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ORIGINAL RESEARCH

The study of performance and emission characteristics of a spark ignition (SI) engine fueled with different blends of pomegranate ethanol

D. Y. Dhande[1] · **Nazaruddin Sinaga**[2] · **Kiran B. Dahe**[1]

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Abstract

This work focuses on exctracting ethanol from waste pomegranate (*Punica granatum*) and the experimental investigation of impact of various mixtures on emissions and engine performance. Ethanol is produced through the fermentation process of waste pomegranate fruits. Four combinations, namely E10, E15, E20, and E25, were prepared and tested for various speeds with a wide open throttle at 10:1 compression ratio. As a result, it was found that the ethanol enrichment increased the fuel consumption and power for braking while the thermal efficiency decreased. CO-produced HC has decreased, but ethanol concentrations have increased the NOx and CO_2 content emitted from the exhaust gas. The 1500RPM engine speed and the E15 combination revealed the optimal values of performance parameters among all the fuel combinations studied.

Keywords Biofuel · Pomegranate ethanol · Pollution control · Emission characteristics · SI. Engine performance

Introduction

The growing vehicle population, increased energy demand by the industry, globalized transportation and the scarcity of fossil fuels necessitate finding an alternative to petroleum fuel [1]. According to world economic outlook 2016, around 70% of energy generation is fulfilled by fossil fuel, and it is still expected till 2030. Higher consumption is accelerating the depletion of fossil fuels stock. This has resulted in oil crises and elevation in its prices [2]. The fuel exhaust emits huge amounts of greenhouse gases including carbon dioxide which may subsequently harm the environment and favours global warming. The benefits of fossil fuel are accountable, but on the other side, the cost for their environmental concern is not avoidable. Among them, coal is the largest source of greenhouse gas production share 45%; secondly, oil, which shares 35% and natural gases for 20% [3]. In the last few decades, gasoline and diesel are developed and widely used as the main fuel of I C Engines. Air pollution due to fuel combustion and emissions from these sources is also a major concern for every country [4]. Due to the global warming threat and stringent government pollution, norms have initiated the need for alternative fuels that can be used in place of conventional fuel or partially on it. The search for stable energy supplies for various energy resources found renewable energy sources are necessary.

The attraction towards alcohol as an alternative fuel has increased through an industrial revolution in the 19th and early twentieth centuries. Among alcohol fuel, methanol, ethanol, propanol, and butanol can be used as alternative fuels. Since ethanol and methanol have properties to enhance the combustion process, they are successfully introduced as an appropriate susbstitue fuel for spark-ignition engines in terms of fuel additives, blend fuel and biofuels. Ethanol's demand and supply almost tripled in the last few decades [5, 6]. Many contries including India, European Union, Brazil and the United States made the use of 10% ethanol-blended gasoline mandatory for vehicles and is commercially available [7, 8]. After successful implementation of 10% ethanol blend, the next target is 20% ethanol blending

✉ D. Y. Dhande
dydhande@aissmscoe.com

✉ Kiran B. Dahe
dahekiran53@gmail.com

Nazaruddin Sinaga
nsinaga19.undip@gmail.com

[1] Department of Mechanical Engineering, AISSMS College of Engineering, Pune, Maharashtra State 411001, India

[2] Department of Mechanical Engineering, Diponegoro University, Semarang 50275, Indonesia

which is predicted to rise upto 30% upto 2050 [9]. The report published by the Central Pollution Control Board (CPCB), India, on alternative fuel, Parivesh [10], provides many options for alternative fuel, which include mainly ethanol, methanol, CNG, LPG, electric vehicles, hydrogen cell, etc. Today, 10% ethanol-blended gasoline fuel is widely used in passenger cars. However, the sources of ethanol production are limited. More ethanol extraction sources are needed to meet the growing demand. Urban waste management is another serious problem in many crowded cities across the world.

The commonly used feedstock for producing ethanol is sugarcane, corn, cassava roots, sugar grass, sugar beet, grape seeds, and much more biomass. Researchers have tried to extract ethanol from waste animal fats also [11]. Brazil and the USA are the main contributors to ethanol production. Ethanol from sugar is mainly produced in Brazil seconded by India, whereas in the US, cornstarch ethanol is produced. Some methods for ethanol production and separation, as well as techniques for chemical and sensory analysis, were reviewed by Shinnosuke Onuki [12]. The fermentation process is mainly used for ethanol production, but further distillation is required for purification. Other alternatives to distillation include ultrasonic irradiation, oxidation of various pollutants by ozone, unheated fractional distillation, and adsorption of pollutants using activated carbon or zeolites. Various types of chemical and sensory type analysis have also been proposed. Pimentel and Patzek [13] discussed the possibility of ethanol produced by means of grass, corn sweet, and wood and production of biodiesel from sunflower and soybean. Nagenderan et al. [14] analyzed the thermal properties of bioethanol extracted from two bio-wastes viz. moringa olefira leaves and Pithecellobium dulce leaves to check the prospect of bioethanol alongside spark-ignition engine performance. The thermal properties analysis of the extracted ethanol was found to be better in comparison to tire oil, bioethanol, and gasoline blends. Bai et al. [15] reviewed several bacteria fermentation technologies of ethanol fermentation derived through starch and sugar feedstock. The ethanol yield and productivity of Zymomonas mobilis were found higher as compared with *Saccharomyces cerevisiae* bacteria but cannot replace *S. cerevisiae* due to its specific substrate spectrum. It was concluded that self-immobilized yeast cells through their flocculation can be used as a substitute for ethanol production. Sarkar et al. [16] and Thakur et al. [17, 18] conducted an extensive review of the spectrum of opportunities and possibilities to introduce ethanol–gasoline mixtures and the performance of the engine with lower and higher mixtures. The reported feedstocks for ethanol production were sugar cane, agricultural biomass, cellulose, crop residues and municipal waste. Fluctuations in thermal efficiency, fuel consumption for braking, indicated power, and braking torque occur depending on the engine's ethanol mix and operating conditions. As the volumetric efficiency and the ethanol ratio increased, the emissions of carbon monoxide and unburned hydrocarbons decreased significantly. CO_2 emissions were higher with ethanol, and NOx emissions increased or decreased depending on engine operating conditions. Dogan et al. [19] carried out experimental and theoretical investigations to infer that ethanol enrichment to the fuel reduces exhaust emissions compared to gasoline, and lowers the cylinder temperature, resulting in an increase in hydrocarbon emissions. Manikandan K [20]. observed moderate increase in torque and engine power and fairly increased fuel consumption with ethanol enrichment for different compression ratios. There was improvement in exhaust emission quality with reduction in HC, CO,NOx and CO_2 particulates. For the E30 blend, fuel consumption and carbon monoxide particultes reduced as compression ratios increased, but CO_2, NOx, and hydrocarbon emissions increased significantly. The ethanol enrichment permits engine to work without knocking effects at higher compression ratios. A decrease in the carbon monoxide (by 13.7%), hydrocarbons (by 25.2%), and fuel consumption (by 8.22%) was noted and improvement of the engine power increased up to 11.1% for the fuel blends after incorporating butanol and ethanol to gasoline blends in the ratios of 2–20% at various speeds and lower loads [21–24].

