Experimental Analysis of Spark Ignition Engine on Exhaust Gas Temperature and Deposit Formation using Alcohol Blend Fuels

Ali Murtaza Ansari*, Liaquat Ali Memon†, Faheem Ahmed Solangi‡, Altaf Alam Noonari§, Arif Rub **

Abstract

Using gasoline engines with alcohol is another method to lessen reliance on fuel. Gasoline can be mixed directly with higher alcohols, like ethanol (E), which are generally derived from non-edible sources and have a high carbon content. Among the issues faced by consumers of fossil fuels include price volatility, supply constraints, environmental damage, increasing demand over time, and greenhouse gas emissions contributing to climate change. Similar effects are seen with gasoline fuel, albeit with distinct issues. Research indicates that the addition of alcohols to gasoline fuel alters its properties. An air-cooled single-cylinder spark ignition engine's exhaust gas temperature characteristics were examined in this work by adding E10 and E20 with ethanol percentages to pure gasoline. A 4-stroke, single-cylinder petrol engine operating at a steady 1350 rpm was used in our tests. With the same working braking power, temperatures of 270 ºC, 274 ºC, and 288 ºC were recorded in the case of G80E20 with a 20% ethanol dosage. Compared to G100 and G90E10, the exhaust gas temperature (EGT) decreased for G80E20 when ethanol concentration was added. These findings imply that there is no need for modifications while using the high concentration blend G80E20 and the low concentration mix G90E10 in gasoline engines.

Keywords**:** Spark Ignition Engine, Blend Fuel, Ethanol, Exhaust Gas Temperature, Deposit formation, Spark Plug.

Introduction

Although the combustion products of fossil fuels and the rise in automotive use have a negative influence on the environment, fossil fuels are essential for power generation and for starting domestic engines (Junshuai et al., 2022). This has led to a global push for low-carbon lifestyles (Cai et al., 2021). Oil, a non-renewable resource used for

*Department of Technology, Faculty of Engineering Science & Technology, Hamdard University, North Nazimabad campus, Karachi 74700, Pakistan, ali.murtaza4646@gmail.com

† Department of Machenical Engineering, Quide-e-Awam University of Engineering, Science & Technology Nawabshah, Nawabshah 67450, Pakistan, liquatali@quest.edu.pk

‡ Corresponding Author: Department of Energy System Engineering, Quaid-e-Awam University of Engineering, Science & Technology Nawabshah, Nawabshah 67450, Pakistan, faheemahmed@quest.edu.pk

§Department of Environmental Sciences, Aror University of Art, Architecture, Design and Heritage, Rohri, Sukkur 65200, Pakistan, noonarialtaf@yahoo.com

** Department of Technology, Faculty of Engineering Science & Technology (FEST) Hamdard University, North Nazimabad campus, Karachi 74700, Pakistan, arifrabba@gmail.com

transportation and power generation, is getting harder to find and its price varies as energy demands increase (Venkatesan et al., 2017). Determining the amount of energy available, the challenges to the global strategy for living below carbon footprints, the current situation of finite fossil fuel supplies and rising fuel costs, and the problems associated with the pollution caused by burning fossil fuels have all prompted research into clean and sustainable energy sources. Investigations into the potential use of internationally suitable, practically accessible, and technically feasible renewable energy sources as an alternative fuel are currently crucial (Soudagar et al., 2020).

More importantly, the environmental problems caused by burning fossil fuels have prompted researchers to find solutions to lower the dangerously high air pollution levels and the possible effects they may have. According to Mohadesi et al. (2014), biofuels have garnered the greatest interest among alternative fuels as the ideal backup fuels for the transportation sector. Because of the increased demand for energy and the depletion of petroleum supplies, biodiesel is a feasible alternative energy source for the transportation sector. The risk of pollution, however, exists. Many countries have only lately begun to produce and use biodiesel. Unfortunately, adding higher amounts of biodiesel is prohibited in many countries. Even at low ratios, blended biodiesel has been recommended by some Asian nations as a long-term emission reduction method.

