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ENERGY, ENVIRONMENT AND GREEN TECHNOLOGIES FOR THE FUTURE SUSTAINABILITY

Investigation of combustion and emission characteristics of an SI engine operated with compressed biomethane gas, and alcohols

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Abstract

Alternative fuels in spark-ignition engines significantly reduce engine exhaust emissions and improve fuel efficiency. This research investigates the performance of a multicylinder SI engine using 10%, 20% (ethanol, methanol, methyl acetate), and 100% compressed biomethane gas (CBG) as alternative fuels. Engine performance parameters (BTE, ITE, ME, BP), BSFC, ISFC, FF, combustion phenomenon (cylinder pressure, crank angle, cylinder volume, mass fraction burned, net heat release, mean gas temperature, cumulative heat release, rate of pressure rise), and emission characteristics (HC, CO, CO_2, NOx) are measured. CBG achieved a maximum BTE of 23.33% compared to all other fuels. Minimum fuel consumption rate of 1.72 kg/h at maximum rpm achieved BSFC value of 0.44 kg/kWh and ISFC value of 0.261 kg/kWh. The highest cylinder pressure of 6.79 bar was achieved in the G90M10 with a cylinder volume of 48.58 cc. NHR of 3.08 j/deg was found in the G80M20 at a crank angle of 376°, and the maximum MGT was 390.20 °C in the G80E20. The highest CHR values of 0.12 kJ at crank angles of 432°, 420°, 422°, and 427° were achieved in the G100, CBG, G80E20, and G90E10. G90M10 reached a maximum value of 0.14 bar/degree of rate of pressure rise at a crank angle of 374°. Average minimum emission gas was found in CBG at a minimum and maximum RPM, indicating that CBG gives the best emission result with engine performance compared to all alternative fuels.

Keywords Alcohols · Engine performance · CBG, Emission · Biogas

Abbreviations

BTE	Brake thermal efficiency
ITE	Indicated thermal efficiency
ME	Mechanical efficiency
BG	Biogas
CBG	Compressed biomethane gas
MGT	Mean gas temperature
MFB	Mass fraction burned
BSFC	Brake specific fuel consumption
ISFC	Indicated specific fuel consumption
FF	Fluid flow
CR	Compression ratio
SOB	Start of burning
EOB	End of burning
NHR	Net heat release
CHR	Cumulative heat release
RPR	Rate of pressure rise
TDC	Top dead center
G100	Pure gasoline fuel
G90E10	90% Gasoline 10% ethanol
G80E20	80% Gasoline 20% ethanol
G90M10	90% Gasoline 10% methanol
G80M20	80% Gasoline 20% methanol
G90MA10	90% Gasoline 10% methyl acetate
G80MA20	80% Gasoline 20% methyl acetate

Introduction

The global economy has weakened following COVID-19. To compensate, gasoline and diesel prices steadily rise in practically all emerging countries. Due to the energy crisis, global warming, high fossil fuel costs, and rigorous emission rules,

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renewable oxygenated fuels have received greater attention in recent decades (Awad et al. 2018a), (Gülüm and Bilgin 2018). So, the globe is transitioning to a sustainable energy period, focusing on energy efficiency and renewable energy sources (Chauhan et al. 2010). In reality, fossil fuels remain the primary source of global energy, with global energy consumption expected to climb by around 33% by 2050 (Hosseini and Wahid 2013), (Saidur et al. 2011). In recent years, the hunt for alternative fuels that offer a harmonious relationship with sustainable development, energy-saving, efficiency, and environmental protection has intensified. Biofuels have the potential to provide a viable solution to the global petroleum dilemma. Automobiles that run on gasoline or diesel also substantially contribute to greenhouse gas emissions. Furthermore, the increasing number of circulating diesel and petrol cars accounts for roughly 20% of global greenhouse gas (GHG) emissions (Iodice et al. 2016), (Rajesh Kumar and Saravanan 2016). Energy policy, planning, and associated issues have become a significant public agenda item in most industrialized and developing countries in recent years. As a result, governments support using alternative fuels in automobile engines. Several alternative fuels, such as gasoline and diesel with natural gas (CNG/CBG), ethanol, methanol, methyl acetate, butanol, and hexanol, have been judged acceptable and cost-effective alternatives for conventional fuels based on these criteria. Because of their excellent physicochemical qualities, ethanol, methanol, butanol, methyl acetate, and other alcohols are essential renewable fuels when blended with pure gasoline among the renewable energies available for spark-ignition (SI) engines (Awad et al. 2018b).

"Some of the experimental studies are as follows: Four-stroke spark-ignition engine, the effects of ethyl alcohol blended fuel with different blending ratios (10, 20, and 30% by volume) on engine performance and exhaust emissions were explored, and the results showed that combining ethanol with gasoline improves BTE and BSFC and lowers exhaust gas temperature, as well as lower CO and HC exhaust emissions, while NOx emissions are higher" (Vivek Pandey and Gupta 2016). As ethanol blends were utilized in lower quantities, engine torque increased by 2.31–4.16%, and BP increased by 0.29–4.77%, while BSFC increased when the ethanol percentage grew from 5.17 to 56.0% (Thakur et al. 2017). "Methanol (M5, M7.5, M10, M12.5, M15) was tested for the performance and combustion characteristics of a four-cylinder, four-stroke, spark-ignition engine (SI). According to the experiments' results, adding methanol enhanced the engine's performance. It was also discovered that increasing methanol concentration lowered CO and HC emissions while increasing CO_2 and NOx emissions" (Shayan et al. 2011). In terms of methanol mixtures (0–15%), there has been a rise in gasoline octane rating, an increase in BTE and ITE, and a drop in knocking (Mallikarjun and Mamilla 2009). "When the compression ratio for the methanol/gasoline blend was increased from CR8 to CR10, the peak pressure and NHR value increased by 27.5% and 30%, respectively, at a speed of 1600 rpm. At a compression ratio of 10:1, the performance results demonstrate a good agreement of improvisation with a 25% rise in BTE and a 19% reduction in BSFC. CO and HC emissions were reduced by 30–40% at a more excellent compression ratio of 10:1, and the same trend was detected at all speeds; however, NOx emissions rose with increasing CR" (Nuthan Prasad et al. 2020), (Jhalani et al. 2021). "At varied loads of 104, 207, 311, and 414 kPa, methyl acetate is used in a single-cylinder spark-ignition engine, which is fueled with base gasoline, M5 (95% base gasoline + 5% methyl acetate), and M10 (90% base gasoline + 10% methyl acetate). According to these findings, adding methyl acetate to base gasoline boosts BSFC while lowering the engine's BTE. Additionally, it was discovered that while methyl acetate does not significantly influence HC emissions, it did reduce CO and increase CO_2. Adding methyl acetate to the NOx data showed a significant increase in NOx emissions" (Cakmak et al. 2018).

Biogas (BG), also known as an alternative or renewable fuel, has been recommended to solve the problem since it has numerous advantages over natural gas, often utilized as a car fuel. BG is mainly a mixture of CH_4 and CO_2 and other gases formed in anaerobic conditions. Both agricultural and industrial wastes can be used to make BG (Holm-Nielsen et al. 2009), (Pradeep Kumar Meena and Sumit Sharma 2022). Removing CO_2 and H_2S from raw biogas and compressing pure biogas at high pressure can be used in the automobile sector and power generation (Larsson et al. 2016). Because CBG possesses qualities similar to CNG, biogas has a great potential to replace natural gas (Subramanian et al. 2013). Furthermore, biomethane might be compressed into a fuel tank as CBG for transportation fuel in a CNG vehicle, which is easy to store and reduces transportation expenses (D. Deublein 2008). "CBG was utilized in a multicylinder engine compared to CNG at 50% maximum load and engine speed (1500–3500 rpm). Results suggest that the engine run with CBG has higher thermal efficiency and reduced NOx and HC emissions. As a result, CBG fuel can replace CNG in spark-ignition engines as an alternate fuel" (Limpachoti and Theinnoi 2021).