Yüksel, F.and Yüksel, B [25]. designed a new carburettor to overcome the cognizence of a stable consistent liquid phase in the implementation of gasoline–ethanol blend fuels. The performance was tested for fuel consumption and exhaust emissions with 60% ethanol and a 40% gasoline blend. It had been noticed that a newer binary fuel scheme with simple alterations in the carburettor could be effective easing the complications in the carburettor system. Yoon et al. [26] studied effect of SI engine performance for higher ethanol blends to confirm that an ethanol-blended fuel or pure ethanol leads to a drastic drop in exhaust emissions under all operating conditions. The performance of exhaust and spark-ignition (SI) engines for various gasoline–ethanol (E5, E10, E15, E20) and E0 (100% gasoline) mixtures for various torques on a constant engine speed was tested by Al-Hasan [27]. and Saikrishnan et al. [28]. Ethanol enrichment in gasoline increased braking power, braking thermal efficiency, specific fuel consumption, nitrogen oxide particulates and reduced hydrocarbon as well carbon emissions. Optimal results were obtained by adding 20% ethanol to pure gasoline. It was observed that the heating value of the gasoline–ethanol mixture dropped and the octane number improved with ethanol addition [29–31]. The use of mixed fuels has been shown to increase torque and fuel consumption marginally, reduce carbon and hydrocarbon emissions dramatically, and increase CO_2 emissions. Engine operating conditions dominated NOx emissions over ethanol content. Yücesu et al. [32] and Najafi et al. [33] implemented artificial neural network technique to study the exhaust pollutants and SI engine performance fueled with various petrol-ethanol mixtures. The ethanol–gasoline blend improved torque and power. Along with HC emissions, brake-specific fuel consumption, carbon monoxide levels have decreased. Conversely, thermal break efficiency, volumetric efficiency, and CO_2 and NOx concentrations have been improved. Experimental results have shown close agreement with the artificial neural network model. Elfasakhany [34]. scrutinized the exhaust a engine fired with lower mixtures of ethanol–methanol in pure petrol. Carbon and unburned hydrocarbons emissions were significantly reduced when fueling vehicles with a mixture of ethanol, methanol and gasoline competing with pure gasoline. The lowest emissions of CO and unburned HC were noticed in the gasoline mixed to methanol, while for the ethanol gasoline combination, there was an intermediate level between the pure gasoline and the ethanol–methenol–petrol mixture. The CO and HC ratio decreases, while the CO_2 increases by adding the methanol and/or ethanol content to the fuel mixture. The methanol–petrol mixture provided the greatest torque and volumetric efficiency. The ethanol–petrol blend showed the highest braking power, and the braking power, torque and volumetric efficiency values using the ethanol–methanol–petrol blend were found for both methanol-to-petrol and ethanol–petrol. Pure petrol provided the lowest braking power, torque and volumetric efficiency. Rao et al. [35] collated the functioning of a small single-cylinder engine for different ethanol–petrol mixtures with pure petrol at consistant load and varying operating speed. A development in overall engine performance was observed by adding adding ethanol to gasoline. Higher gasoline–ethanol fuel blend (E40), was considered appropriate for low engine speed, while neat gasoline can be replaced by lower ethanol–gasoline fuel blend (E10) without modification due to identical performance.

From the above literature, it has been concluded that blending ethanol with petrol helps to improve SI. Engine performance as well as reduced greenhouse gas emissions, thereby improving the environment. Depending on conditions of climate and soil, various countries are inspecting various sources of feedstock for ethanol production as a substitute for fossil fuel. Although many researchers have pointed out that ethanol might help to improve the environment, promote sustainable rural development and improve income distribution, the production of the ethanol as well as feedstock is less as compared to demand. Therefore, there is a necessity to discover alternative sources of ethanol production. Currently, the various sources of feedstock used for ethanol production are sugarcane, wheat and rice straw, corn, cassava roots, sugar grass, sugar beet, grape seeds, moringa olefira, and Pithecellobium dulce leaves.

