mainstream, ushering in a cleaner and greener future for generations [16–20].

Another approach to the net-zero target is that International ocean shipping's GHG emissions are reduced via new regulations from the International Maritime Organisation. Hydrogen is a suggested alternative fuel, but its use is still in its early stages. Several factors explain the underdeveloped state of hydrogen-based energy for the shipping industry, and suggestions were given to promote hydrogen-powered maritime industries for cleaner and more sustainable global trading [21]. Biodiesel synthesis and its potential as a fuel substitute in diesel-ethanol engine blends. Results showed that the addition of ethanol improved the blends' performance characteristics. Also, optimising a diesel engine fueled with ternary blends of Solketal-biodiesel-diesel found that using Solketal as an oxygenated additive could improve engine performance and reduce harmful emissions. [22,23].

Biogasoline, a drop-in fuel, is a crucial solution to greenhouse gas emissions and energy security in the complex transportation sector. Its potential to effortlessly replace conventional petrol without car or infrastructure modifications enables a pragmatic shift to sustainable mobility. This transformation has challenges, highlighting the necessity

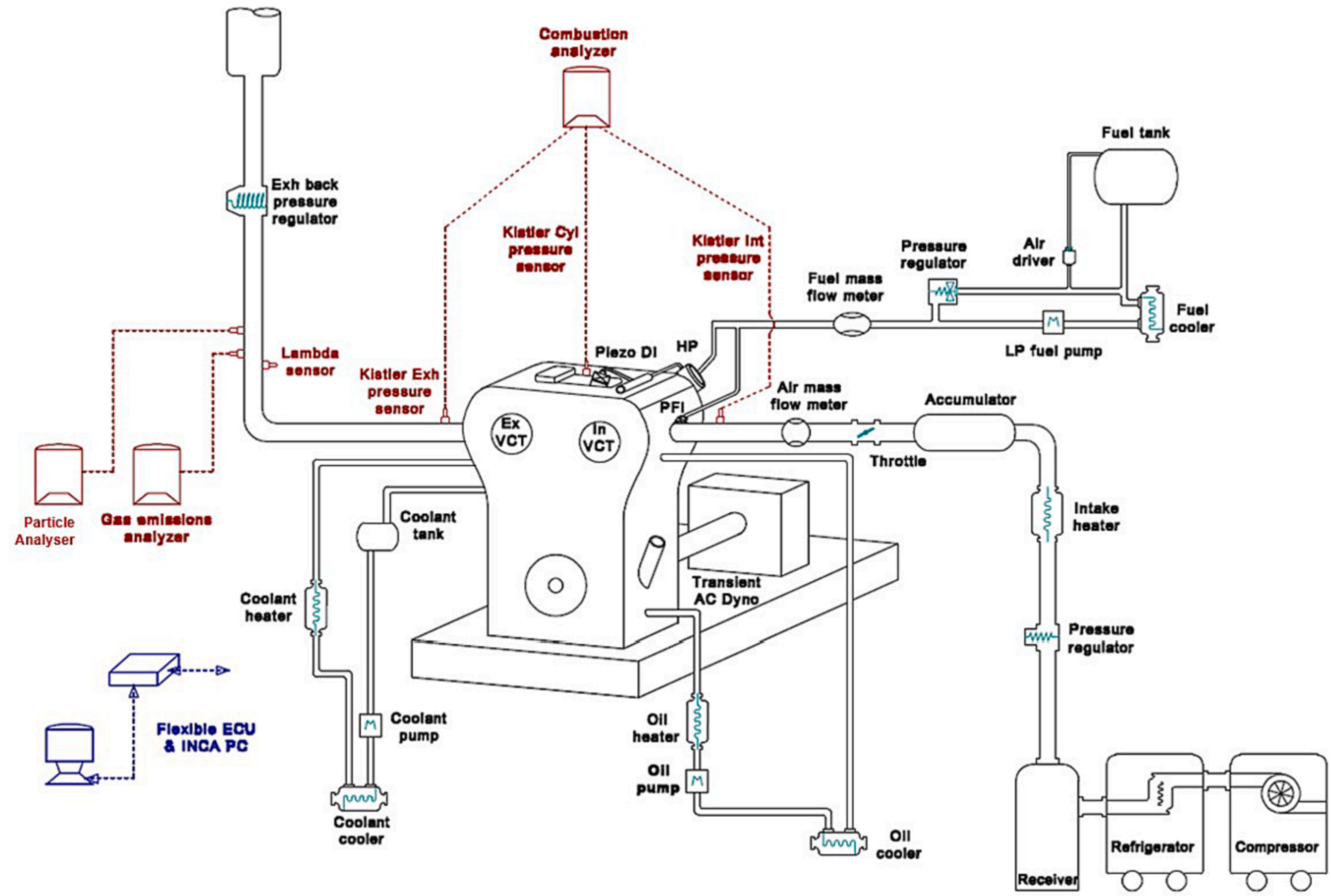

Fig. 4. Schematic of the test bed. The single-cylinder engine is connected to an external boosting system, Combustion analyser, Flexible ECU, Emission analyser and PM analyser.

Table 3
tests properties.

Parameter	unit	Load sweep study	Low load matrix	High load matrix
Engine speed	RPM	3000	2000	3000
Indicated mean effective pressure (IMEP)	bar	SWEEP (2 to 28 bar with 2 bar step)	4.6	16
DI start of injection	degrees BTDCf	300	SWEEP (275–350 CAD with 25 CAD step)	SWEEP (275–350 CAD with 25 CAD step)
DI injection pressure	bar	150	SWEEP (50–200 bar with 50 bar step)	SWEEP (50–200 bar with 50 bar step)
Intake cam timing(IMOP)	degrees ATDCg	82	82	82
Exhaust cam timing (EMOP)	degrees BTDCg	140	140	140
Relative AFR	–	1 up to exhaust temperature threshold	1	1
Boosted air temperature	°C	40	40	40
Target (CA50)	degrees ATDCf	8 and retreated to avoid knocks	8	retarded to knock limits
Coolant and oil temperature	°C	90	90	90

for multifaceted approaches [24,25]. Biogasoline is environmentally friendly. However, feedstock availability and diversity are concerns. Researching various biomass sources and advances in feedstock production and conversion technology could overcome these restrictions. Biogasoline's economic viability depends on improving production efficiency, lowering costs, and optimising refining [26,27].

The transition towards more environmentally friendly energy sources has been characterised by the emergence of initial biofuels, signifying an initial step in this transformative process. Nonetheless, the execution of their strategy raises questions regarding the simultaneous competition for resources and the broader need for sustainability. On the other hand, the advent of second-generation biofuels tackles these complex issues by employing non-food feedstocks strategically and utilising modern conversion techniques. This strategic approach demonstrates their capacity to enhance energy production efficiency while addressing environmental concerns. The growing progress in technology and the recognition of economies of scale have led to an evident rise in the prominence of second-generation biofuels [28–30].

This paper will experimentally investigate the impact of the research octane number on the combustion characteristics, performance, and emissions of two second-generation biogasolines with 20 % ethanol. 99 RON E20 and 95 RON E20 are introduced as a drop in fuels and fulfil the EN288 standard. The study compares both fuels to a 95RON E10 fossil fuel in a full load sweep with a fully direct injection at 100 bar. It maintains the same operation condition at each load to identify the main characteristics and the divergence of the biogasoline fuels from the fossil fuel. Therefore, study in depth the fuel matrix at low and high loads of each fuel to identify the operation range and the fuel sensitivity to the combustion boundary conditions and the emission characteristics. The

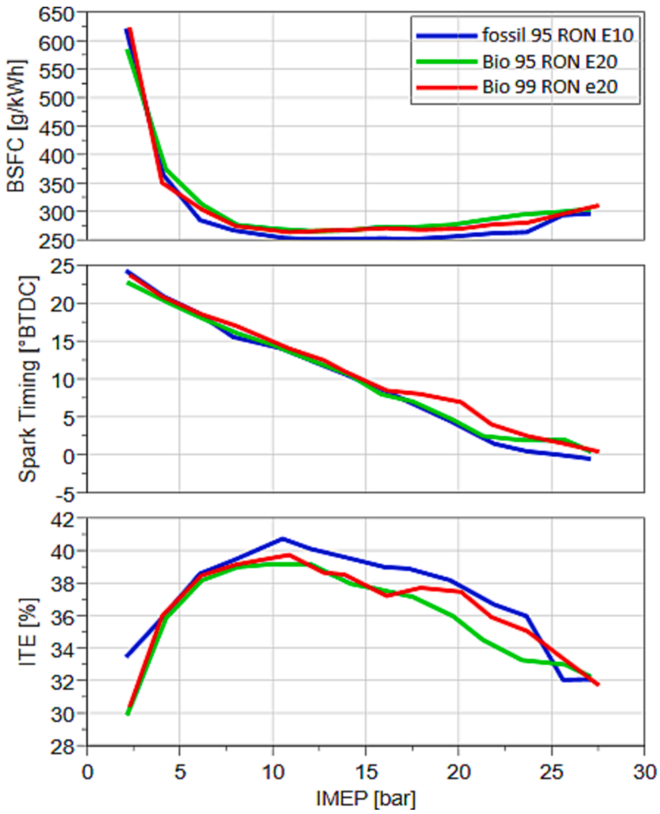

Fig. 5. Indicated thermal efficiency, spark timing and BSFC comparison with varying IMEP at 3000 rpm.