According to Abomohra et al. (2020), biodiesel is currently utilized in several nations and offers numerous benefits. Biodiesel, which is manufactured in large quantities using various techniques, is one resource that is left over after use. Used oils, vegetable fats, and animal fats are the main ingredients in the esterification process used to produce biodiesel (Cai et al, 2022). Nonetheless, employing garbage as feedstock can drastically lower the cost of making biodiesel (Khan et al., 2014). Many characteristics of diesel and biodiesel are similar, but biodiesel is different because it contains more oxygen, which encourages full combustion and, as a result, produces more energy (higher cetane number) (Lin et al, 2009). However, according to McCarthy et al. (2011), burning biodiesel generates less energy than burning diesel.

In recent years, researchers have advanced our understanding of nanoparticles and their applications. Metals, ceramics, and polymers make up the majority of nanoparticles. Nanoparticles of iron, carbon, aluminum, and titanium are commonly employed (Burda et al., 2005). The burning of liquids containing carbon nano-additives has been the subject of numerous investigations (Shaafi et al., 2015).

Alcohols are secondary energy transporters in liquids and improve combustion. Recent years have seen the addition of oxides of silicon, graphene, titanium, iron, cobalt, copper, cerium, aluminum, and silver to a wide range of mixtures. In order to retain engine production at its maximum levels with lower exhaust emissions, scientists have found that adjusting the physicochemical characteristics of gasoline works better than changing the engine's construction.

The literature has documented a wide variety of metal-and metal oxide-based nanoadditives (Khond et al, 2016). One of the most crucial elements in controlling the discharge from an internal combustion engine and maximizing performance is the temperature of the gaseous mixture exiting the combustion chamber (Kalam et al., 2011).

This happens because of the interplay between the cylinder's igniting process and the exhaust gas temperature (EGT) as well as the "after combustion" processes that occur inside the drain manifold (Agarwal et al., 2011). EGT can also help with engine diagnostics and maintenance scheduling, which can lead to a longer machine life (Wang et al., 2017). Some of the factors that contribute to EGT include a partially impermeable air entrance, a dirty or constrictive air filter, limited airflow to or through the radiator, and the weather (pressure, temperature, and humidity) (Parlak et al., 2006). For the next generation of high-performance engines that run close to engine material limits, EGT is also useful in determining the temperatures of the cylinder head, cylinder liner, and piston—all critical factors (Algayyim et al., 2024).

This study is unique because it examines a particular air-cooled spark ignition engine running on locally obtained ternary blend fuels, a combination that hasn't gotten much attention in previous research. In contrast to earlier research that mostly concentrated on conventional single-component biofuels or water-cooled biofuels, the current study assesses the performance and emission characteristics of a special fuel blend under actual operating conditions that are pertinent to air-cooled engines that are frequently utilized in local applications.

The E10 and E20 ternary blends used in this study were chosen for their engine compatibility and practical and technical significance to current fuel regulations. Because of their better octane rating, lower emissions of hydrocarbons and carbon monoxide, and attractive combustion properties, ethanol–gasoline blends up to 20% are frequently used in commercial applications. Without needing significant changes to the current spark ignition engine architecture, the blend ratios E10 and E20 enable the assessment of the incremental effects of ethanol content on engine performance and emission behaviour. Additionally, using ethanol that is produced nearby helps achieve energy diversification and environmental objectives.

This research was to regulate the optimum ingredient for a gasoline and alcohol combination. It was done as part of the process of developing a new mixture that could be utilized in a gasoline engine and had a low to high ethanol content per volume. Examine how the exhaust gas temperature of a SI gasoline engine changes when regular gasoline fuel is mixed with ethanol concentrations of low and high (20% in volume), E10 + G90 (20% + 89% in volume), and G80E20.

Nomenclature	
E	Ethanol
E10	Ethanol 10%+ gasoline 90%
E20	Ethanol 20%+ gasoline 80%
SIE	Spark Ignition Engine
EGT	Exhaust gas temperature
N	Engine speed, rev/min
SP	Spark Plug
D	Deposition