Many researchers have worked on alcohol fuels, but very little research has shown the effects of ethanol, methanol, and methyl acetate alcohols on engine performance and emissions. This research has used three types of alcohol fuels: ethanol, methanol, and methyl acetate mixed with 10% and 20% gasoline fuels and 100% CBG. So, here is a comparison of the performance and emission parameters of the multicylinder SI engine using four alternate fuels.

Material and method

Fuels properties

In this experimental process, three types of alcohol blends of ethanol, methanol, and methyl acetate have been used with gasoline fuel, which is pure fuel up to 98–99%. It is a volatile, colorless liquid with a distinct aroma and flavor resembling alcohol. And by making BG from solid organic waste (fruit, vegetable wastes) and removing CO_2 and H_2S composition, pure biogas is compressed at 200 bar pressure and filled in a high-pressure bar cylinder. Different fuel properties of these fuels are given in Table 1.

Experimental setup

Experimental setup used is a Maruti Wagon R with a maximum power of 47.70 kW @ 6200 rpm. It is a four-cylinder, four-stroke, variable speed, water-cooled, and petrol engine, whose details are given in Table 2. Various alcohols such as ethanol, methanol, and methyl acetate have been tested by mixing 10% and 20% (G90E10, G80E20, G90M10, G80M20, G90MA10, G80MA80) with gasoline. Gasoline and alcohol blend readings were taken in a burette tube at an interval of 60 s. Experiment data has been taken by setting the load from the dynamometer to 4 kg and varying the speed from 2000 to 4500 rpm. And pure CBG has also been studied on the same parameters. Using CO_2 and H_2S scrubbers to purify the raw biogas, pure biogas, i.e., up to 96.6% CH_4, is obtained, whose composition is checked with a biogas analyzer.

For use, the CBG is fed into a high-pressure cylinder using a compressor. For safety features, a gas stop valve, pressure gauge, gas conversion kit, and gas filter have also been installed, which are shown in Fig. 1b. During the experiment, water is supplied from cooling waters used to cool the engine setup, whose flow is adjusted by rotameters. Compression studies of gasoline, alcohol blends, and CBG fuels have been performed. The resulting combustion parameters include cylinder pressure, rate of pressure rise, mass fraction burned, pressure volume, net heat release, mean gas temperature, and cumulative heat release. Thermal efficiencies, BSFC, ISFC, etc., have been studied in performance parameters. All experimental data was saved from the NI unit to the computer with the help of IC Engine software, shown in Fig. 1a. Apparatus used for studying these fuel blends and the different properties of CBG are given in Table 1. CO_2, CO, HC, and NO_X gases from the AVL emission apparatus were also checked (Table 3).

Table 2 Details of experimental setup

Engine specification	Details
Stroke length	72.00 (mm)
Cylinder bore	68.50 (mm)
Connecting rod length	112.50 (mm)
Compression ratio	9.2:1
Swept volume	265.34 (cc)
Engine type	Maruti Wagon R 4 strokes 4 cylinders
No. of cylinders	4
Maximum power output at 6200 rpm	47.70 kW
Cooling system	Water cooling close system
Orifice diameter	40 mm
Dynamometer arm length	210 mm
Fuel pipe diameter	33.90 mm
Number of cycles	10

Table 1 Fuel properties (ethanol, methanol, methyl acetate, and CBG)

Fuel properties	Unit	G100%	E10%	E20%	M10%	M20%	MA10%	MA20%	CBG
Chemical formula	-	C_5-C_{12}	C_2H_5OH	C_2H_5OH	CH_3OH	CH_3OH	$C_3H_6O_2$	$C_3H_6O_2$	CH_4
Density at 40 °C	kg/m^3	721	734	735	723	736	737	757	0.90
Lower heating value	MJ/kg	44	42.38	40.76	41.59	39.18	41.75	39.5	48.5
RON	-	94.5	96.3	98.5	97.1	98.8	99.5	107.5	127
MON	-	84.3	84.5	86.2	84.2	86.1	97.3	104.8	119
Stoichiometric air/fuel ratio	-	14.8	14.3	13.5	14.1	13.3	13.9	13.1	17.2
Reid vapor pressure at 38 °C	-	55.7	56.3	57.1	94.5	95.8	54.2	52.7	-
Flash point °C	-	26.3	30.5	29.8	28.2	27.5	21.5	18.1	-
Fire point °C	-	25.1	28.9	29.7	29.9	31.5	28.3	31.48	-
Methane (CH_4)	%	-	-	-	-	-	-	-	96.6
Hydrogen sulfide (H_2S)	%	-	-	-	-	-	-	-	0.0 ppm
O_2	%	-	-	-	-	-	-	-	0.4
CO_2	%	-	-	-	-	-	-	-	3.0

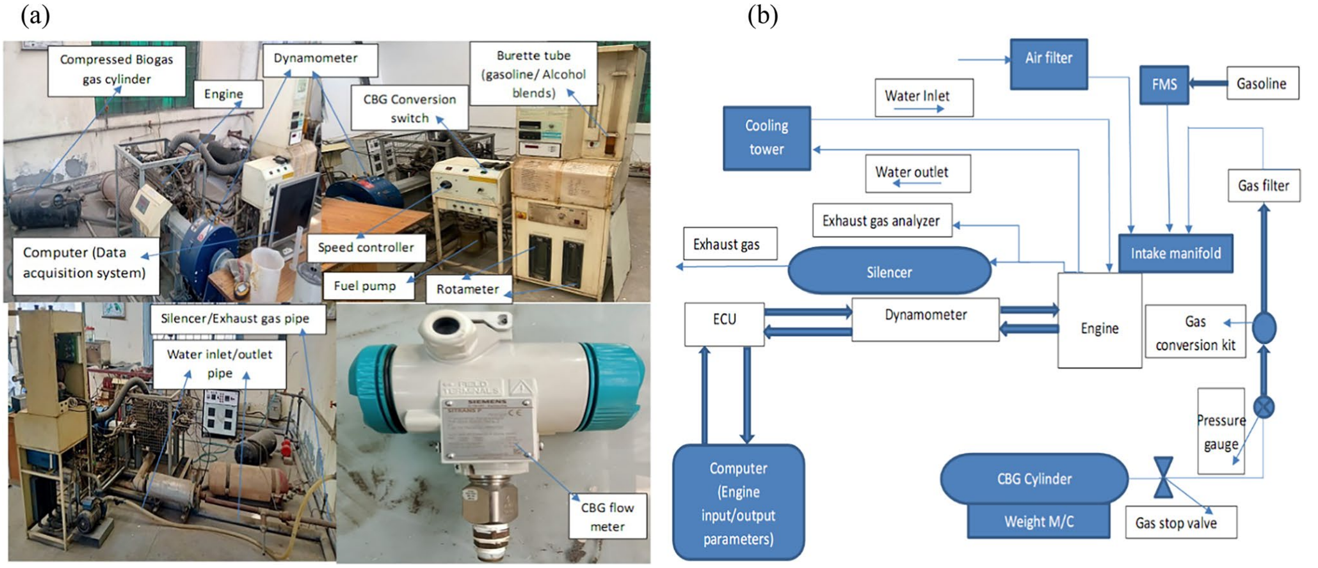

Fig. 1 **a** Experimental setup with parameters measuring instruments. **b** Schematic diagram of experimental setup

Table 3 Apparatus used during experiment

Apparatus	Name of the company
Biogas analyzer	OX-300B, Nunes Instruments
Biogas compressor	Italy tech
Viscometer	Anton Paar
Junkers calorimeter	H. L. Scientific Industries
Emission gas analyzer	AVL

Results and discussion

Engine parameters have been studied at 4 kg constant load and different speeds. Given below are various parameters such as engine performance (BP, BTE, ITE, ME), BSFC, ISFC, FF, and combustion phenomena (cylinder pressure, crank angle, crank angle, cylinder volume, mass fraction burned, NHR, mean gas temperature, cumulative heat release, rate of pressure rise) and emission parameters (HC, CO, CO_2, NO_X) have been studied.