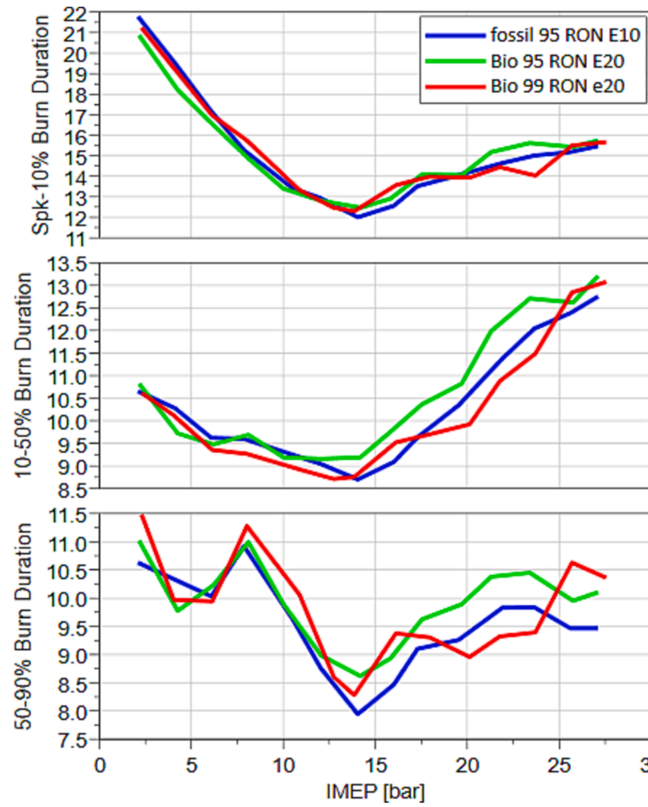

Fig. 7. Combustion duration comparison with varying IMEP at 3000 rpm.

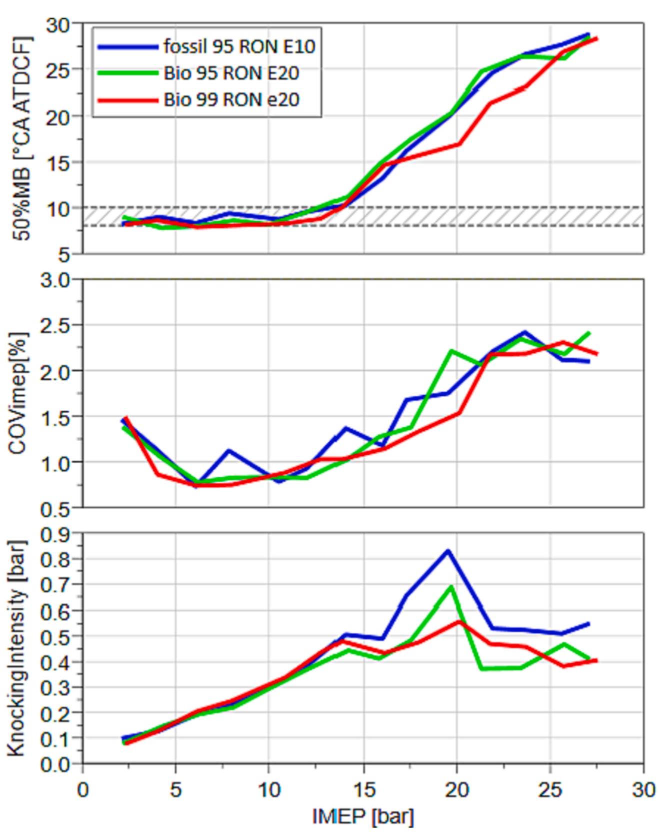

Fig. 6. The comparison of 50 % burn location, combustion stability, and knock intensity with varying IMEP at 3000 rpm.

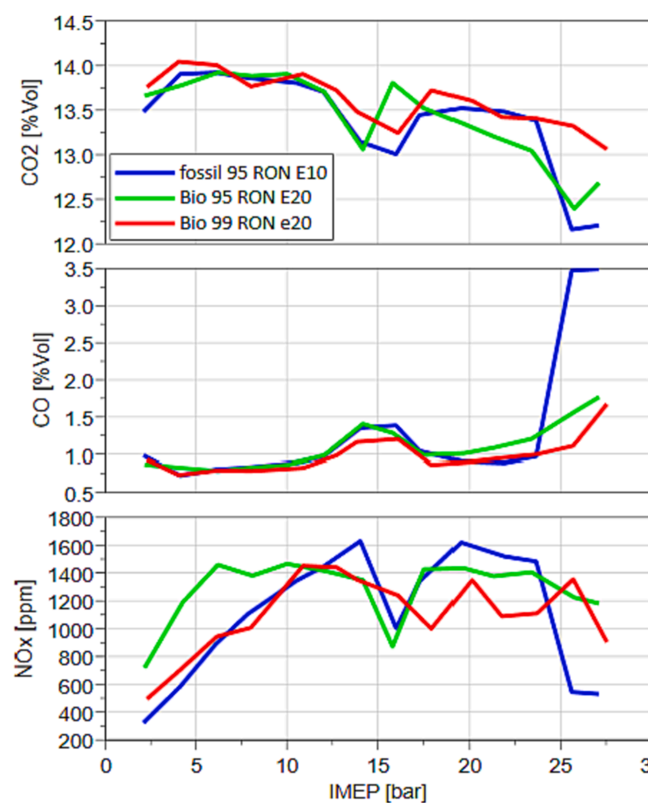

Fig. 8. CO_2, CO, NO_x emission analysis.

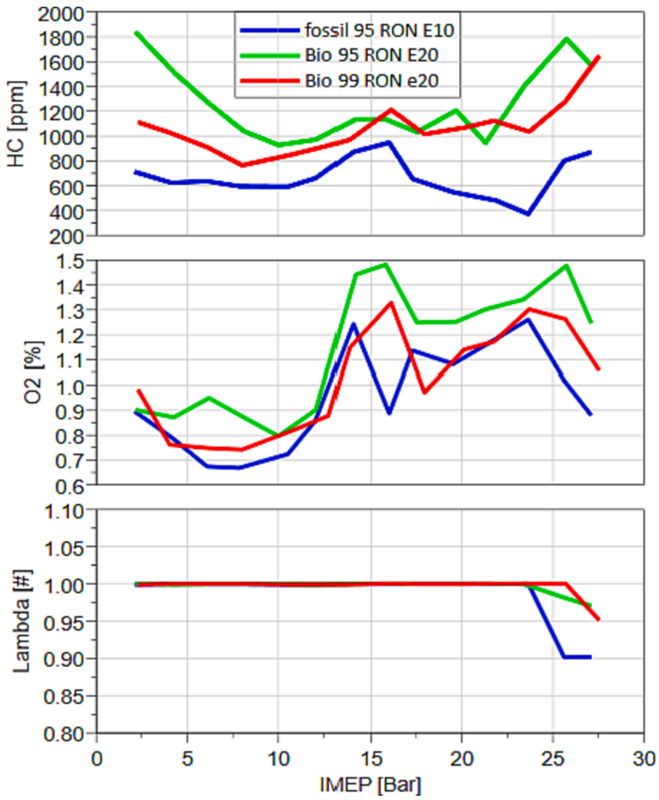

Fig. 9. Unburned hydrocarbon, O_2, and lambda value.

main outcomes were aligned with the previous studies on varying the research octane number for fossil fuels [31,32].

Materials and methods

Fuel

This investigation used two distinct bio-gasolines (95 Bio E20 and 99 Bio E20) with research octane ratings of 95 and 99 and a constant amount of ethanol of 20 %. These two biofuels' engine performance, combustion, and emission characteristics were compared to that of the baseline fossil fuel (95 Fossil E10), which contains 95 RON and 10 % ethanol.

Coryton has successfully developed the next iteration of biofuels, which is offered as a prototype sample for engine testing. The sample has a range of octane numbers and ethanol percentages and aims to provide an improved fuel alternative for the market. Higher (RON) advantages have been gained, such as higher Fuel quality, which reflects on the thermal efficiency, including antiknock rating, which is critical in enabling optimal operation strategies. The production process for the bio-gasoline involved several steps. Bioethanol was initially generated from biomass or agricultural waste, such as grass. To increase enzyme accessibility, the lignocellulosic biomass underwent pretreatment, where it was subjected to enzymatic hydrolysis, which converted it into sugars. These sugars were then fermented to ethanol with the assistance of various microorganisms. Fig. 1 illustrates that the bio-ethanol was dehydrated into ethylene and subsequently transformed into longer-chain hydrocarbons at a temperature range of 300–400 °C. This transformation occurred in a zeolite catalyst's presence [33]. According to RED II definition, this bio-gasoline has an impressive greenhouse reduction exceeding 80 %, and it stands as a remarkable step towards a more sustainable future. This fuel has a higher final boiling point. This can be attributed primarily to its augmented aromatic content. In terms of availability, the current status highlights the presence of a single operational industrial-scale plant. This facility boasts an impressive capacity of around 20 million litres per year, showcasing a noteworthy production capability. The chemical composition of the biofuels, shown in Fig. 2, has been tailored to maintain a constant ethanol content of 20 % while achieving different research octane ratings. This adjustment ensures that the impact of ethanol on the fuel's properties remains constant, allowing for a focused examination of other components that contribute to octane levels and overall performance.