In recent years, pomegranate (Punica granatum) has received considerable attention due to its antiviral, anticancer, antibacterial and antioxidant properties. The researchers found that pomegranate peel is a good raw constituent for second-generation ethanol production, which could accelerate the rate of ethanol production in major pomegranate producing countries, including India, Iran, China and the United States [36–38]. There is also a major problem with the management of solid waste in cities in the tropics, which produce a lot of pomegranates. The effects of mixing pomegranate ethanol and gasoline on discharge and spark-ignited engine function have not been addressed yet. Therefore, it is necessary to evaluate the emissions and the performance of spark-ignition engines for various pomegranate ethanol mixtures, which will help reduce agricultural waste and thus provide an eco-friendly solution for ethanol production to meet future demands.

The work presented here is an important study to investigate the possibility of extracting ethanol from waste pomegranate fruit (*Punica granatum*) and gasoline mixture on the emission characteristics and working of spark-ignited engines. Ethanol is extracted from waste pomegranate fruit using the fermentation method and fermenting agent *Saccharomyces cerevisiae*. The exctracted ethanol was blended with pure petrol in the fractions of 10, 15, 20 and 25%. The effect of these compounds on single cylinder, four-stroke gasoline engine performance and the pollutants emitted have been studied for various engine speeds at constant load and compression ratios. The effects of these compounds on single-cylinder, four-stroke gasoline engine performance and emitting pollutants have been studied for different engine speeds at constant load and compression ratios. Trial results show that the ethanol concentration of gasoline a significantly improves engine performance and reduces exhaust gas emissions, providing an environmentally friendly solution, which helps in pomegranate waste management. A distinct drop in hydrocarbon and carbon emissions was noticed in all fuel blends, but the CO_2 and NO_x releases were found to increase with the addition of ethanol. The results also showed that engine speed of 1500RPM and E15 (15% ethanol + 85% gasoline) were found to be optimal among all fuel blends studied. Braking power and fuel consumption by braking have been slightly reduced, while ethanol mixing to pure gasoline has been shown to decrease thermal efficiency.

Materials and methods

In this section, the experimental setup, along with instrumentation, the method of bioethanol preparation from waste pomegranate fruit, and test procedure are explained thoroughly. The tables provide test engine specifications and heating values of fuel combinations.

Table 1 Technical specifications of the test Engine

Manufacturer	Kirloskar
Type	Spark ignition with water cooling
No. of cylinders	Single
No. of strokes	4
Bore diameter	87.5 mm
Stroke –length	110 mm
Swept volume	661 cc
Compression ratio	10:1
Max. power output	4.5 kW @ 1500 RPM
Max. engine Speed (rpm)	1800
Air density (kg/m^3)	1.17
Dynamometer	AG-10 eddy current (SAJ Test Plants Pvt. Ltd)
Combustion chamber	Hemispherical bowl in piston type
Inlet valve open	4.5° before TDC
Inlet valve close	35.5° after BDC
Exhaust valve open	35.5° before BDC
Exhaust valve Close	4.5° after TDC
Maximum pressure	77.5 kg/cm^2
Injection Pressure	210 bar
Ingition timing	23° before TDC

Experimental set-up

The setup consists of a single cylinder, four-stroke and variable compression ratio engine. The technical specifications are listed in Table 1. The necessary instruments are provided to measure combustion pressure, fuel flow, air flow, crank angle, temperature and load level. The detected signal is connected to a computer using a high-speed data acquisition device. This setup consists of an air box, fuel gauge unit, manometer, twin fuel tank, air and fuel gauge transmitter, piezo power unit enclosed in a standalone panel box with process guide. The rotometer is used for flow measurement in coolers and calorimeters. The engine is powered by open programmable electronic controls, ignition coil, fuel pump, throttle status sensor, trigger sensor and fuel spray nozzle.

The test engine is coupled with eddy current dynamometer having top speed of the 6000RPM, 11.5 N-m torque and 3.5 kg load. The load on the engine was detected using a strain gauge load cell coupled to the dynamometer, and the speed was measured using a rotation sensor mounted on the shaft. Thermocouples were used to record exhaust, oil and cooling water temperature in the engine. Controlled supply of cooling water was provided at a constant temperature throughout the study. The technical details of the measuring instruments are listed in Table 2. The five-channel exhaust gas analyzer Hg-540, with technical details listed in Table 3, was employed to detect CO_2, HC, CO and NOx emissions. The CO_2, CO and O_2 particulates are measured as a volume fraction, and total non-flammable hydrocarbon and NOx emissions are measured in ppm (vol.) throughout each engine cycle operation. A probe is inserted inside the engine exhaust tube to detect the exhaust component. The nozzle is properly closed to ensure a leak test before each discharge test. The smoke opacity was tested using AVL-437 smoke meter.

Table 2 Technical details of measuring instruments

Measurement	Equipment	Range	Accuracy	Uncertainty (%)
Engine speed	Speed measurement unit with rotation sensor	0–9999 RPM	± 10 RPM	± 0.2
Temperature	K-type thermocouple	0–1000 °C	± 1 °C	± 0.1
Flow rate	Volumetric fuel Flow meter	0–500 mm	± 0.1 mm	± 1
Pressure	Manometer	0–50 mm	± 1 mm	± 1
Load	Load Cell	0–50 kg	± 0.1 kg	± 0.2
Crank angle	Crank angle encoder	0–360°CA	± 1°CA	± 0.2
Pressure	Pressure transducer	0–25 MPa	± 0.1 MPa	± 0.1
	Eddy current dynamometer	7.5 kW	–	± 0.56

Table 3 Technical details of gas analyser

Equipment	Measurement	Range	Accuracy	Uncertainty (%)
5 Channel gas analyser (Airrex HG-540)	CO	0–9.99% vol	± 0.001% vol	± 0.5
	CO_2	0–20% vol	± 0.01% vol	± 5.0
	HC	0–15,000 rpm	± 1 ppm	± 5.0
	NOx	0–5000 ppm	± 1 ppm	± 10.0
Smoke meter (AVL-437)	Smoke opacity	0–100%	± 0.02%	± 0.1