Engine performance

Figure 2a shows that at a constant load of 4 kg, the engine speed was 2000 rpm, and the brake power value was 1.73 kW; at that time, the highest brake thermal efficiency of 23.33% CBG was achieved. Compared to gasoline, CBG has a higher octane rating and more excellent knock resistance. CBG burns more efficiently than gasoline or diesel, and very little of it remains unburned. As a result, engines designed explicitly for CBG have more excellent compression ratios and hence higher stated efficiency. BTE of CBG from a minimum rpm of 2000 to a maximum rpm of 4500 was superior than the other fuels. G100 fuel had a BTE value of 21.76% at 2000 rpm, and the highest BTE value of 17.28% in the alcohol fuel was obtained in the G80E20, and the lowest value was 13.25% in the G90M10. At a maximum of 4500 rpm, the BTE value of CBG was 16.76%, 15.63% for G100, and 14.69% for G90M20. Alternative fuels G90M20, G80MA20, and CBG have BTE values higher than the G100 at 2500 and 3000 rpm, meaning all these alternative fuels have the potential to replace gasoline fuels. Similarly, in a study, BTE values of G90E10 and G80E20 and G70E30 blends in a four-stroke engine at 2000 to 3000 rpm were found to be 16.2%, 18.9%, and 21.2% (Vivek Pandey and Gupta 2016). The BTE value of methanol blend G88M12% is achieved at 18.5% at 2000 rpm, 21.5% at 2500 rpm, and 23.5% at 3000 rpm (Mohammed Kamil and Ibrahim Thamer Nazzal 2016). G90MA10 blend at constant 1500 rpm has achieved BTE values ranging from 10 to 28% at effective pressure (104 to 414 kPa) (Cakmak et al. 2018).

Figure 2b shows that at 2000 rpm, the maximum value of ITE was achieved at 48.52% in G100, 38.65% in alcoholic fuel (G80E20), and 31.09% in CBG. CBG has a higher calorific value than gasoline and alcohol fuel, and the fuel flow rate is also higher at minimum rpm and constant load. Hence, the value of ITE at low speed was lower in CBG. At a maximum of 4500 rpm, the highest ITE value was obtained in CBG at 28.35%, G100 gained 17.8%, and the ITE value in the alcohol fuel (G90M20) was reached at 16.64%. As the rpm increases from 2000 to 4500, the value of ITE decreases in G100 and other alcohol blends, but the value of ITE in CBG has increased compared to other fuels. At higher speeds, CBG consumes

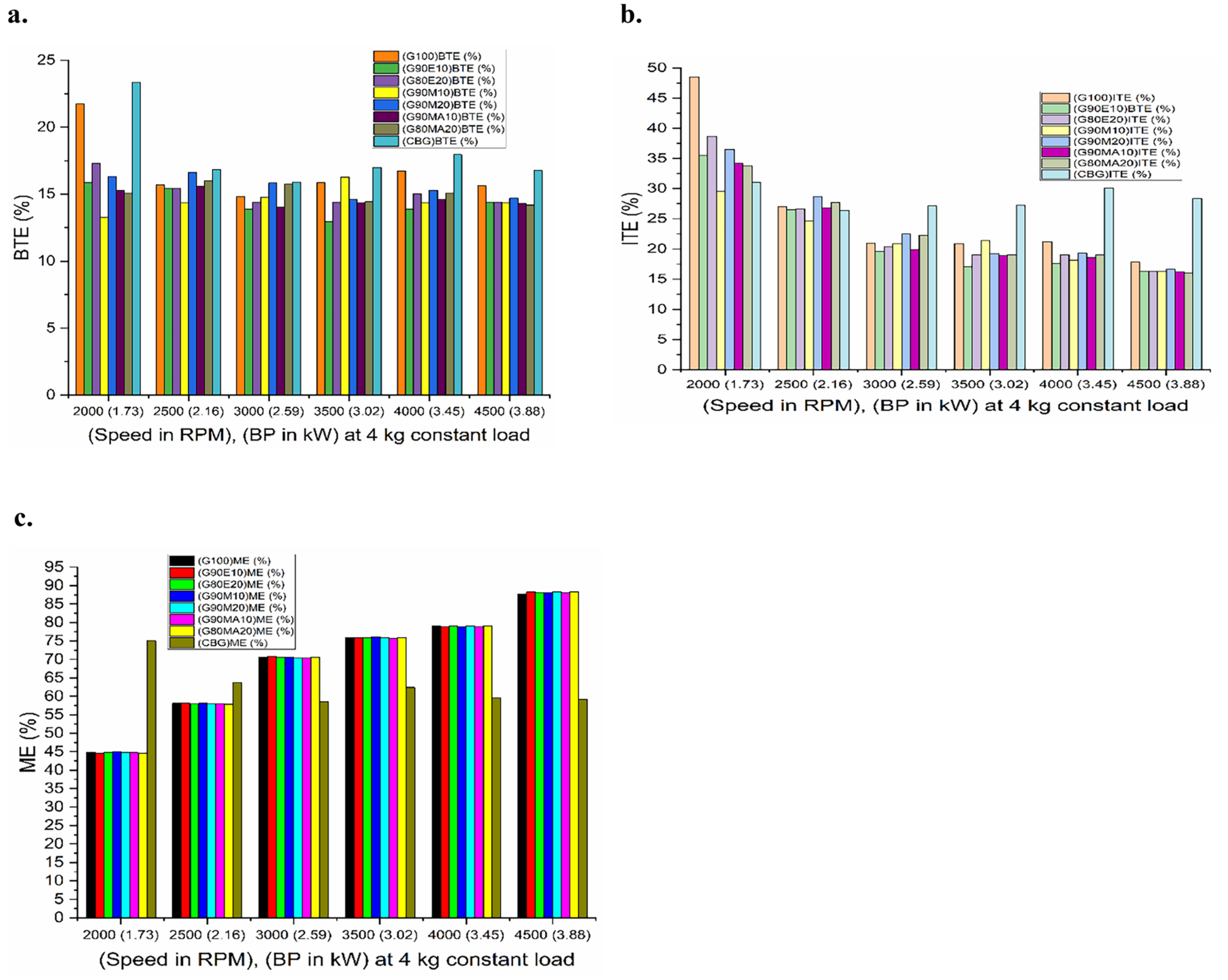

Fig. 2 **a** Brake thermal efficiency, brake power varies w.r.t Speed. **b** Indicated thermal efficiency, brake power varies w.r.t speed. **c** Mechanical efficiency, brake power varies w.r.t speed

less fuel rate than other fuels, due to which the value of ITE was found to be higher in CBG at higher speed. In Fig. 2c, CBG has less friction loss at low rpm than other fuels, and the difference between indicated power and brake power is less. Hence, the value of ME (75.04%) at low rpm was found to be higher in CBG. And as the speed increases, the friction loss also increases in CBG, so the ME value is found to be less at higher rpm than in other fuels. In contrast, the friction loss in gasoline and alcohol blends decreases, so the ME value was lower in CBG and higher in gasoline and alcohol blends.