Table 1 provides a comprehensive overview of the characteristics of the test fuels used in the study. The baseline fossil fuel used in the investigation adheres to the EN228 fuel standard, which encompasses a broad range of fuel performance criteria while imposing stringent specifications. These specifications include a low particle index achieved through intricate blending techniques. The selection of this fuel standard as a benchmark for bio-gasoline fuels ensures a robust and rigorous evaluation. Blended biofuels were prepared and analysed with a consistent ethanol concentration of 20 % but varying octane numbers. This allows for a systematic examination of the effects of octane rating on fuel performance, combustion, and emissions. The Particle Mass (PM) index is also introduced as an additional indicator and predictor of particulate emissions for each fuel. The PMI number considers the fuel's vapour pressure and the double bond equivalence of each fuel compound in the overall fuel mixture. Equation (1) calculates the final PMI value, which serves as a quantitative measure of the particulate emission characteristics of each fuel [35].

$$PMIndex = \sum_{i=1}^{n} I_{[443K]} = \sum_{i=1}^{n} \left(\frac{DBE + 1}{V.P(443K)_i} \times Wt_i \right) \quad (1)$$

Where DBE is the double bond equivalent, VP represents the vapour pressure, and Wt is the weight.

Engine setup

A highly efficient and heavily downsized single-cylinder engine, supplied by MAHLE Powertrains, was employed to assess the impact of the research octane number of the 2nd generation bio-gasoline on both engine performance and emissions. This approach of utilising a downsized engine allows for a more streamlined and cost-effective engine development process and reduces engine control unit (ECU) complexity. As shown in Fig. 3, the engine has been attached to a completely instrumented AC dynamometer testbed. The cylinder head of this engine includes two intake valves, two exhaust valves, and double overhead camshafts featuring hydraulically changeable cam phasers capable of adjusting up to 40 degrees crank angle. The centrally mounted direct injector can operate at pressures as high as 200 bar, ensuring precise fuel delivery. Also, an additional port fuel injection (PFI) injector is installed in the engine's intake manifold. This PFI injector can inject fuel at pressures of up to 8 bar. The ignition system incorporates a centrally positioned spark plug with a 100 mJ coil-onplug configuration, enhancing combustion. A MAHLE Flexible ECU (MFE) was used to control the engine operation. The detailed specification of the single-cylinder engine is depicted in Table 2.

The test cell is equipped with a comprehensive Data Acquisition system that facilitates precise monitoring and analysis of engine performance. This system incorporates advanced components, including a NI-USB 6353 fast card and a NI-USB 6210 card, to handle data acquisition tasks effectively. The NI-USB 6353 fast card can handle up to 32 analogue inputs at an impressive speed of 1.25 MS/s. This high sampling rate enables the system to capture data with exceptional accuracy and detail. The NI-USB 6210 card also serves as an extra-time domain card, further enhancing the system's capabilities. With this sophisticated setup, the Data Acquisition system can effortlessly record data in crank and time domains.

Furthermore, the system can seamlessly integrate data from additional pressure and temperature sensors in the time domain. An in-house

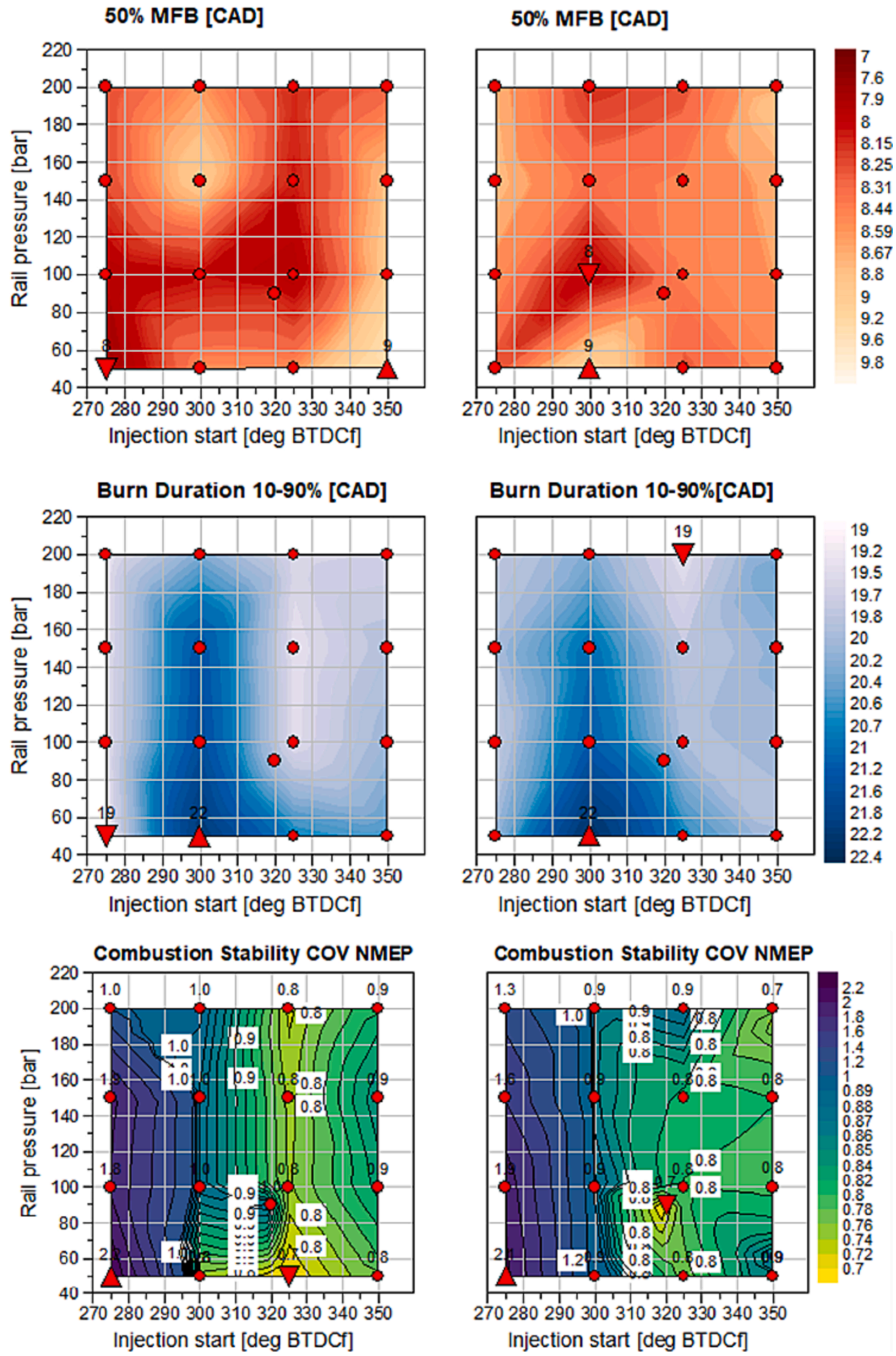

Fig. 10. Combustion phasing, Burn duration and combustion stability at 4.6 bar IMEP, 2000 rpm. Left column: 99 Bio E20 and right column: 95 Bio E20. The X-axis represents injection timing, and the Y-axis represents injection pressure.

combustion analyses program facilitates real-time monitoring and data recording. This program enables live monitoring of primary combustion parameters and recording in-cylinder pressure data for up to 300 cycles.

The testbed configuration shown in Fig. 4 was used for this study, incorporating an independently operated external boosting system. The intake and exhaust pressures were monitored using two piezoresistive pressure sensors operating fast to ensure accurate measurements. Coolant and oil temperatures were also carefully controlled to maintain stable and uniform conditions across all steady-state test settings. For monitoring engine-out emissions, a combination of HORIBA (MEXA-584L) for CO/CO_2, Signal analyser (Ambitech model 443) Chemiluminescent NO/NO_x, and Rotork Analysis model 523 flame ionisation detection (FID) hydrocarbon (HC) analysers were employed. These instruments allowed for precise measurement and analysis of exhaust emissions.