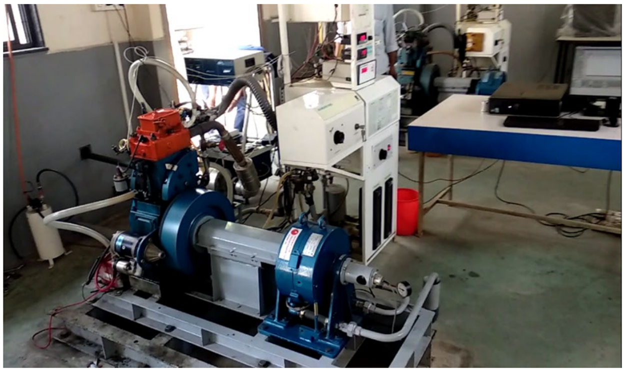

Fig. 1 The engine setup used for experimentation

All experiments were performed under maximum load conditions and a compression ratio of 10:1. Ethanol mixed gasoline was fed to the engine from a fuel tank with a glass fuel metering column. Initially, the tests were carried out with unleaded petrol at various speeds (1300–1800 RPM) at fixed fuel injector pressure and injection angle to generate the baseline data. Then, the tests were carried out for various pomegranate ethanol blends. All analyses were performed as per the testing standards SAE J1312. Figure 1 depicts the experimental setup used for experimental work in the laboratory. The conduction of all the experiments and the recording of the results took place under steady-state conditions. A computerized data acquisition system (NI USB-6210, 250 kb/sec, 16 bit) was used in data collection, storage and analysis.

Ethanol preparation

The different methods used for producing ethanol using these raw materials are as follows:

- Production from ethane using steam (the "synthetic" route) which is a widely used industrial method;
- Manufacturing from sugars and starches by the fermentation method using yeasts; and
- Manufacturing from biomass waste by utilizing bacteria.

In this work, the waste pomegranate was used as a feedstock for ethanol. The necessary steps followed for the production of bioethanol are illustrated in Fig. 2. A simple continuous solid fermentation process, shown in Fig. 3, was implemented to save the production cost. The homogeneous bioethanol mixture was ensured using highly purified ethanol (99.5%).

The complete process of ethanol production is explained in the below sections:

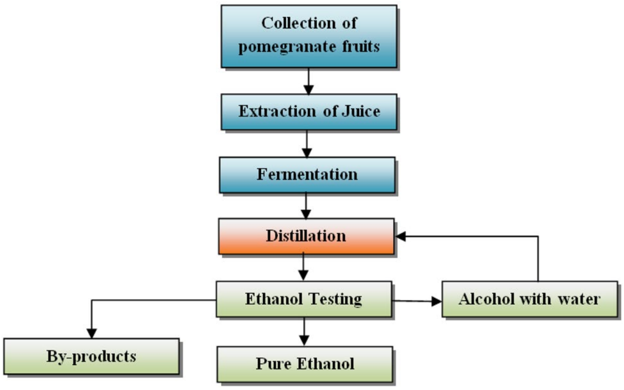

Fig. 2 Pomegranate ethanol production flow chart

Collection of fruits and extraction of juice

The pomegranate waste fruits were collected from the local market, which is the biggest market for fruits and has a very high amount of waste fruits in the surrounding. The pomegranate fruit available in the market is of different varieties, i.e., *Ganesh, Bhagwa, Arakta,* and *Mrudula.* Among them, *Bhagwa* variety was selected due to its rich content of sugar concentration, which helps in increasing the rate of fermentation. After the collection of fruits, the juice was extracted and was collected in the large container for further processing. The basic properties of pomegranate juice like sugar content and the pH of the juice and were found 112.56 gm/l and 3.22, respectively.

Fermentation

After extraction of pomegranate juice, the juice was collected in the plastic jar for the fermentation process. The fermentation was achieved using *Saccharomyces cerevisiae* bacteria as it has high fermentation efficiency. The starters were propagated in MGYP broth and were preserved in the refrigerator. Fermentation medium and the juice were appropriately mixed and stored at 37 °C for 72 h, the stored fermentation liquid stirred after every 6 h during day time for better microbial action and multiplication of fermentation activity.

Distillation

The pure liquid was separated from a mixture using the distillation process. It works when the liquids consist of various boiling points. This is the conventional method for separation of ethanol from water. The steam water distillation technique was used for the separation of ethanol from the fermented pomegranate juice mixture. First, the pomegranate fermented juice mixture was in a flask and heated.