Brake specific fuel consumption (BSFC) and indicated specific fuel consumption (ISFC)

Figure 3a shows that in the alcohol G90M10, the highest FF value was obtained at 1.13 kg/h at 2000 rpm, and the G100 value was 0.65 kg/h. The lowest FF value at the lowest rpm was 0.88 kg/h and 0.55 kg/h in G80E20 blends and CBG, respectively. Fuel ITE with a higher flow rate will have higher BSFC and lower BTE value. In BSFC at 2000 rpm, G100 found 0.38 kg/kWh; the lowest BSFC value in the alcohol blend was 0.51 kg/kWh in the G80E20 and the highest at 0.97 kg/kWh in the G90MA10. A value of 0.32 kg/kWh was achieved in CBG, the lowest value among all the fuels overall, due to which the BTE value of CBG was achieved the highest. At the maximum rpm, i.e., at 4500 rpm, the value of FF in the G100 is 2.03 kg/h. The lowest value of 2.29 kg/h in alcohol blends is found in G90E10, and the highest is 2.5 kg/h in G80MA20. FF in the CBG value is obtained at 1.72 kg/h, which is the lowest compared to other fuels. At same rpm, the BSFC in CBG was 0.44 kg/kWh, while the G100 got 0.52 kg/kWh and G90M10 and G90MA10 got 0.6 kg/kWh. CBG consumes

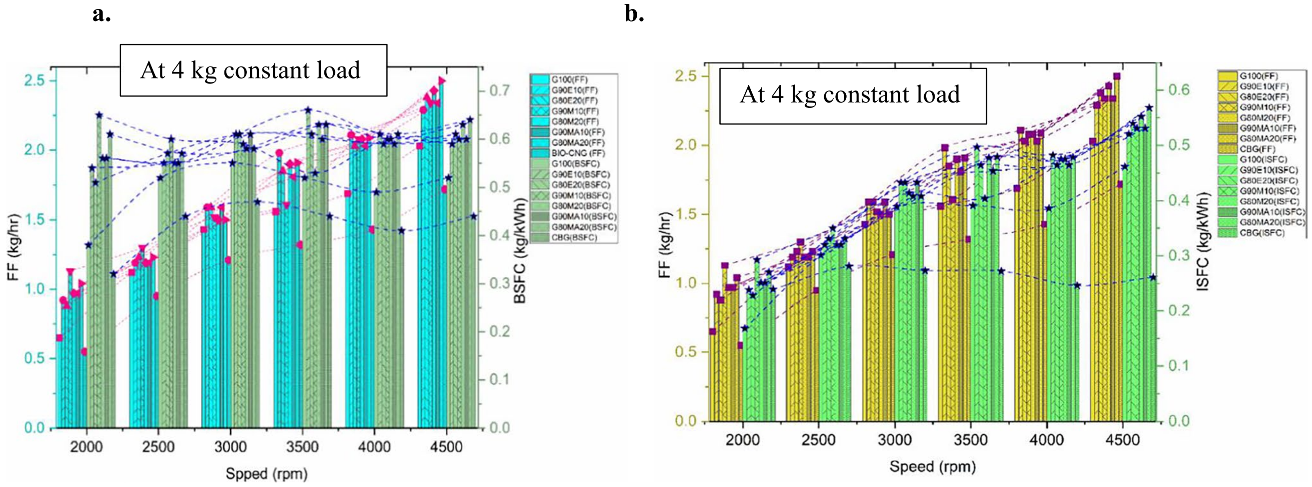

Fig. 3 **a** Fluid flow, brake specific fuel consumption varies w.r.t speed. **b** Fluid flow, indicated specific fuel consumption varies w.r.t speed

less fuel than other fuels at higher engine speeds, thereby increasing the engine's efficiency. Gasoline, G90E10, and G80E20 at 2000 to 2500 rpm have BSFC values in the range of 0.375 to 0.4 kg/kWh. As the RPM increases, the value of BSFC will also increase to a limit (Vivek Pandey and Gupta 2016). The BSFC value in G88M12 blends from 2000 to 3000 rpm has been found in the range of 0.42 to 0.4 kg/kWh (Mohammed Kamil and Ibrahim Thamer Nazzal 2016). At constant 1500 rpm and brake mean effective pressure (104 to 414 kPa), the MA5 and MA10 have obtained BSFC values between 0.9 and 0.3 kg/kWh (Cakmak et al. 2018).

In Fig. 3b, the ISFC value in the G100 was achieved at the minimum speed, i.e., 0.168 kg/kWh at 2000 rpm. Among alcoholic fuels, the IFSC was found to be 0.293 kg/kWh at the highest FF value in G90M10. The IFSC value of 0.228 kg/kWh was obtained in G80E20 at the lowest value of FF. CBG had the lowest value of FF compared to other fuels, while IFSC had a value of 0.239 kg/kWh. IFSC value at 4500 rpm in G100 was found to be 0.461 kg/kWh. In alcohol fuel G80MA20, the IFSC value was found to be 0.568 kg/kWh at the maximum FF value. IFSC value of 0.261 kg/kWh in CBG at maximum rpm was obtained, which was the lowest fuel consumption among all the fuels.

Combustion phenomenon

Figure 4a shows the start of burning (SOB) fuel in G100 and alcohol fuel when cylinder pressure is between 3 and 4 bar, and the crank angle is 335° before TDC. In CBG, SOB starts when cylinder pressure is 4.25 bar, and crank angle is 335° before TDC.

Experimental setup for CBG testing is started on gasoline fuel; when the engine cylinder pressure reaches 4 bar, SOB is started on CBG fuel. So, in gasoline and alcohol blends, the SOB starts above 3 bar pressure, while in CBG, the SOB starts above 4 bar pressure. The SOB of a 100% gasoline and all alcohol mixture is started between 3 and 4 bar/335°. Whereas in the case of CBG, it began at 4.25 bar/335°, as the engine has to run at a higher speed than pure gasoline before running on CBG fuel, the cylinder pressure value also increased in the case of CBG. Cylinder pressure is calculated by taking an average of 10 cycles for each fuel. Ten percent fuel burn in all fuels starts just after TDC when cylinder pressure is 6 to 6.5 bar at a crank angle of 375°, and 90% fuel burn occurs in all fuels when cylinder pressure is 5 to 5.75 bar, and the crank angle is 415°. Maximum cylinder pressure was up to 6.79 and 6.76 bar, respectively, in the G90M10 and G90M20, and the lowest cylinder pressure achieved was 5.54 bar in the G80MA20 fuel when the crank angle was 385° after TDC. Maximum cylinder pressure in CBG is 6.06 bar at a 377° of crank angle after TDC, and its end-of-burning (EOB) fuel starts when cylinder pressure reaches 2.75 bar at a crank angle of 415° after TDC. In G100 and other alcohol fuels, when the cylinder range gets 1.25 bar at a crank angle of 450° after TDC, EOB starts in these fuels. CBG completes the EOB cycle earlier than gasoline, and alcohol blends because unburned particles are negligible in CBG, and the combustion cycle ends earlier. Whereas gasoline and alcohol blends contain more unburned particles, their EOB cycle is longer than CBG.