Experimental procedure

The overall test process for this study was divided into two different parts. First, The single-cylinder engine tests were conducted at a constant speed of 3000 RPM. To compare the performance and emissions of biofuels with baseline gasoline, load sweeps were performed at the same engine speed while maintaining consistent engine settings such as cam timing, fuel injection pressure, and timing. This approach eliminated

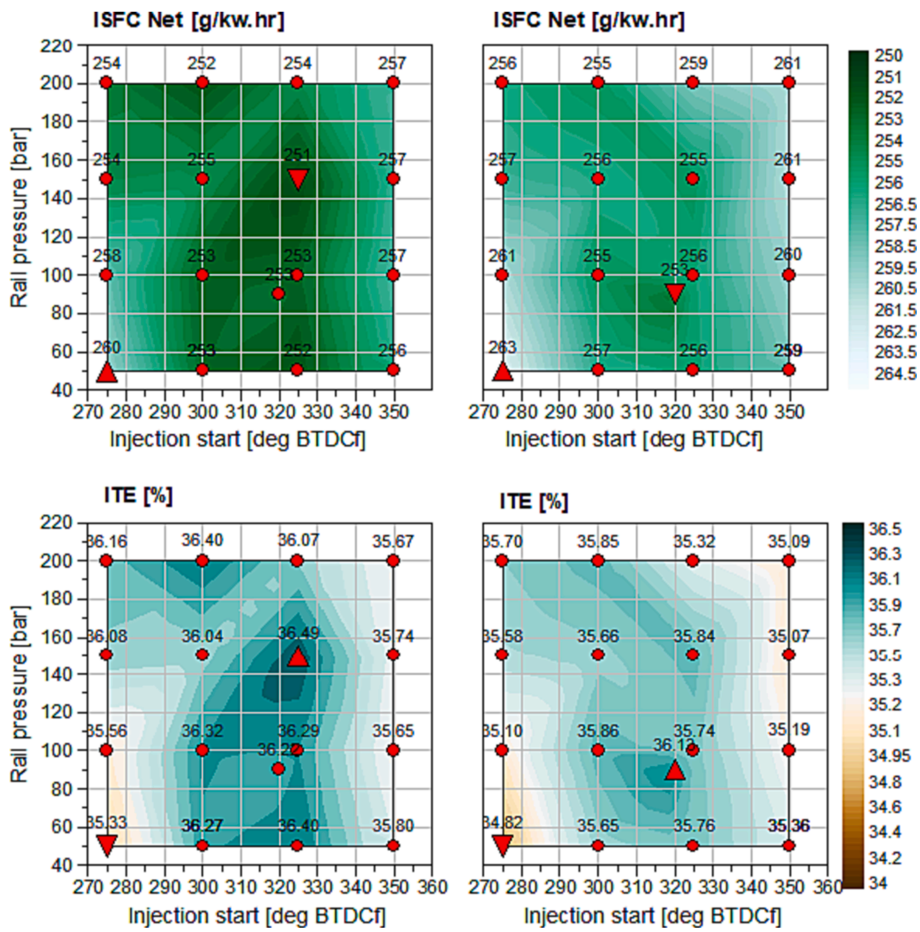

Fig. 11. ISFC and indicated brake thermal efficiency comparison for varying injection timing and pressure at 4.6 bar IMEP, 2000 rpm. Left column: 99 Bio E20 and right column: 95 Bio E20.

any variability in comparability, allowing for a precise analysis of the biofuel's effects on different loads. These tests were essential to evaluate the engine's characteristics at various loads and optimise all operational parameters for each load. In the second part of the study, the focus shifted towards investigating the impact of fuel injection pressure and the start of fuel injection timings. By examining these variables, the researchers aimed to understand their influence on engine performance and emissions. This analysis involved conducting low and high-load fuel matrix tests, which allowed for a detailed comparison between the two bio-gasolines. The objective was to analyse the effect of higher ethanol content and assess the performance profile of each bio-gasoline under varied injection angles and pressures. The low-load fuel matrix test was performed at an engine speed of 2000 RPM and an IMEP (Indicated Mean Effective Pressure) of 2.4 bar.

This configuration simulated average low-load operating conditions, enabling a comprehensive understanding of the engine's behaviour. Similarly, the high-load fuel matrix test was conducted at 16 bar IMEP and 3000 RPM to investigate the engine's performance and emission characteristics under different injection timings and pressures. Furthermore, the emissions were analysed over various operating conditions to study the effects of RON of bio-gasoline across various engine operation points. In all of the test conditions, both water and oil temperatures were maintained at a constant 90 °C, providing a stable environment for the investigation. Also, the intake air temperature was set to 40 °C with absolutely zero per cent humidity. These precise conditions ensured that the experiment's outcomes would be reliable and unaffected by external factors. Finally, all test limitations and setup points are summarised in Table 3 below.

Results and discussions

Beginning with comparing biofuels to fossil fuels in a lambda sweep test at 3000 rpm. Therefore, both biofuels at high and low fuel matrices were compared to comprehend the efficacy of each fuel across a broad range of operating conditions.

Assessment of Engine Performance and Emission Characteristics: Bio-fuels vs. Fossil Fuels at 3000 RPM

This experiment aims to assess both Bio-gasoline fuels in comparison to fossil fuels as a drop-in fuel. The test setup started by fixing the engine speed at 3000 rpm and keeping the cam profile fixed at each IMEP load to maintain the optimum cam overlaps. Moreover, to ensure the operational conditions are fixed for every testing point, the intake air system is equipped with an external heater with a PID controller to keep the temperature fixed at 40 degrees Celsius. Also, the injection pressure and angle have been fixed for all testing points, and the engine is running on closed lambda control at the stoichiometric in all testing points except when the exhaust temperature reaches the threshold temperature at a high load. Over-fueling strategies have to be introduced to cool down the exhaust.

Fig. 5 shows the main performance results of the load sweep from 2 bar IMEP to 28 bar IMEP. The thermal efficiency trend shows that the second-generation biofuels match with the fossil fuel. However, the comparative analysis indicated that 99 Bio E20 displayed slightly higher thermal efficiency compared to 95 Bio E20, particularly noticeable under high-load conditions. This advantage can be attributed to the higher knock resistance, resulting in advanced spark ignition timing

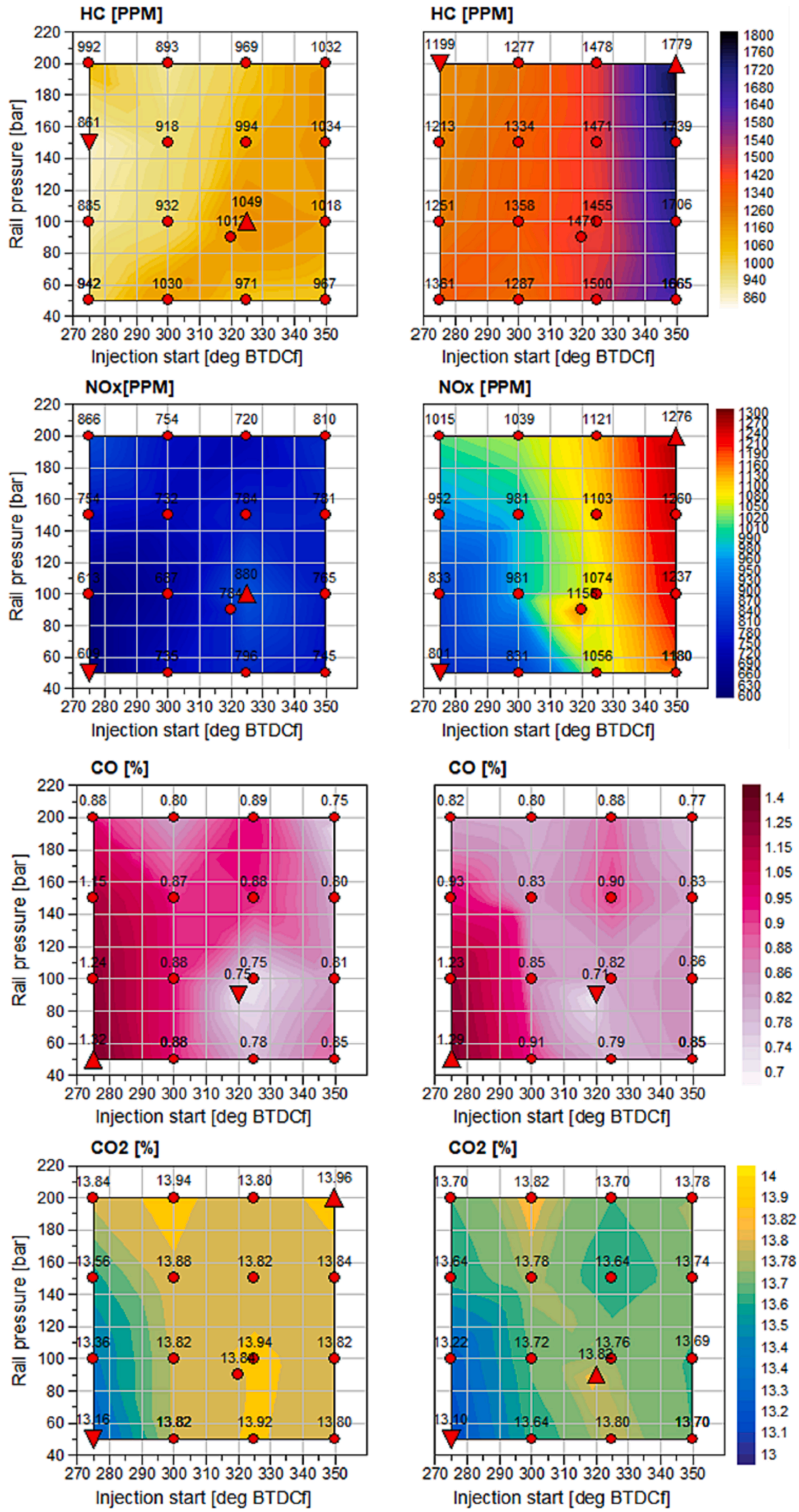

Fig. 12. engine-out emission analysis. THC, NO_x, CO and CO_2 comparison for varying injection timing and pressure at 4.6 bar IMEP, 2000 rpm. Left column: 99 Bio E20 and right column: 95 Bio E20.