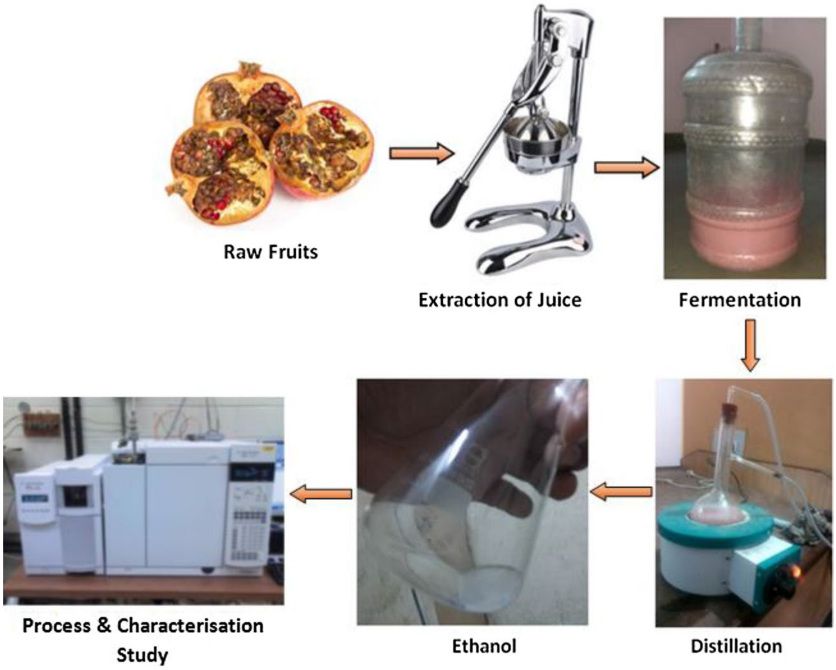

Fig. 3 Pomegranate ethanol production process

The ethanol evaporates first as it has a lower boiling point compared to water. The resulting ethanol vapour was later cooled and then condensed in the condenser to obtain a pure liquid. As the temperature rises, the water starts evaporating and mixes with some part of ethanol, which was collected into a separate container. The accumulated liquid containing water vapours and ethanol was again distilled to get anhydrous alcohol.

Testing of pomegranate ethanol properties

The ethanol exctracted from the waste pomegranate fruits was stored in a sealed bottle, and chemical analysis of the chemical composition of the sample was performed using gas chromatography methods. The gas chromatography technique was used in the chemical composition analysis of the resulting ethanol. A liquid sample was placed in the injection port with the help of a syringe where it was softened. It then passes through the column with the help of continuous flow carrier flow (mobile phase), especially H_2 (for TCD). It was then separated and found in the acquisition port, which can be seen on a computer screen representing the peaks. The gas can be used as a carrier to facilitate separation. The various chemical elements of the sample pass through the column at diverse rates depending on their properties and interaction with the distinct filling of the column. Table 4 lists the chromatography results for chemical analysis of the derived pomegranate ethanol.

Table 4 Chemical composition of pomegranate ethanol

Test	Specifications	Result
Assay (by GC) (v/v)	89.5–91.5% Ethanol 4.0–5.0% Methanol 4.5–5.5% IPA	90.54% Ethanol 4.54% Methanol 4.92% IPA
Water, max	0.2%	0.14%
Residue after evaporation, max	10 ppm	< 5 ppm
Appearance	Clear	Pass
Specific gravity	0.7902–0.7912 @ 20 C	0.7904
Color (Pt–Co)	10 max	< 10
Odor	Pass	Pass
Titrable acid	0.0003 meq/g	0.0001 meq/g
Titrable base	0.0002 meq/g	< 0.0001 meq/g
Fluorescent background	Pass	Pass
Identification	Pass	Pass
Substances reducing KMnO4	Pass	Pass
Solubility in Water	Pass	Pass
Refractive Index @25 °C	1.3580–1.3610	1.3585

Pomegranate ethanol blends preparation

Blending is a process of mixing two fluids having almost the same characteristic properties by volume. Gasoline was blended with pomegranate ethanol by volume. These two fuels readily mix and do not lead to phase separation. The pomegranate ethanol is miscible with gasoline. The tests were performed with four blends of gasoline

Table 5 The calorific value of pomegranate ethanol and its blends

Specification	Ethanol	Gasoline	Calorific value (kJ/kg)
E00	0%	100%	44,200
E10	10%	90%	42,185
E15	15%	85%	41,235
E20	20%	80%	40,430
E25	25%	75%	39,578
E100	100%	0%	29,500

and pomegranate ethanol mixed on a volumetric basis in the ratios of 10% (E10), 15% (E15), 20% (E20), and 25% (E25). The calorific values of pomegranate ethanol and its blend were measured using a bomb calorimeter. The measured calorific values for pure ethanol (E100), unleaded gasoline (E00) and different prepared blends are tabulated in Table 5.

Engine testing methodology

A single cylinder, 4-stroke spark ignition was utilised for experimental trials. Bioethanol obtained from waste pomegranate mixed with pure gasoline in various proportions was used to evaluate emission characteristics and performance, and to compare with pure gasoline fuel. Ethanol was mixed with pure gasoline just before the start of the trial to ensure a homogeneous fuel mixture and avoid water reaction. The engine was initially powered on clean fuel until it reached a steady state capable of generating basic data. The engine operating speed changed from 1300 to 1800 RPM by the interval of 100 rotations. Engine speed and fuel consumption were recorded, and thermal efficiency and fuel consumption were also monitored. All trials were performed with a constant compression ratio (10:1) and fully open throttle. Exhausts were recorded using an exhaust gas analyzer. The engine load has increased to full load, and the fuel injector trigger pressure and fuel injection angle have remained unchanged. The engine was driven to keep the engine stable enough for fuel to burn completely, and the engine started using a pomegranate ethanol and gasoline mixture as fuel. The same process was repeated for the engine when mixed with various ethanol mixtures. The entire process was repeated thrice, and an average of three tests was considered for evaluation of parameters. The load test and emission test procedures are explained below:

Procedure for load test

1. The engine fuel tank was filled with fuel blend to be tested before start of the engine.
2. Cooling water pump supply was started.
3. Rotameters were set at the required water levels for the proper mass flow rate of water
4. The load and speed indicators were switched ON.
5. Fuel flow was opened using PFI controller.
6. Interfacing the laptop installed with Labview software (Enginesoft) to the engine for reading the data.
7. The engine was started with no load condition and wait for 5 min to reach steady state.
8. The throttle needs to be rotated very slowly to increase the air supply rate.
9. The load was changed by controlling the load knob very slowly and carefully.
10. Try to adjust both throttle position and load knob to get required constant speed.
11. Air consumption was measured in the attached software.
12. Fuel consumption rate is measured from stand-alone box fuel controller using stop watch for 12 cc of fuel consumption.
13. The required equivalence ratio was adjusted using throttle and fuel map from the software.
14. The engine was let to run for 10 min to achieve the equilibrium for each test condition before taking the final results.
15. Save the obtained data in the desired folder.
16. Obtain data for different loading conditions.
17. Then stop the engine using the software and then keep the throttle and load knob to zero levels. Then close the fuel supply.
18. Repeat a similar test for different Ethanol-gasoline blends.