In Fig. 4b, the highest cylinder pressure value was found at 6.79 bar in the G90M10 when the cylinder volume was 48.58 cc, and in the G90M20, with a cylinder volume of 49.86 cc, the pressure value was 6.76 bar. Maximum cylinder pressure in G100 was 5.84 bar when the cylinder volume was 49.86 cc, and in CBG, the maximum pressure was 6.06 bar at a cylinder volume of 39.97 cc. Among all the fuels, the G80MA20 raised the lowest cylinder pressure to 5.54 bar when the cylinder volume value was 46.15 cc.

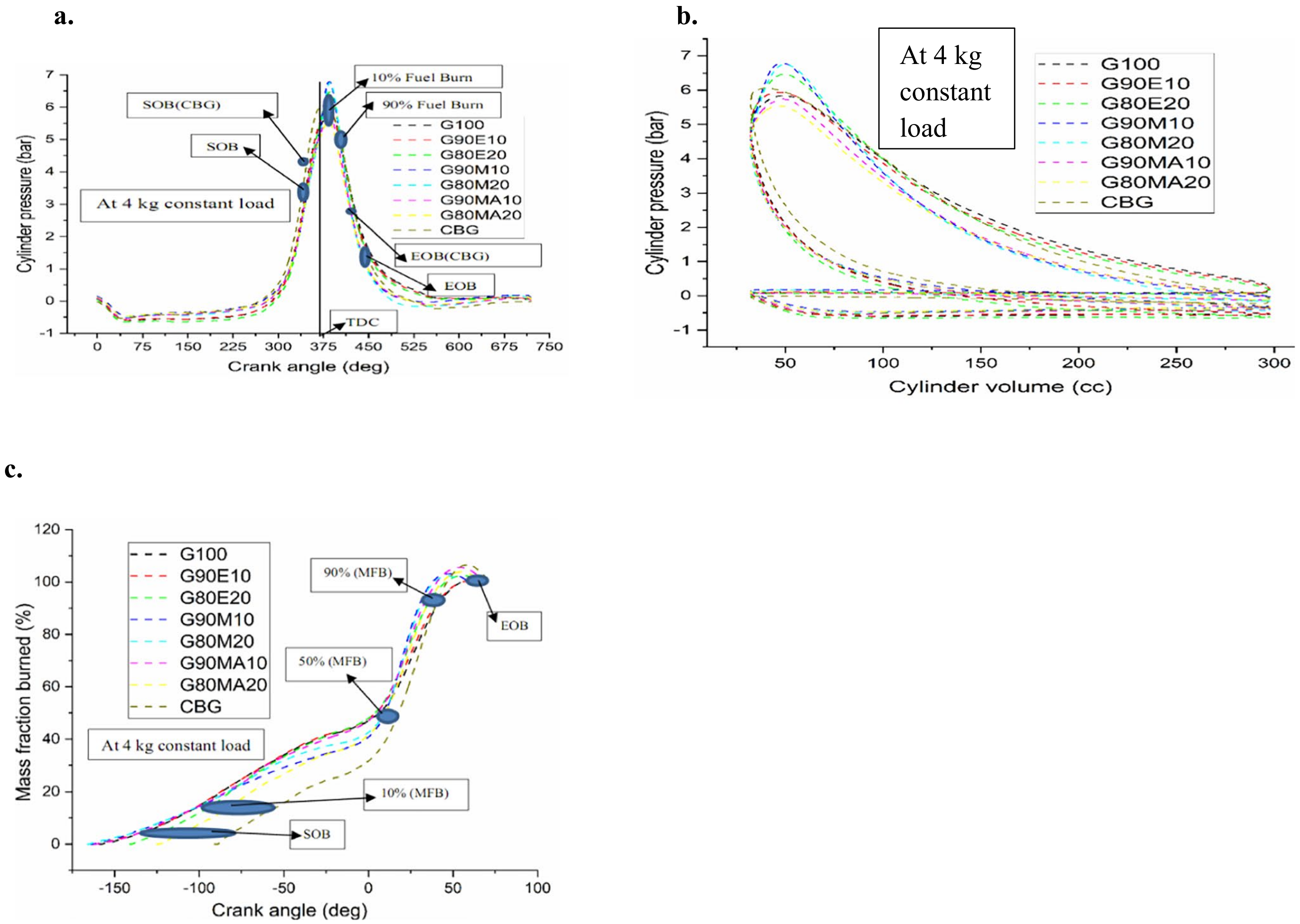

Fig. 4 **a** Cylinder pressure vs crank angle, **b** cylinder pressure vs cylinder volume, **c** mass fraction burned vs crank angle

Piston advances from TDC to BDC with the intake valve already open. As the piston completes its stroke, the volume keeps growing. When the piston is at BDC, the maximum volume is attained. Because the piston action creates volume and the vacuum effect draws air into the cylinder, the pressure is below atmospheric pressure throughout the stroke. Compression stroke starts once the piston has passed BDC. Volume begins to fall, and the pressure rises during this phase. Intake valve is still open even after the piston has passed BDC because it takes some time for the pressure inside the cylinder to exceed the pressure outside. Pressure progressively rises as the piston approaches TDC. When the ignition is started, the pressure increases until it reaches its peak. Since the cylinder's high pressure pushes the piston, the volume increases, and the pressure gradually decreases. Piston is back at the BDC after the power stroke. Once more, the cylinder's volume is at its maximum value, and its pressure is similar to the atmosphere. Cumulative heat release to total heat release ratio is known as MFB. Apparent heat release can be roughly calculated if the MFB is known as a function of crank angle. Value of MFB in CBG was lower than in gasoline and alcohol, as there is complete combustion in CBG.

In Fig. 4c, before TDC, at a crank angle of 165 to 124°, G100 and alcohol fuel are just fuel-burning, whereas, in CBG, combustion starts when the crank angle is 89°. G100 and alcohol blends have a 5% MFB crank angle at 138.2 to 108.82° before TDC, while the CBG has this value at 79.55°. And when the crank angle is 138 to 93.76° before TDC, the G100 and alcohol blends burn 10% of the fuel, while the CBG burns when the crank angle is 67.27°. Fifty percent of MFB was found in G100 and rest alcohols at 9.08 to 2.91° after TDC, whereas in CBG, it was located at 16.95°. After TDC, 90% of MFB was detected in G100 and the rest in alcohols at 38.85 to 28.26°, while CBG was found at 38.16°. EOB in G100, alcohol blends, and CBG were located at 71 to 28.26° after TDC.