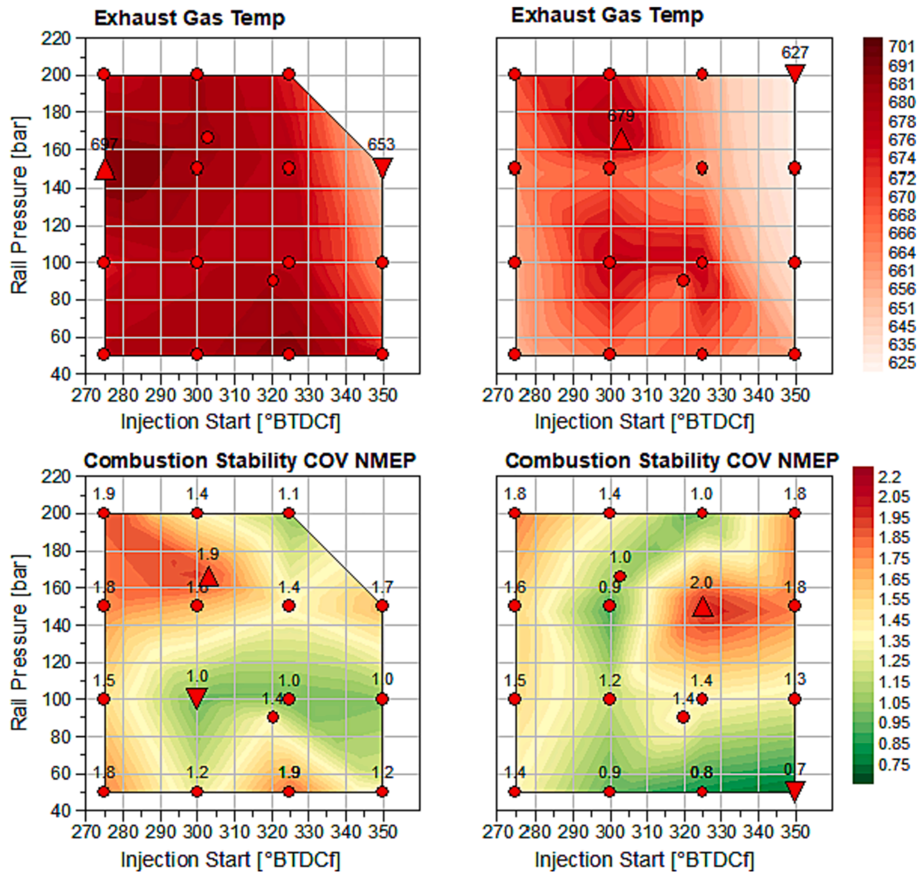

Fig. 13. Combustion phasing at high load operation (3000 rpm and 16 bar IMEP). Left column: 99 Bio E20, right column: 95 Bio E20.

without engine knock. This optimised spark timing, in turn, facilitated a modest yet discernible increase in thermal efficiency, especially during high-load engine operations.

Fig. 6 shows that the combustion was tuned to run at MBT, which is 8 degrees at 50 % burn. The spark timing started moving at load above 14 bar IMEP to mitigate the engine Knock. The knock intensity graph shows that the 99 octan number has a higher knock resistance than the 95 octan number, even though both have 20 % ethanol. The burn duration of the three fuels showed a similarity, as shown in Fig. 7. The time from start to 10 % burn has almost the same trend for every fuel. The 10 to 50 % burn duration graph shows the minimum burn duration at 14 bar due to running at the MBT before being forced to retard the spark timing to combat the Knock.

The emission results show the lambda value was kept constant up to 24 bar IMEP load; then, the rich mixture was introduced to cool down the exhaust pipe. As shown in Figure 8, 99 Bio E20 produced less NO_x emission than 95 Bio E20. CO and CO2 emissions almost have the same values for each fuel up to 24 bar IMEP. At higher loads, the variation of these emissions was mainly caused by the fuel-enriching strategies, as reflected by the lambda in Fig. 9.

Fig. 9 shows the unburned hydrocarbon emissions. The hydrocarbon emission has a slight offset as the biofuels contain a heavier chemical substance from the feedstock production process. The higher hydrocarbon can be mitigated in the tailpipe using advanced emission-captured methods such as positive crankcase ventilation or an evaporative emissions control system. However, the 99 Bio E20 shows less emissions compared to the 95 Bio E20 at the optimum operation conditions at each load. Finally, the lambda was varied from 24 IMEp to 28 IMEp as it is a function of the spark angle and the energy each fuel produces to maintain the exhaust temperature under 750 degrees Celsius.

The overall outcomes of the experimental test are Both biofuels are similar to fossil fuels in terms of performance and emissions. The Higher octane number biofuel has higher knock resistance than fossil fuel, leading to higher thermal efficiency at higher load due to spark advance ability.

The primary outcome of this experiment shows that both biofuels are suitable replacements as drop-in fuels as the critical combustion parameters, efficiency, and emissions are similar to the fossil fuel through the high octane 99 Bio E20 shows slightly better overall performance. In the next section, a fuel matrix study will be analysed at both low and high loads.

Optimisation of bio-gasoline at low-load operation

This experiment aimed to improve engine performance by meticulously exploring fuel injection variables for both bio-gasoline with varied research octane numbers for low-load operation. The start of injection was varied from 275 CA BTDC to 350 CA BTDC with a 25°CA interval, and the injection pressure was increased from 50 bar to 200 bar with a 50 bar increment at 4.6 bar IMEP and 2000 rpm. This section comprehensively analyses fuel's combustion, performance, and emission characteristics under different injection pressure conditions and timing for low-load engine operation.

Fig. 10 shows the combustion phasing and burn duration for 99 Bio E20 and 95 Bio E20 for different injection pressures and timing at 4.6 bar IMEP. It can be seen that both combustion phasing and combustion duration are identical for both fuels when the spark timing was kept at MBT. The combustion phasing, identified by the 50 % Mass Fraction Burned (50 % MFB), demonstrates a strikingly narrow range of variation, spanning a mere 7 to 9 crank angle degrees (CA). This observation stands steadfast despite fuel injection timing and pressures. Moreover,

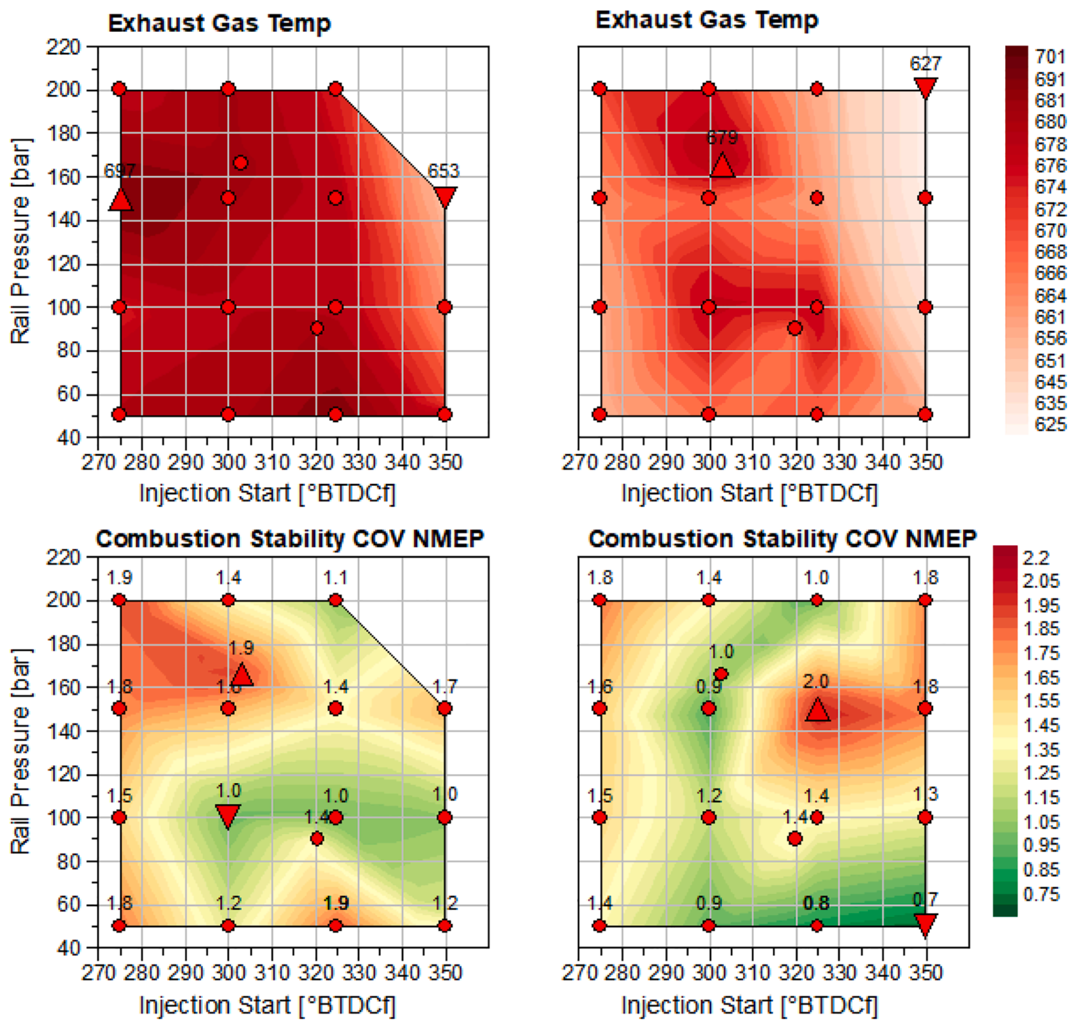

Fig. 14. Exhaust gas temperature and COV at 3000 rpm, 16 bar IMEP. Left column: 99 Bio E20, right column: 95 Bio E20.