Procedure for emission test

1. Switch on the HG-450 gas analyzer and allow it to settle down to display zero readings of emissions.
2. Perform the leak check test, zero check test and HC residue test to get accurate readings.
3. Start the engine and run for the required operating conditions.
4. Hold the gas analyzer probe at the exhaust gas outlet. Note down the stabilized value readings shown on the display.
5. Remove the gas analyzer probe from the exhaust gas outlet and wait for 5 min to settle display at zero readings.

Table 6 Estimated uncertainties for the performance and combustion analysis

Parameter	Uncertanity (%)	Parameter	Uncertanity (%)
Air flow rate	1.1	Brake power	1.3%
Liquid fuel flow rate	0.1	Brake thermal efficiency	1.6
Engine load	0.1	Brake specific fuel Consumption	1.3
Engine speed	1.3	Volumetric efficiency	1.7
Cooling water flow rate	1.1	CO,CO2,NOx and HC	3.3
Temperature	0.8	Cylinder pressure	1.5
Cylinder volume	0.1		

6. Repeat a similar test for different loads of gasoline and ethanol-gasoline blends.

Uncertainty analysis

The sequential perturbation technique is employed for the estimation of the uncertainties of various parameters participating in experimentation. The estimated uncertainties are listed in Table 6. Due to uncertainties associated with the measuring instruments, the calculated accuracy for the performace was found withing ± 4% and for combustaion analysis, it was ± 2.8%.

Experimental results and discussion

The results of experimental studies related to the emissions and performance of spark ingnited engine fired by various mixtures of pomegranate ethanol–gasoline are discussed in this section. All experiments were conducted under full-throttle conditions and for a constant full load with a compression ratio of 10:1. Other operating conditions were the same in all experimental tests. The following sections compare engine performance results, including fuel consumption, thermal braking efficiency, and engine braking power for pure gasoline and various fuel mixes. Performance results include carbon monoxide, carbon dioxide, nitrogen oxides and hydrocarbons particulate concentrations. All results were plotted for various engine speeds RPM under full load.

Performance parameters

Brake thermal efficiency

A comparative analysis of the brake thermal efficiency (BTE) of various ethanol–petrol mixtures at various operating speeds is shown in Fig. 4. It was noted that the thermal efficiency drops down with rise in engine running speed.

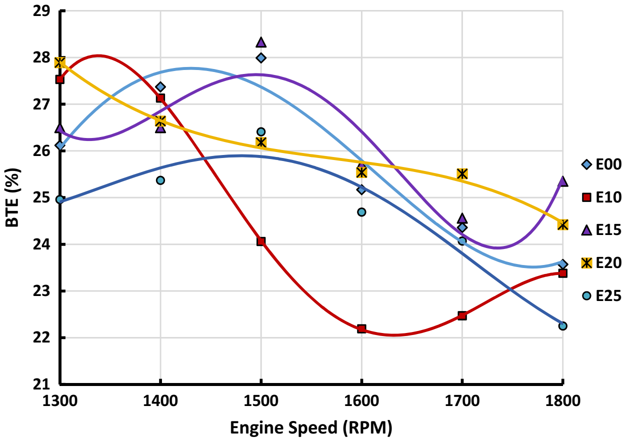

Fig.4 Brake thermal efficiency (BTE) variation at different engine speeds

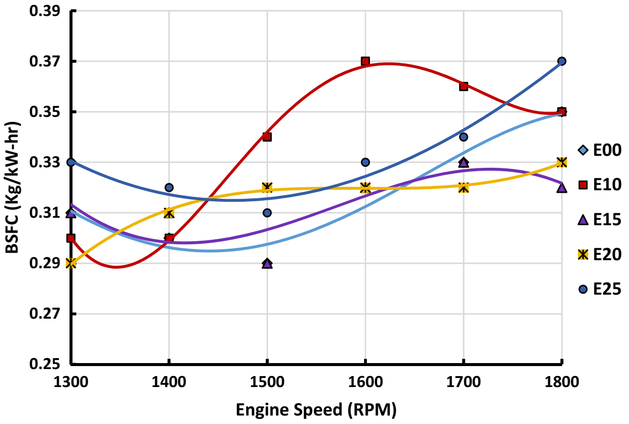

Fig. 5 Brake-specific fuel consumption (BSFC) variation with engine speed

For the E15 blend, the maximum brake thermal efficiency of 28.33% was observed when the engine was running at 1500 RPM. Except for the E10 blend, the highest efficiency of each blend was found at 1500 RPM, which later decreased due to an increase in speed. BTE increased to a peak at 1500 RPM and then decreased for E15 and E25 blends. The same trend was observed for pure gasoline. The reduction in BTE due to increased engine speed may be due to the higher octane number of ethanol correlated to pure petrol, which allows more fuel compression restricting auto-ignition [39]. Also, more compression with ethanol concentration, may cause stocking and setting of compression ratio with neat gasoline resulting in lower BTE at higher engine speeds. Incomplete combustion can also cause a decrease in thermal efficiency.