Conversion of chemical energy from the reactants in the charge into thermal energy is measured by the NHR profile, which is estimated from the cylinder pressure trace. Heat and mass transfer are not taken into account by the NHR profile. As shown in Fig. 5a, the maximum NHR value of the average ten cycles in the G100 was 2.47 j/deg at a crank angle of 387°; similarly, the CBG averaged an NHR value of 2.41 j/deg at a crank angle of 388°. And the highest NHR value among alcohol blends was 3.08 j/deg at a crank angle of 376° in the G80M20 mixture. NHR value of the average cycle across all fuels was the highest at a crank angle of 376 to 388°. Figure 5b shows that the maximum mean gas temperatures in G100, G80E20 alcohol blends, and CBG with crank angles of 412°, 406°, and 411° were 384.2 °C, 390.20 °C, and 388.17 °C, respectively. The lowest MGT, 324.97 °C, was achieved in the G80MA20 at a 406° of crank angle. CBG and alcohol fuels are highly flammable as compared to gasoline fuels. In addition to raising exhaust gas temperature and having a slower flame propagation speed than gasoline, CBG also has a higher auto-ignition temperature than other fuels. Therefore, CBG and alcohols G100E80 were found to have higher MGT values. In Fig. 5c, the highest CHR values of 0.12 kJ were found in the G100, CBG, G80E20, and G90E10 at crank angles of 432°, 420°, 422°, and 427°, respectively. And the lowest CHR value of 0.10 kJ is found in G80MA20 and G90MA10 at the crank angles of 419° and 418°. Due to CBG and ethanol blends are highly inflammable, the flame consumes the unburned mass. Hence, the maximum value of CHR was found in

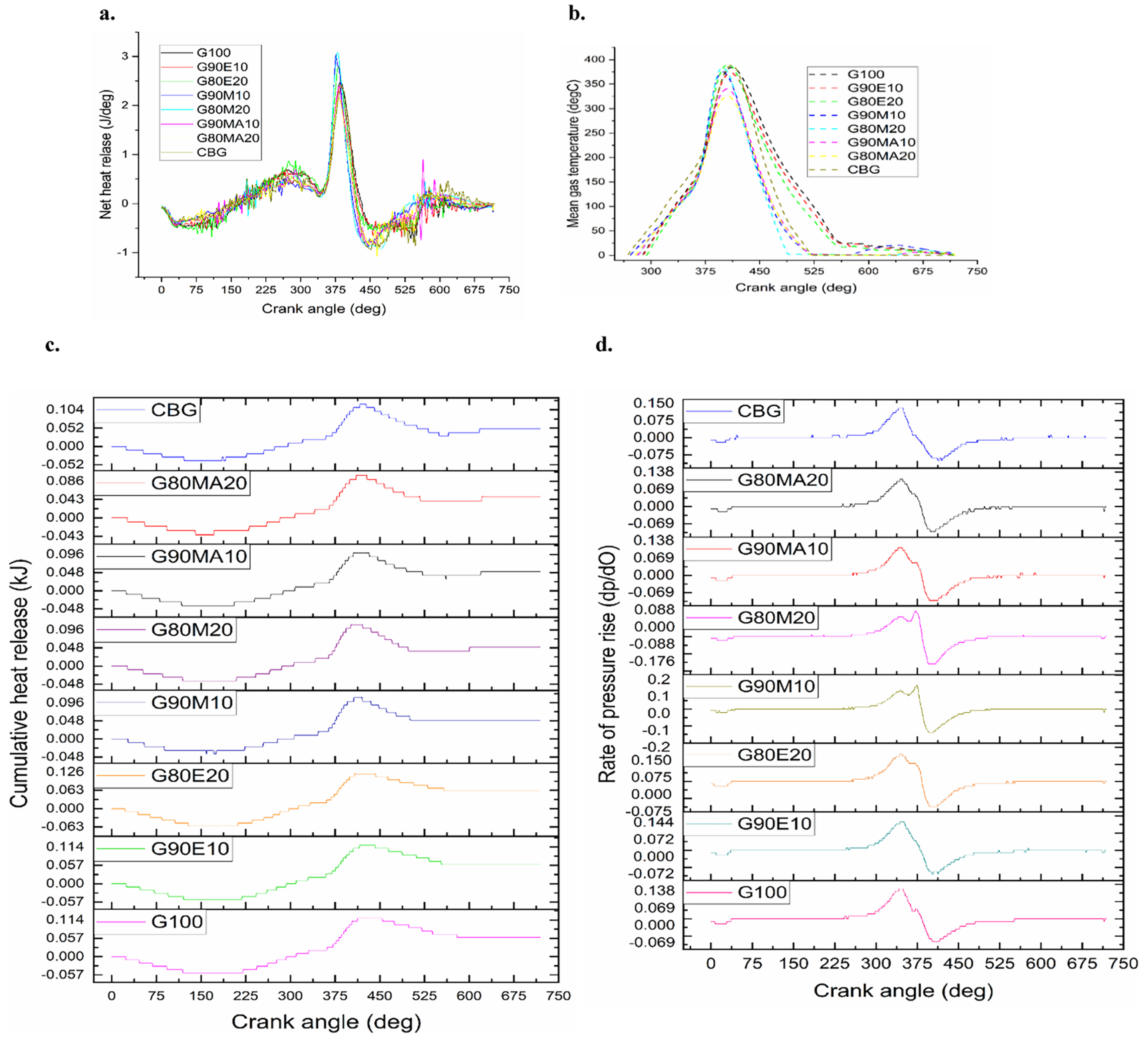

Fig. 5 **a** Net heat release vs crank angle. **b** Mean gas temperature vs crank angle. **c** Cumulative heat release vs crank angle. **d** Rate of pressure rise vs crank angle

these fuels, whereas in methyl acetate, it got a minimum value of CHR due to low flame.

Figure 5d shows that the G100, CBG, and G90M10 had maximum RPRs of 0.12, 0.13, and 0.14 bar/degree at 344°, 348°, and 374° of crank angles, respectively. At 344° and 346° of crank angles, the lowest RPR value of 0.11 bar/degree was achieved in G90MA10 and G80MA20. Gasoline, CBG, and methanol blends found the most significant increase in gas pressure during combustion, due to which the RPR value was higher in these fuels. Methyl acetate was found to have the lowest pressure increase during combustion, due to which the value of RPR was found to be the lowest in these blends.

Emission characteristics

Figure 6a presents that at 2000 rpm, the highest 20% and 22% CO_2 were obtained in the blends G90M10 and G90M20, respectively, and the lowest 3% was obtained in CBG. And at the highest 4500 rpm, G100 and G80M20, CO_2 yielded were 13% and 21%, respectively, while CBG produced 6% CO_2, which means CBG green energy is considered the best alternative fuel of all fuels. Atoms of carbon and hydrogen constitute gasoline. CO_2 is created during combustion when oxygen is from the air and carbon from the fuel mix (CO_2). Similarly, in methanol bands and gasoline, the value of CO_2 has increased from the minimum speed to the maximum speed, which means that the CO_2 emission from methanol blends increases. Due to its low carbon content, CBG burns more cleanly than petroleum-based products. In addition, compared to gasoline and alcohol fuels, CBG emits 10 to 15% less CO_2. Maximum amount of CO is due to the burning of G100 fuel, which causes environmental pollution. In Fig. 6b, from the lowest speed to the highest speed, the maximum amount of CO was found in G100, from 1.64 to 2.63%.