the analysis of overall burn duration, using the 10–90 % Mass Fraction Burned (10–90 % MFB) metric, reveals minimal disparities between the two bio-gasoline variants. Notably, the most prolonged combustion duration was consistently observed at an injection timing of 300 CA BTDC for both fuels, regardless of the variation in injection pressure and RON. The combustion stability is shown in Fig. 10. Even during low-load operations, where maintaining stable combustion can sometimes be more challenging, 99 Bio E20 and 95 Bio E20 exhibit admirable stability. This stability is reflected in the COV values, which stay comfortably within the specified 3 % boundary. The proven combustion stability at low load conditions provides a strong case for considering both 99 Bio E20 and 95 Bio E20 as promising candidates for drop-in fuels in gasoline engines.

Fig. 11 presents essential engine performance parameters, such as Indicated Specific Fuel Consumption (ISFC) and Indicated Thermal Efficiency. Notably, both 99 Bio E20 and 95 Bio E20 exhibit nearly identical ISFC values, owing to their minimal difference in energy density. Interestingly, 99 Bio E20 demonstrates a slightly higher Indicated Thermal Efficiency compared to 95 Bio E20. Across a range of operating conditions, both fuels display higher efficiency when the injection commences between 300 and 325 degrees crank angle before top dead centre (CA BTDC). However, a noteworthy distinction arises in the optimal injection pressure range for achieving higher efficiency with each fuel. The image distinctly portrays a broader and more pronounced dark region for 99 Bio E20, as opposed to 95 Bio E20. This suggests that 99 Bio E20 can deliver enhanced efficiency over a broader range of injection pressures compared to 95 Bio E20. Overall, The variation of the thermal efficiency was low and within 1 % when the fuel injection pressure and the start of injection timings were changed significantly.

The engine-out emissions of both fuels for different injection conditions is shown in Fig. 12. It can be observed that 95 Bio E20 displays slightly higher hydrocarbon emissions compared to 99 Bio E20. This difference in HC emissions could be attributed to the composition or combustion characteristics of the fuels. The higher initial boiling point of 95 Bio E20 may hinder the fuel from vaporising effectively, resulting in increased HC emissions. Notably, when injection timing is advanced and injection pressure is increased, there is an observable rise in HC emissions. This trend indicates the possible contribution of the wall-wetting effect caused by fuel spray impingement on the piston top. Interestingly, employing a slightly delayed injection timing alongside low injection pressure reduces HC emissions for both fuels. This highlights the potential of a more conservative injection strategy to mitigate HC emissions by promoting more optimal combustion conditions. A higher NO_x emission was observed for 95 Bio E20 due to the higher diffusion burning than 99.

Bio E20. Furthermore, the figure illustrates that the lowest NO_x emissions are achieved with the most delayed injection timing (around 270 CA BTDC) coupled with low injection pressure. This outcome can be attributed to the combination of retarded combustion and lower combustion temperatures, which favourably influence NO_X emissions. Similar Carbon Monoxide (CO) and Carbon Dioxide (CO_2) emissions are observed for both fuels. The lowest CO and CO_2 emissions are noted at

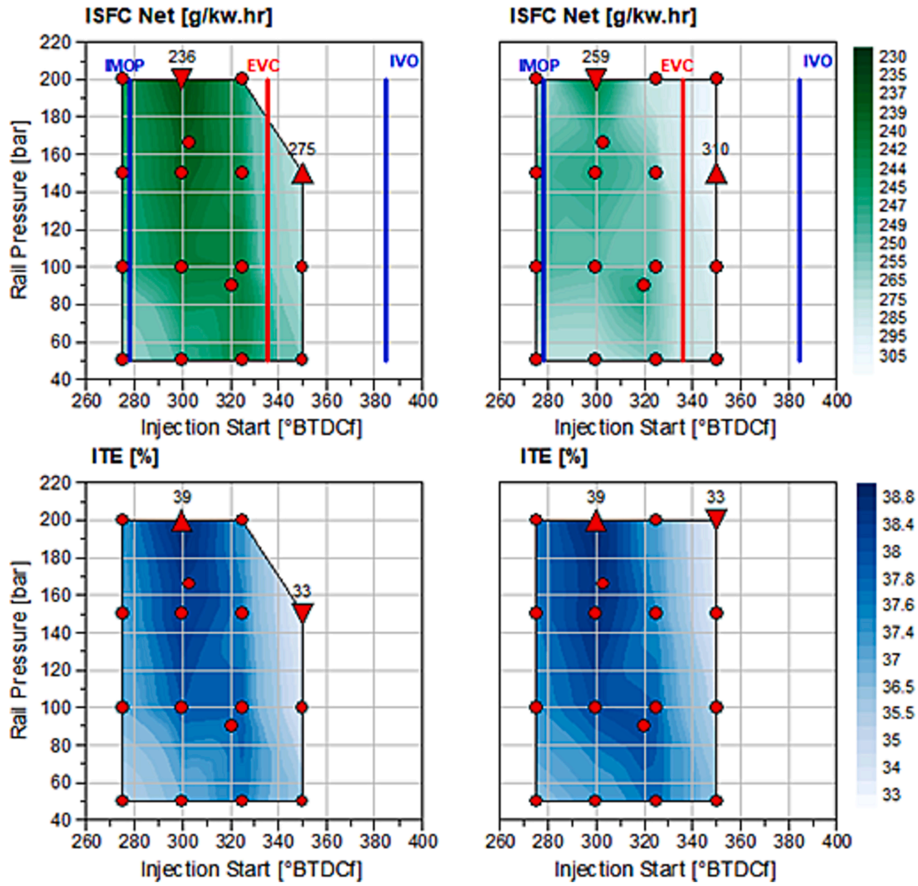

Fig. 15. ISFC and Indicated thermal efficiency at 3000 rpm, 16 bar IMEP. Left column: 99 Bio E20, right column: 95 Bio E20.

late injection points, with injection pressure exerting minimal influence on these emissions.

Optimisation of bio-gasoline at high-load operation

The low-load operation of the biofuel at various injection pressures and SOIs is covered in the previous section. The impact of fuel injection parameters on both biofuels when operating high loads will be covered in this section. To achieve this, the engine's operating parameters were adjusted to 3000 rpm, 16 bar IMEP, 50–200 bar of injection pressure, and 350–275 CA BTDC of SOI. The biofuel's combustion, performance, and emission characteristics were compared during this high-load engine operation.

Combustion phasing, which is represented by 50 % MFB and 10–90 % burn duration, is depicted in Fig. 13. The combustion phasing varies between 10 and 14 CA for both fuels. There was no significant difference between the fuels regarding combustion behaviour at high-load operation. Fig. 14 shows biofuel's exhaust gas temperature and cycle-to-cycle variation during the high-load operation. The exhaust gas temperature surges beyond the 600-degree Celsius threshold for both fuel variants due to the increased fuel mass undergoing combustion. A slightly elevated exhaust gas temperature was discerned for the 99 Bio E20 case. The cycle-to-cycle variation for both biofuels remains impressively contained within the 2 % range. This compelling observation substantiates the inherent stability of combustion across the various injection pressure and SOI configurations explored in this study. Such consistency underscores the robust nature of combustion, reinforcing the reliability of these biofuels under high-load operating conditions.

The detailed depiction of the Indicated Specific Fuel Consumption (ISFC) and Indicated Thermal Efficiency in the supplied Fig. 15 provides useful information. Both biofuels demonstrate similar fuel consumption patterns, translating into closely aligned efficiency trends due to their equivalent calorific values. Notably, the observed Indicated Thermal Efficiency peak is around 39 %. Maximum efficiency was recorded for both fuels when the SOI was at 300 CA BTDC, and the injection pressure varied between 100 and 200 bar. When injection begins during the valve overlapping period, higher fuel consumption and reduced efficiency are seen.