Brake-specific fuel consumption

The difference in brake-specific fuel consumption (BSFC) values for various mixtures of pomegranate ethanol and gasoline are shown in Fig. 5. BSFC rises as the rotational speed and ethanol mixing in gasoline increases. The E10 blend has 12.12% higher BSFC than pure gasoline at 1600RPM engine speed, while the E15 blend has 12.12% lower BSFC than pure gasoline at 1500RPM. The BSFC in the E15 mix was found to be the lowest of all combinations when the engine operated at higher speeds. From the trials, it was witnessed that fuel consumption occurs with ethanol addition. BSFC decreases at low speeds and increases at high speeds.

Brake power

Figure 6 shows the effect of various fuel mixtures on engine braking power. For higher blends, the braking power increases as the ethanol propotion in gasoline rises at all operating speeds due to the increased average effective pressure. As the latent heat of evaporation of the mixed fuel outperforms gasoline, the air/fuel charge cools, resulting in a more dense charge at lower temperatures, increasing volumetric efficiency and engine braking power. Ethanol enrichment provides more oxygen for complete combustion, improving braking torque and engine power.

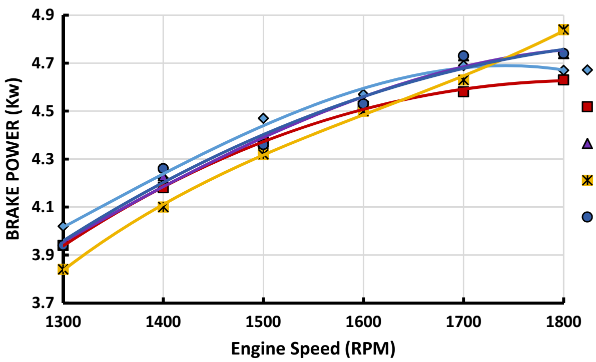

Fig. 6 Brake power variation with engine speed

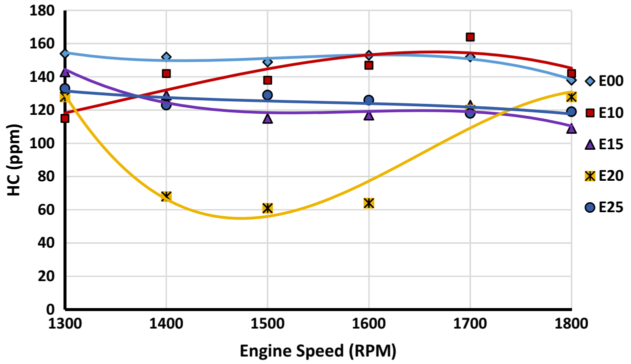

Fig. 7 Hydrocarbon emission fluctuation with engine speed

The braking power achieved with the E15 and E25 is more of all fuel blends and is the highest (4.73 kW) at 1700 RPM.

Emission parameters

Hydrocarbon (HC)

Figure 7 shows that non-combustible hydrocarbon (HC) emissions are reduced by an increase in ethanol content compared to refined petrol. Improved mixing of gasoline and air results in better combustion resultiung in reducing HC emissions. This effect is because of improved air–fuel ratio of ethanol–petrol blends due to the oxygen content in ethanol. Low HC emissions were found for a combination of E20 compared to pure fuel and other blends.

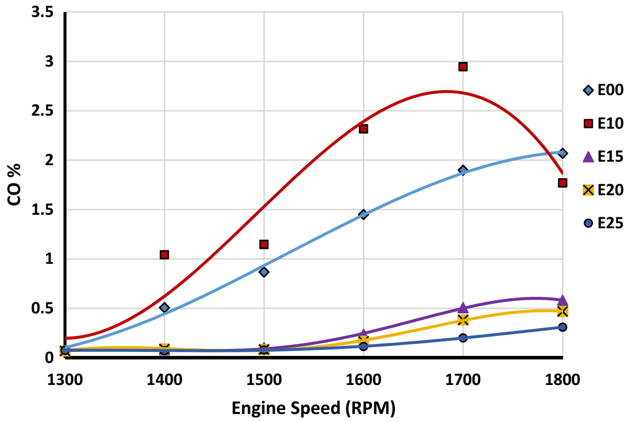

Fig. 8 Carbon Monoxide (CO) emission fluctuation with engine speed

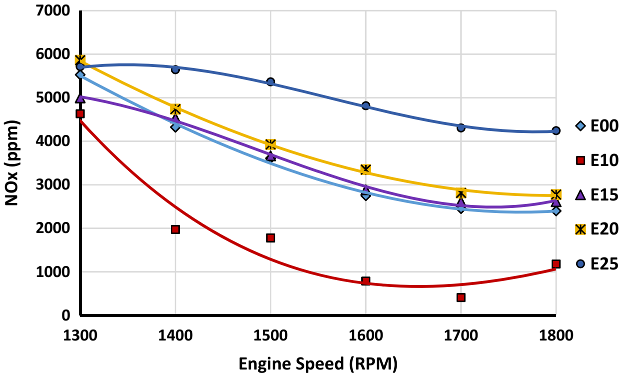

Fig. 9 Nitrogen oxide (NOx) emission variation with engine speed

Carbon monoxide (CO)

Figure 8 depicts the variation in the carbon monoxide (CO) emissions against engine speed for different ethanol–gasoline blends.

Inadequate air volume in the air/fuel mixture can result in carbon monoxide emissions. Ethanol enrichment in gasoline enables more oxygen mixing with gasoline, improving engine combustion. As a result of better mixing, there is a drop in carbon atom concentration, molecule diffusivity, high flammability and improved combustion efficiency, which reduces carbon monoxide emissions. CO emissions decrease with increasing ethanol blending compared to pure gasoline excluding the E10 blend. The maximum reduction in CO emissions for the E15, E20 and E25 blends was 88.36%, 90.32% and 90.89%, respectively, at full load compared to 1500 RPM of gasoline fuel.