The highest CO content of 1.45 to 1.08% was found in G90E10 among alcohol blends, and the lowest CO content

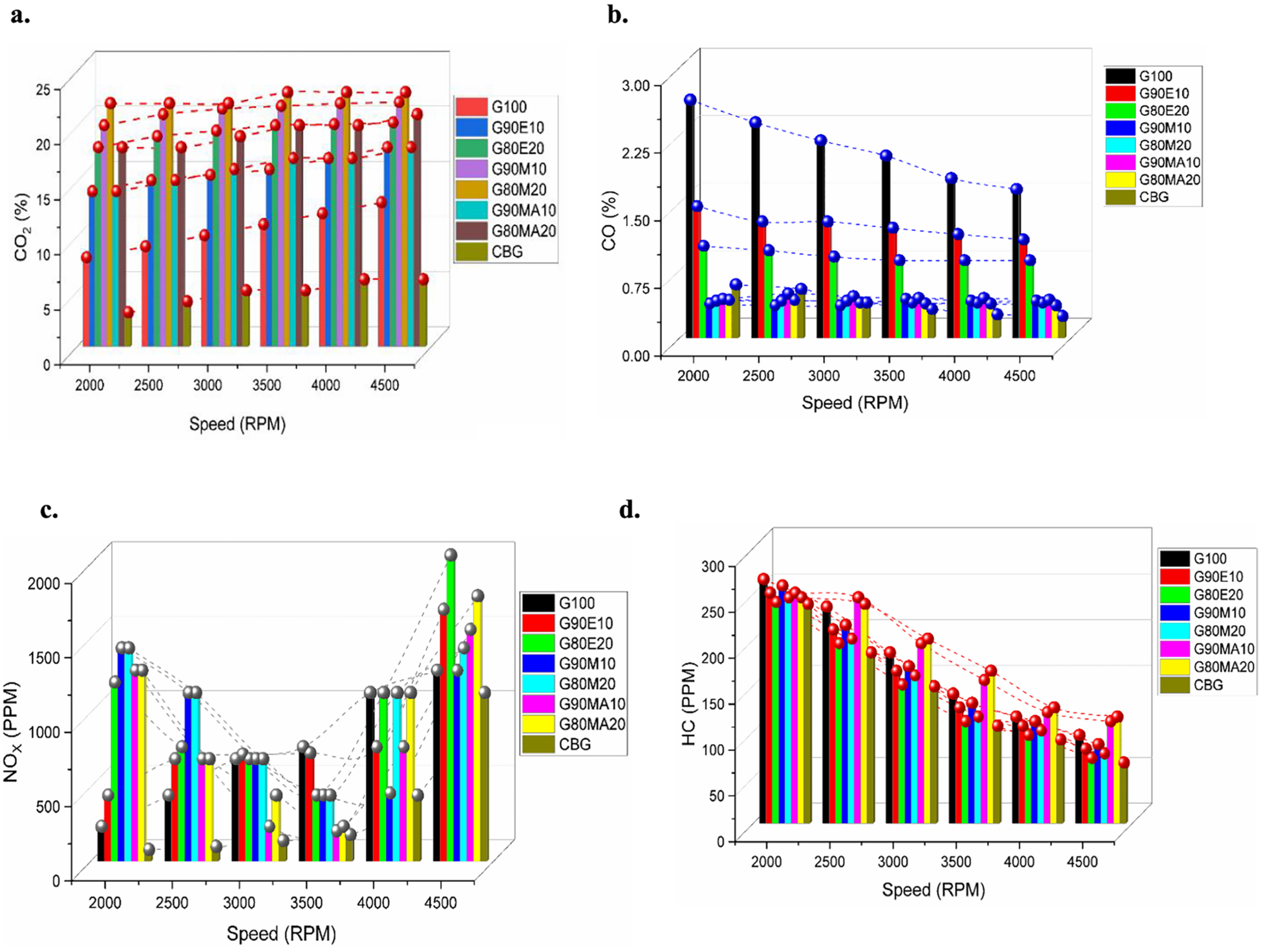

Fig. 6 **a** Carbon dioxide vary w.r.t speed. **b** Carbon monoxide vary w.r.t speed. **c** Nitrogen oxide vary w.r.t speed. **d** Hydrocarbon vary w.r.t to speed

at the highest speed was 0.232% in CBG. Due to incomplete combustion, a lack of oxygen, inadequate mixing, or all three, gasoline fuel was discovered to have a high CO content. Alcohol benefits engine performance and lowers exhaust since it has a high vaporization heat, octane number, and flammability temperature. Because alcohol is an oxygenate, meaning its molecules include oxygen, it burns efficiently and CO emissions are thus decreased. To assist the alcohol burn thoroughly, the oxygen atoms within it interact with the oxygen molecules in the surrounding air. When combined with alcohol, this extra oxygen makes gasoline burn more efficiently. Due to the low oxygen gas concentration in CBG, relatively little CO gas is generated.

As shown in Fig. 6c, the NO_X value in fuel G100 and alcohol blends G90M10 and G80M20 was found to be 225 and 1425 PPM at a minimum of 2000 rpm, while in CBG, its value was found to be 70 PPM. At maximum rpm, G80E20, G80MA20, and G100 have NO_X values of 2050, 1775, and 1275 ppm, respectively, while CBG has achieved 1125 ppm at the highest RPM, which means CBG emits the lowest NO_X from gasoline and other alcohol fuels and pollutes the environment less. Because engine speed affects NOx emissions, when engine speed increases, more fuel is used, temperatures rise, and NOx emissions increase. During combustion, nitrogen is oxidized to NOx. Fuel burns more in the gasoline and alcohol band, which increases combustion temperature, cylinder pressure, and heat release, due to which these fuels were found to have higher NOx values . In contrast, CBG had lower fuel consumption, allowing the engine performance increases, and NOx is also emitted less.

Figure 6d shows that the HC values at minimum speed were 265, 258, and 238 PPM, respectively, in G100, G90M10, and CBG. And the HC values at maximum speed were 110, 115, and 65 PPM in the G90MA10, G80MA20, and CBG, respectively. Gasoline and alcohol blends have higher hydrocarbon emissions because the fuel does not burn entirely at low speeds. As the speed of the engine increases, the fuel starts burning well, so the value of HC is obtained less in all the fuels at higher rpm. CBG fuel burns well at minimum RPM to maximum RPM, due to which the HC value in CBG is rarely achieved at all RPMs.

In a study found, CO_2 values are ranging from 11 to 13% in gasoline at 2000 to 5000 rpm, CO values are ranging from 1.5 to 4.5%, and HC values are ranging from 180 to 450 ppm (Geok et al. 2009). Blends G85M15 and G70M30 at 2000 to 4000 rpm yielded CO values ranging from 0.14 to 0.06%, CO_2 in the range of 13.5 to 14.8%, and HC values ranging from 150 to 90 ppm (Shayan et al. 2011). The CO values ranged from 0.5 to 0.75% in blends G90E10 and G80E20 at 2000 to 4500 rpm, and HC values ranged from 145 to 65 ppm (Iodice and Cardone 2021). The CO_2 values ranged from 12.5to 13.75% in blend G75E25 at 2000 to 4500 rpm, and the NOx values ranged from 800 to 600 ppm (Thangavelu et al. 2015). In methyl acetate blends G95MA5 and G90MA10, CO values ranged from 0.3 to 3.8% at constant 1500 rpm, while HC values ranged from 80 to 170 ppm and CO2 values ranged from 10.5 to 13% (Cakmak et al. 2018).

Conclusion

At a constant load of 4 kg, from a minimum speed of 2000 rpm to a maximum speed of 4500 rpm, the FF rate (0.55–1.72 kg/h and BSFC 0.32–0.44 kg/kWh) in CBG fuel has been achieved, which is the lowest compared to gasoline and alcohol fuel blends, resulting in the highest BTE value in CBG at 23.33%. At a cylinder volume of 39.97 cc, the CBG achieved the highest cylinder pressure of 6.06 bar, and the G80MA20 achieved the lowest cylinder pressure of 5.54 bar among all fuels when the cylinder volume was 46.15 cc. At lower rpm, friction loss is higher in G100 and alcohol blends and lower in CBG, resulting in higher ME (75.05%) in CBG at lower rpm. SOB started at all fuels when the crank angle was 335°, and the cylinder pressure was between 3 and 4.50 bar. Its end-of-burning (EOB) began when the crank angle was 415° after TDC. Ninety percent mass of fraction burned in G100, alcohol blends, and CBG fuel after TDC was found at 38.85 to 28.26° of crank angle. In contrast, the EOB mass fraction was between 71 and 28.26° after TDC.