Different engine-out emissions are shown in Fig. 16. Significantly high THC emission was noted during the early start of the injection during this high-load operation. During this early injection, more fuel hit the piston top, creating a fuel film that is not mixing properly with the air and creating heavier hydrocarbon emissions for both fuels. HC emission shoots up beyond the analyser's measuring capability for 99 Bio E20 during early SOI and higher injection pressure. Due to the extremely high HC emission during SOI, 320–350, CA BTDC is inappropriate for high-load operation. The HC emission was reduced when the injection start was delayed, and the injection pressure was moderately increased. Lower NO_x emissions were detected even in that zone. Overall, the sweet working zone for emissions is between SOI 280–300 and injection pressure between 120 and 180 bar.

Conclusion

This study investigates the suitability of two novel biofuels (99 Bio E20 and 95 Bio E20) as a drop-in fuel in the spark ignition engine. Through comprehensive experimentation, this research scrutinises the combustion dynamics, performance metrics, and emission characteristics of these biofuels in comparison to a baseline fossil fuel at 3000 rpm and varying IMEP conditions. Furthermore, systematically varying injection parameters gained a deeper understanding of their response under low and high load circumstances. However, The transition

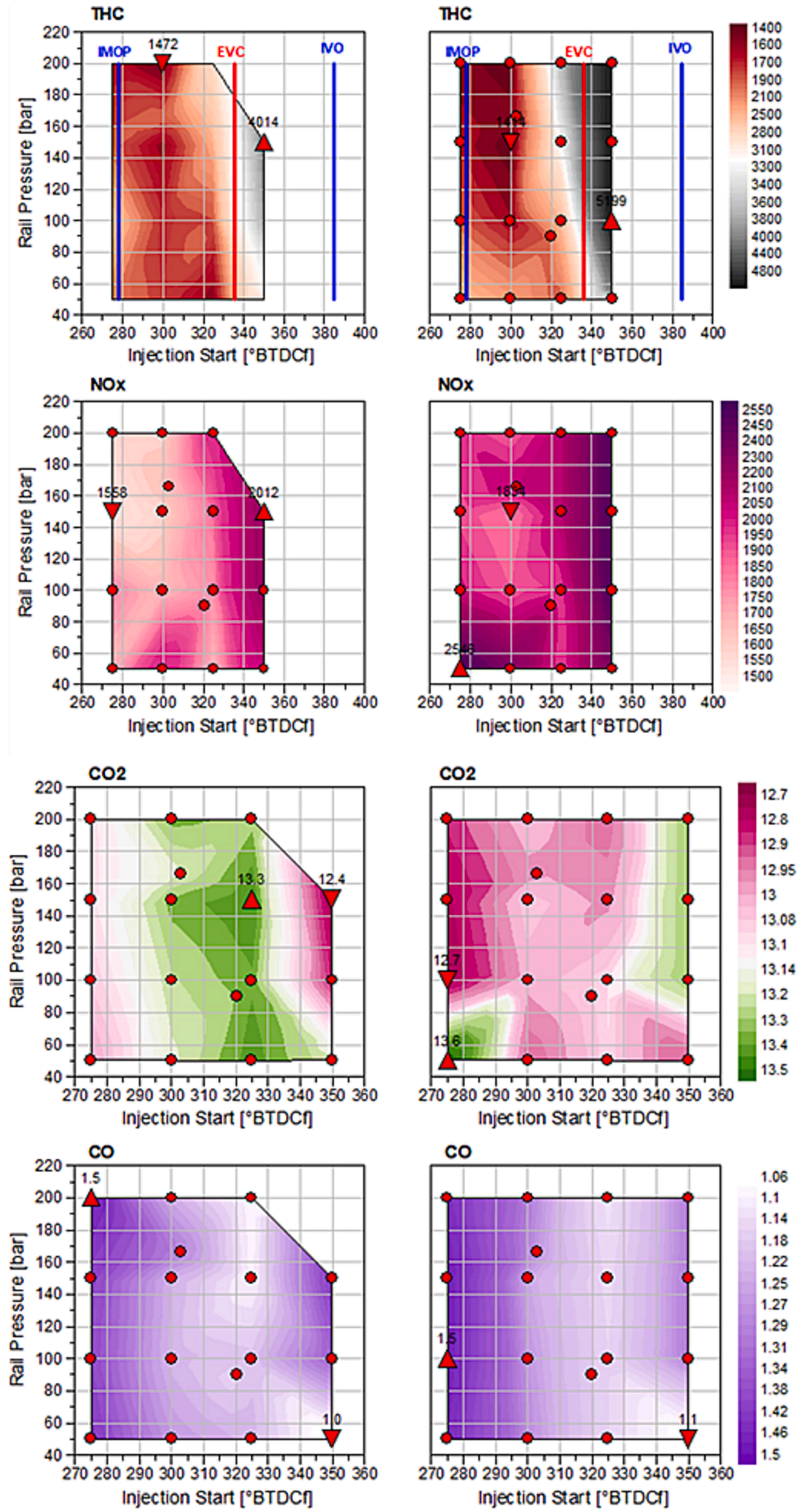

Fig. 16. ISFC and Indicated thermal efficiency at 3000 rpm, 16 bar IMEP.Left column: 99 Bio E20, right column: 95 Bio E20.

towards achieving biofuels that can directly replace petroleum fuels is laden with obstacles, but it offers significant prospects for attaining a sustainable energy future. Through research, innovation, and policy support, the scientific community can surmount technical, economic, and environmental limitations and enable the complete utilisation of biofuels in the worldwide energy framework. The following is a summary of the key findings.

At 3000 rpm and load sweep from 2 bar to 28 bar IMEP, the biofuel behaves similarly to the fossil fuel. This parity in performance indicates that the two fuels can be employed interchangeably across a range of operating conditions. Notably, the biofuel 99 Bio E20 demonstrated a slightly elevated thermal efficiency in contrast to the fossil fuel, particularly at high load conditions. Also, 99 Bio E20 shows higher knock resistance. It was observed that both biofuels displayed slightly higher hydrocarbon emissions compared to fossil fuels due to their chemical composition, which contains higher aromatics. Both fuels have similar emission behaviour to baseline fossil fuels except for high load conditions (above 24 bar IMEP) due to the rich combustion.

At low load operation, i.e 4 bar imep and 2000 rpm, both biofuels exhibited similar combustion phasing when the injection pressure was varied from 50 bar to 200 bar, and the SOI injection was varied from 350 CA BTDC to 275 CA BTDC. The 50 % MFB varies between 7 and 9 degrees CA under these various injection conditions. The most extended combustion was seen at SOI 300 CA BTDC at all injection pressures examined. When the injection pressure and SOI were changed, the variation in thermal efficiency was within 1 %. 99 Bio E20 has a wider operational regime during low-load operation than 95 Bio E20.

When the engine was operated at a high load, i.e. 16 bar at 3000 rpm, both biofuels had stable combustion, with combustion phasing ranging from 10 to 14 CA for both fuels at varied injection pressures and SOI. 99 Bio E20 has a little shorter burn time than 95 Bio E20. The exhaust gas temperature rose above 600 degrees during the high-load operation. Because of their comparable energy density, both fuels have similar fuel consumption. At SOI 300 CA and injection pressures ranging from 100 to 200 bar, the maximum recorded indicated thermal efficiency is roughly 39 %. Due to elevated HC emission, early SOI and higher injection pressure were not recommended for high-load operation.

Overall, this study demonstrated that, from a combustion, performance, and emission standpoint, bioderived gasoline fuel derived from 2nd generation feedstock has the potential to be used as a drop-in fuel in existing spark ignition engines with no hardware modifications. The study shows that Biofuels are essential for a zero-carbon future. However, sustainable biofuel production is crucial to ensure low-carbon alternatives to traditional fossil fuels while considering land use, water consumption, and biodiversity conservation. This approach maximises benefits while minimising trade-offs.

CRediT authorship contribution statement

Mohamed Mohamed: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Abinash Biswal:** Writing – review & editing, Writing – original draft, Formal analysis. **Xinyan Wang:** Writing – review & editing, Supervision. **Hua Zhao:** Writing – review & editing, Supervision. **Anthony Harrington:** Writing – review & editing. **Jonathan Hall:** Writing – review & editing, Resources, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mohamed Mohamed reports financial support was provided by Mahle Powertrain. Mohamed Mohamed reports a relationship with Brunel University London that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix

Table: Uncertainty in Measurements.