Nitrogen oxide (NOx)

Figure 9 indicates that as the ethanol ratio of the fuel increases, NOx emissions increase, while decreasing at all operating rates of various ethanol mixtures. Oxygen concentration and combustion chamber temperature determine NOx formation. Ethanol with OH groups helps incomplete combustion and combustion chamber temperature drops as the proportion of ethanol rise. This suggests that the combustion chamber temperature is low and produces low NOx emissions for low blends. At 1700 RPM, the NOx reduction for the E10 mixture is 30% less than for gasoline fuel. It has been noticed that NOx emissions rise when the ethanol mix in pure gasoline increases. Compared to gasoline at 1800 RPM, the E15, E20 and E25 blends exhibit rises of 8.88%, 15.72% and 76.93%. This occurs due to the proximity of the combustion process to a stoichiometric process that increases the flame temperature, thus increasing NOx emissions.

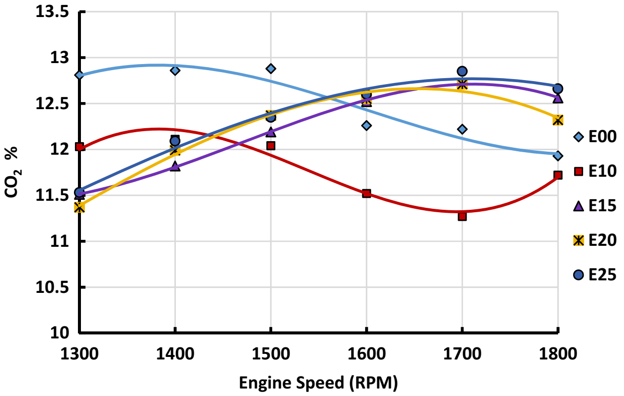

Fig. 10 Carbon dioxide (CO_2) emission fluctuation with an engine speeds

Carbon dioxide (CO_2) emissions

Figure 10 shows the CO_2 emissions for various operating speeds for different pomegranate ethanol mixtures. It was evident that CO_2 proportion increases with the more mixing of ethanol in the higher blend. CO_2 emissions depend on combustion and CO emissions concentration. Adding the ethanol percentage makes the engine richer and improves engine combustion, resulting in increased CO_2 emissions. For pure gasoline fuel, the CO_2 level in exhaust gas emissions at 1700 RPM was 12.22%, and for the E15, E20, and E25 blends, it was 12.73%, 12.71%, and 12.85%, respectively. At 1700 RPM, the CO_2 concentrations of E15, E20 and E25 increased by 4.17%, 4% and 5.15%, respectively, compared to pure gasoline.

Conclusion

In the work presented here, tests were conducted with a single cylinder, four-stroke spark-ignited engine with various pomegranate ethanol–petrol combinations for various engine speeds. The test results can be outlined as follows:

1. Addition of pomegranate ethanol to gasoline increases fuel consumption, brake capacity and decreases thermal efficiency, reducing HC and CO emissions, but increasing NOx emissions and CO_2 emissions.
2. Engine speed of 1500 RPM and E15 (15% ethanol + 85% gasoline) mix were found to be the optimum values for engine speed and fuel.

3. For the E15 blend, the highest brake thermal efficiency of 28.33% was obtained when the engine was running at 1500 RPM. Except for the E10 blend, the highest efficiency of each blend was found at 1500 RPM, which later decreased with increasing speed. BTE increased to its peak at 1500 RPM, then declined in the E15 and E25 blends. The same trend was observed for pure gasoline. For all blends, brake thermal efficiency is higher compared to unleaded gasoline at all engine speeds.
4. An increase in BSFC was found with an increase in the ethanol propotion and operating speed. BSFC decreases at lower speeds while increasing at higher speeds. The E10 blend has 12.12% higher BSFC than pure gasoline at 1600RPM engine speed, while the E15 blend has 12.12% lower BSFC than pure gasoline at 1500RPM. The BSFC in the E15 blend was found to be the lowest of all blends when the engine was running at a higher speed.
5. When the ethanol mix in gasoline increases at all operating speeds of the engine, the brake power increases. The braking power gained in relation to the E15 and E25 is more of all fuel blends and is the highest (4.73 kW) at 1700 RPM.
6. In comparison to pure petrol, as the ethanol propotion increases, the emissions of unbrunt hydrocarbons (HC) decrease. The lowest emission of HC was found in the E20 mixture compared to pure petrol and other mixtures. The maximum drop in HC for the E20 and E15 blends was observed at engine speeds between 1400 and 1600 RPM compared to unleaded petrol.
7. CO emissions decrease with increasing ethanol blend compared to pure fuel excluding E10 blend. The maximum drop in CO emissions for the E15, E20 and E25 blends was 88.36%, 90.32% and 90.89%, respectively, at full load compared to 1500 RPM of gasoline fuel.
8. Increasing the ethanol fraction of fuel increases NOx emissions, while decreases at all operating speeds of various ethanol mixtures. For the E10 blend, a 30% reduction in NOx emissions compared to gasoline fuel was observed when the engine was running at 1700 RPM. NOx emissions have been shown to increase as the ethanol proportion in pure gasoline increases. Compared to gasoline at 1800 RPM, the E15, E20 and E25 blends saw rises of 8.88%, 15.72% and 76.93%.
9. When ethanol is added, the CO_2 concentration increases with higher blends. At 1700 RPM of pure gasoline fuel, the CO_2 concentration was 12.22%, for E15, E20 and E25 it was 12.73%, 12.71%, and 12.85%, respectively, and for the E15, E20 and E25 blends, the CO_2 concentration increased by 4.17. %, 4% and 5.15%, respectively, compared to neat gasoline when the engine ran at 1700 RPM.

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