All alcohol blends have different properties due to their various characteristics, resulting in the G80M20 having an NHR value of 3.08 j/deg at a crank angle of 376°, which was higher than the NHR values for all fuels. The maximum mean gas temperature value in the G80E20 blends was achieved at 390.20 °C at a crank angle of 406 °C. At 432°, 420°, 422°, and 427° of crank angles, the G100, CBG, G80E20, and G90E10 achieved the highest CHR values of 0.12 kJ. The value of CO_2, CO, HC, and NOx emission gases in CBG at minimum speed to maximum speed is deficient compared to other fuels. Due to the low carbon content in CBG, it less pollutes the environment than gasoline and alcohol fuels. And it burns cleaner than petroleum-based products. Therefore, CBG fuel is also the best solution for solid organic waste, is the best alternative to gasoline fuel, and is eco-friendly. Our results suggest that CBG has the best results among all fuels in terms of engine performance, combustion, and emissions.

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Data Availability Not applicable.

Declarations

Ethical approval As authors, we would like to tell you that this is our original work, and this paper has not been submitted anywhere except in this journal.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

Awad OI, Mamat R, Ali OM et al (2018a) Alcohol and ether as alternative fuels in spark ignition engine: a review. Renew Sustain Energy Rev 82:2586–2605. https://doi.org/10.1016/j.rser.2017.09.074

Awad OI, Mamat R, Ibrahim TK et al (2018b) Overview of the oxygenated fuels in spark ignition engine: environmental and performance. Renew Sustain Energy Rev 91:394–408. https://doi.org/10.1016/j.rser.2018.03.107

Cakmak A, Kapusuz M, Ganiyev O, Ozcan H (2018) Effects of methyl acetate as oxygenated fuel blending on performance and emissions of SI engine. Environ Clim Technol 22:55–68. https://doi.org/10.2478/rtuect-2018-0004

Chauhan BS, Kumar N, Du Jun Y, Lee KB (2010) Performance and emission study of preheated Jatropha oil on medium capacity diesel engine. Energy 35:2484–2492. https://doi.org/10.1016/j.energy.2010.02.043

D Deublein AS (2008) Biogas from Waste and Renewable Resources. Wiley-VCH Verlag GmbH & Co KGaA, Weinheim, Germany

Geok HH, Mohamad TI, Abdullah S et al (2009) Experimental investigation of performance and emissions of a sequential port injection compressed natural gas converted engine. SAE Tech Pap

Gülüm M, Bilgin A (2018) A comprehensive study on measurement and prediction of viscosity of biodiesel-diesel-alcohol ternary blends. Energy 148:341–361. https://doi.org/10.1016/j.energy.2018.01.123

Holm-Nielsen JB, Al Seadi T, Oleskowicz-Popiel P (2009) The future of anaerobic digestion and biogas utilization. Bioresour Technol 100:5478–5484. https://doi.org/10.1016/j.biortech.2008.12.046

Hosseini SE, Wahid MA (2013) Feasibility study of biogas production and utilization as a source of renewable energy in Malaysia. Renew Sustain Energy Rev 19:454–462. https://doi.org/10.1016/j.rser.2012.11.008

Iodice P, Cardone M (2021) Ethanol/gasoline blends as alternative fuel in last generation spark-ignition engines: a review on co and hc engine out emissions. Energies 14:4034. https://doi.org/10.3390/en14134034

Iodice P, Senatore A, Langella G, Amoresano A (2016) Effect of ethanol–gasoline blends on CO and HC emissions in last generation SI engines within the cold-start transient: an experimental investigation. Appl Energy 179:182–190. https://doi.org/10.1016/j.apenergy.2016.06.144

Jhalani A, Sharma D, Soni S et al (2021) Feasibility assessment of a newly prepared cow-urine emulsified diesel fuel for CI engine application. Fuel 288:119713. https://doi.org/10.1016/j.fuel.2020.119713

Larsson M, Grönkvist S, Alvfors P (2016) Upgraded biogas for transport in Sweden - effects of policy instruments on production, infrastructure deployment and vehicle sales. J Clean Prod 112:3774–3784. https://doi.org/10.1016/j.jclepro.2015.08.056

Limpachoti T, Theinnoi K (2021) The comparative study on compressed natural gas (CNG) and compressed biomethane gas (CBG) fueled in a spark ignition engine. E3S Web Conf 302:01005. https://doi.org/10.1051/e3sconf/202130201005

Mallikarjun MV, Mamilla VR (2009) Experimental study of exhaust emissions & performance analysis of multi cylinder S.I. engine when methanol used as an additive. Int J Electron Eng Res 1:201–212

Mohammed Kamil, Ibrahim Thamer Nazzal (2016) Performance evaluation of spark ignited engine fueled with gasoline-ethanol-methanol blends. J Energy Power Eng 10:. https://doi.org/10.17265/1934-8975/2016.06.002

Nuthan Prasad BS, Pandey JK, Kumar GN (2020) Impact of changing compression ratio on engine characteristics of an SI engine fueled with equi-volume blend of methanol and gasoline. Energy 191:116605. https://doi.org/10.1016/j.energy.2019.116605

Pradeep Kumar Meena, Sumit Sharma AP (2022) Evaluation of in-house compact biogas plant thereby testing four-stroke single-cylinder diesel engine. In: Introduction to Artificial Intelligence for Renewable Energy and Climate. Scrivener Publishing, pp 277–343

Rajesh Kumar B, Saravanan S (2016) Use of higher alcohol biofuels in diesel engines: a review. Renew Sustain Energy Rev 60:84–115. https://doi.org/10.1016/j.rser.2016.01.085

Saidur R, Abdelaziz EA, Demirbas A et al (2011) A review on biomass as a fuel for boilers. Renew Sustain Energy Rev 15:2262–2289. https://doi.org/10.1016/j.rser.2011.02.015

Shayan SB, Seyedpour SM, Ommi F et al (2011) Impact of methanol – gasoline fuel blends on the performance and exhaust emissions of a SI engine. Int J Automot Eng 1:219–227

Subramanian KA, Mathad VC, Vijay VK, Subbarao PMV (2013) Comparative evaluation of emission and fuel economy of an automotive spark ignition vehicle fuelled with methane enriched biogas and CNG using chassis dynamometer. Appl Energy 105:17–29. https://doi.org/10.1016/j.apenergy.2012.12.011

Thakur AK, Kaviti AK, Mehra R, Mer KKS (2017) Performance analysis of ethanol–gasoline blends on a spark ignition engine: a review. Biofuels 8:91–112. https://doi.org/10.1080/17597269.2016.1204586

Thangavelu SK, Chelladorai P, Ani FN (2015) Emissions from petrol engine fueled gasoline-ethanol-methanol (GEM) ternary mixture as alternative fuel. MATEC Web Conf 27:2–5. https://doi.org/10.1051/matecconf/20152701010

Vivek Pandey, Gupta VK (2016) Technical assessment of performance emission characteristics of an SI engine using ethanol-gasoline blended fuel. Int J Eng Res V5:422–426. https://doi.org/10.17577/ijertv5is070431