Measurement	Device	Manufacturer	Measurement range	Linearity/Accuracy
Engine speed	AC Dynamometers (Asynchronous)	Sierra Cp Engineering	0–6000 rpm	±1 rpm
Engine torque	AC Dynamometers (Asynchronous)	Sierra Cp Engineering	−50–500 nm	±0.25 % of FS
Clock Signal	EB582	Encoder Technology	0–25000 rpm	0.2 CAD
Intake air mass flow rate	F-106 AI	Bronkhust	4–200 kg/h	±0.2 % of reading
In-cylinder pressure	Piezoelectric pressure sensor Type 6125C	Kistler	0–30 MPa	≤±0.4 %
Intake pressure	Piezoresistive pressure sensor Type 4049A	Kistler	0–1 MPa	≤±0.5 %
Exhaust pressure	Piezoresistive pressure sensor Type 4049B	Kistler	0–1 MPa	≤±0.5 %
Oil pressure	PX309-10KGI	omega	0–0.8 MPa	<±0.2 %
Temperature	Thermocouple K Type	RS	233–1473 K	≤±2.5 K
Fuel injector current signal	Current probe PR30	LEM	0–20 A	±2 mA
PM emissions	DMS 500	Cambustion	0–5000 PPS	–
CO emissions	MEXA-584L	Horiba	0–12 vol%	≤±1.0 % of FS or ± 2.0 % of readings
CO_2 emissions	MEXA-584L	Horiba	0–20 vol%	≤±1.0 % of FS or ± 2.0 % of readings
O_2	MEXA-584L	Horiba	0–25 vol%	≤±1.0 % of FS or ± 2.0 % of readings
THC emissions	Rotork Analysis Model 523	Signal	0–5000 ppm	≤±1.0 % of FS or ± 2.0 % of readings
NO/NO_2 emissions	CLD 150 (Heated Chemiluminescence Detector)	Cambustion	0–500 ppm or 0–10 k ppm	≤±1.0 % of FS or ± 2.0 % of readings

References

[1] Tol RS. Europe's climate target for 2050: an assessment. Intereconomics 2021;56 (6):330–5.
[2] Strategy NZ. Build back greener. London, UK: HM Government; 2021.
[3] Aszódi A, et al. Comparative analysis of national energy strategies of 19 european countries in light of the green deal's objectives. Energy Conver Manage: X 2021;12: 100136. https://doi.org/10.1016/J.ECMX.2021.100136.
[4] ElFar OA, Chang CK, Leong HY, Peter AP, Chew KW, Show PL. Prospects of industry 5.0 in algae: customisation of production and new advance technology for

clean bioenergy generation. Energy Conver Manage: X 2021;10:100048. https://doi.org/10.1016/J.ECMX.2020.100048.
[5] Das TK, Kundu D. Feasibility and sensitivity analysis of a self-sustainable hybrid system: a case study of a mountainous region in Bangladesh. Energy Conver Manage: X 2023;20:100411. https://doi.org/10.1016/J.ECMX.2023.100411.
[6] Biswal A, Kale R, Teja GR, Banerjee S, Kolhe P, Balusamy S. An experimental and kinetic modeling study of gasoline/lemon peel oil blends for pfi engine. Fuel 2020;267:117189.
[7] Debnath D, Khanna M, Rajagopal D, Zilberman D. The future of biofuels in an electrifying global transportation sector: imperative, prospects and challenges. Appl Econ Perspect Policy 2019;41(4):563–82.
[8] Demirbas A. Progress and recent trends in biofuels. Prog Energy Combust Sci 2007;33(1):1–18.
[9] Subramaniam Y, Masron TA, Azman NHN. Biofuels, environmental sustainability, and food security: a review of 51 countries. Energy Res Soc Sci 2020;68:101549.
[10] Bhutto AW, Qureshi K, Abro R, Harijan K, Zhao Z, Bazmi AA, et al. Progress in the production of biomass-to-liquid biofuels to decarbonise the transport sector–prospects and challenges. RSC Adv 2016;6(38):32140–70.
[11] Elbaz AM, Wang S, Guiberti TF, Roberts WL. Review on the recent advances on ammonia combustion from the fundamentals to the applications. Fuel Communications 2022;10:100053.
[12] "The future of hydrogen,," *IEA, Paris*, June, 2019.
[13] Rocha MH, Capaz RS, Lora EES, Nogueira LAH, Leme MMV, Reno MLG, et al. Life cycle assessment (lca) for biofuels in brazilian conditions: a metaanalysis. Renew Sustain Energy Rev 2014;37:435–59.
[14] Pereira LG, Cavalett O, Bonomi A, Zhang Y, Warner E, Chum HL. Comparison of biofuel life-cycle ghg emissions assessment tools: the case studies of ethanol produced from sugarcane, corn, and wheat. Renew Sustain Energy Rev 2019;110:1–12.
[15] A. Harrington, J. Hall, M. Bassett, E. Lu, and H. Zhao, "Combustion characteristics and exhaust emissions of a direct injection si engine with pure ethanol and methanol in comparison to gasoline," tech. rep., SAE Technical Paper, 2022.
[16] Mayer M, Hofmann P, Geringer B, Williams J, Moss J. Influence of different fuel properties and gasoline-ethanol blends on low-speed pre-ignition in turbocharged direct injection spark ignition engines. SAE Int J Engines 2016;9(2):841–8.
[17] Yu X, Zhao Z, Huang Y, Shi W, Guo Z, Li Z, et al. Experimental study on the effects of egr on combustion and emission of an si engine with gasoline port injection plus ethanol direct injection. Fuel 2021;305:121421.
[18] K. Nithyanandan, H. Wu, M. Huo, and C.-F. Lee, "A preliminary investigation of the performance and emissions of a port-fuel injected si engine fueled with acetone-butanol-ethanol (abe) and gasoline," tech. rep., SAE Technical Paper, 2014.
[19] J. Hall, A. Harrington, A. Cooper, M. Bassett, N. Hiett, D. Richardson, A. Martens, and S. Sapsford, "Technical assessment of the feasibility of the use of bio-gasoline as a drop-in gasoline fossil fuel replacement," tech. rep., SAE Technical Paper, 2022.
[20] Inbanaathan PV, et al. Comprehensive study on using hydrogen-gasoline-ethanol blends as flexible fuels in an existing variable speed SI engine. Int J Hydrogen Energy 2023;48(99):39531–52. https://doi.org/10.1016/J.IJHYDENE.2023.03.107.
[21] Hoang AT, et al. Technological solutions for boosting hydrogen role in decarbonisation strategies and net-zero goals of world shipping: challenges and perspectives. Renew Sustain Energy Rev 2023;188:113790. https://doi.org/10.1016/J.RSER.2023.113790.
[22] Santhoh N, et al. Poultry fat biodiesel as a fuel substitute in diesel-ethanol blends for DI-CI engine: experimental, modeling and optimisation. Energy 2023;270:126826. https://doi.org/10.1016/J.ENERGY.2023.126826.
[23] Sharma P, et al. Using response surface methodology approach for optimising performance and emission parameters of diesel engine powered with ternary blend of solketal-biodiesel-diesel. Sustainable Energy Technol Assess 2022;52:102343. https://doi.org/10.1016/J.SETA.2022.102343.
[24] M. Mohamed, H. Zhao, A. Harrington, and J. Hall, "Experimental investigation of combustion characteristics, performance, and emissions of a spark ignition engine with 2 nd generation bio-gasoline and ethanol fuels," tech. rep., SAE Technical Paper, 2023.
[25] Peralta-Yahya PP, Keasling JD. Advanced biofuel production in microbes. Biotechnol J 2010;5(2):147–62.
[26] Giampietro M, Ulgiati S, Pimentel D. Feasibility of largescale biofuel production. Bioscience 1997;47(9):587–600.
[27] F. Contino, F. Foucher, F. Halter, G. Dayma, P. Dagaut, and C. Mounaïm-Rousselle, "Engine performances and emissions of second-generation biofuels in spark ignition engines: The case of methyl and ethyl valerates," tech. rep., SAE Technical Paper, 2013.
[28] Atabani AE, Silitonga AS, Badruddin IA, Mahlia T, Masjuki H, Mekhilef S. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. Renew Sustain Energy Rev 2012;16(4):2070–93.
[29] A. H. Hirani, N. Javed, M. Asif, S. K. Basu, and A. Kumar, "A review on first-and second-generation biofuel productions," *Biofuels: greenhouse gas mitigation and global warming: next generation biofuels and role of biotechnology*, pp. 141–154, 2018.
[30] K. Nakata, D. Uchida, A. Ota, S. Utsumi, and K. Kawatake, "The impact of ron on si engine thermal efficiency," tech. rep., SAE Technical Paper, 2007.
[31] A. Hoth, C. P. Kolodziej, T. Rockstroh, and T. Wallner, "Combustion characteristics of prf and tsf ethanol blends with ron 98 in an instrumented cfr engine," tech. rep., SAE Technical Paper, 2018.
[32] Teoh YH, How HG, Yu KH, Chuah HG, Yin WL. Influence of octane number rating on performance, emission and combustion characteristics in spark ignition engine. J Adv Res Fluid Mech Thermal Sci 2018;45(1):22–34.
[33] "Are biofuels and e-fuels the only sustainable solution to power our existing fleet of internal combustion engines? - Coryton." https://coryton.com/latest/are-biofuels-and-e-fuels-the-only-sustainable-solution-to-power-our-existing-fleet-of-internal-combustion-engines/ (accessed Sep. 30, 2022).
[34] The Opportunity For Sustainable Fuels In High-Performance Engines - Coryton." https://coryton.com/latest/the-opportunity-for-sustainable-fuels-in-high-performance-engines/ (accessed Sep. 30, 2022).
[35] Chapman E, Winston-Galant M, Geng P, Latigo R, Boehman A. Alternative fuel property correlations to the Honda particulate matter index (PMI). SAE Tech Pap 2016;2016. https://doi.org/10.4271/2016-01-2250.