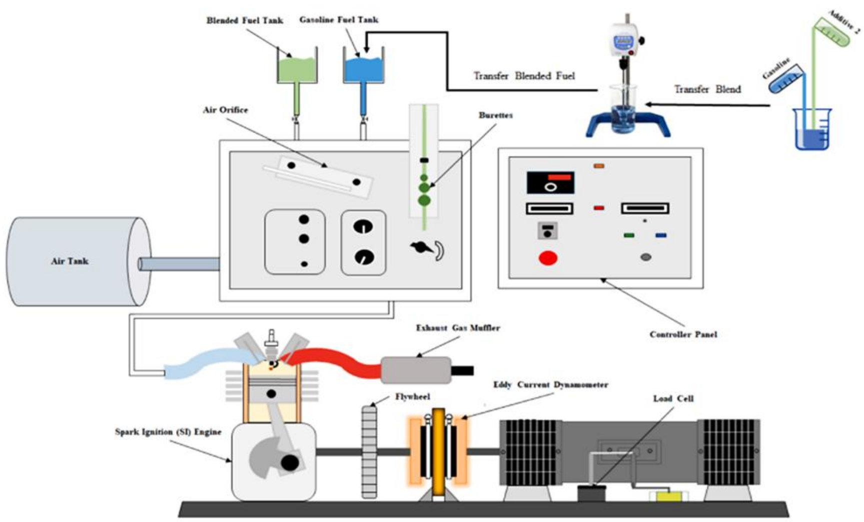


Figure 1: Schematic diagram of engine test bed.

Material and Methods

The engine being studied is situated in the thermodynamics lab of QUEST University Nawab Shah's Mechanical Engineering Department. The experimental setup's schematic diagram is displayed in Figure 1 above. A 4-stroke, 1-cylinder gasoline locomotive is chosen and installed on a test rig to highlight its key characteristics. The test engine was supplied with fuel from two fuel tanks, one for mix fuels and the other for gasoline G100. The eddy current dynamometer is attached to the engine.

For real-time monitoring, K-type thermocouples with an accuracy of ±0.5°C and a response time of roughly one second were used to measure exhaust gas temperatures (EGT). These thermocouples were coupled to a digital data gathering system. Using pressure transducers and calibrated dynamometers, engine performance metrics were noted. Using a scanning electron microscope (SEM) with magnifications ranging from 500× to 5000× and an accelerating voltage of 15 kV, surface and deposition investigations were carried out. Before imaging to guarantee excellent surface resolution, samples were meticulously cleaned, dried, and gold-coated. The data were statistically examined using mean values and standard deviations, and each test was carried out in triplicate to guarantee the validity of the experimental findings.

The fuel samples that were mixed with ethanol Prior to using ethanol concentration mix fuel, the G90E10 and G80E20 engines were first run on gasoline to establish baseline conditions. The fuel combinations displayed above were generated by them. Table 1 displays the physiochemical properties of pure gasoline or ethanol as well as the engine requirements. G100 gasoline was the fuel mixture with the greatest carbon content in the test engine.

Table 1: Fuel Properties.

Properties	Ethanol
Molecular formula	C_2H_5OH
Viscosity (Pa·s) at 20 ◦C	0.789
Research octane number	108–129
Flammability limits (% vol.)	4.3–19
Stoichiometric air–fuel ratio	9.02

The testing was conducted using a four-stroke, single-cylinder, air-cooled, spark-igniting engine connected to an eddy current dynamometer. Table 2 displays this engine's main specs. Figure 2 depicts the fuel samples' physical characteristics.

Figure 2: Visual view of test fuels (a) Gasoline (b)G90E10 (c) G80E20.

Table 2: Engine Specification.

Engine Model	Four Stroke, Spark Ignition
Swept volume	0.304mm3
Engine type	Single cylinder
Briggs & Stratton OHV	P8160
Fuel	Petrol
Number of strokes	4
Cooling system	Air cooled

Each fuel sample was analyzed as part of the inquiry. After the engine was disassembled to extract the engine head for analysis, the three remaining test fuels were used in the same manner. Lastly, each engine head sample that was gathered was examined using Scanning Electron Microscopy (SEM). SEM techniques have been used to identify the deposit accumulations on the exhaust valve surface.

Experimental Work

Figure 3 illustrates how adding alcohols to the gasoline blend at different power outputs affects the exhaust gas temperatures, in contrast to applications employing pure gasoline and alcohol blend fuels. As anticipated, exhaust temperatures rose in tandem with power output. The gasoline's ethanol blend G90E10 percentage was lower and its exhaust gas temperatures were marginally higher. The temperatures were slightly lower, nevertheless, when the blend was mixed with a high concentration ratio of blend fuel G80E20 (Moustafa et al., 2025).

When injecting liquid fuel under high pressure, the presence of an alcohol blend affects the injection parameters and the way the fuel particles spread out in the hot air. As a result, during expansion and combustion, the rate of heat release is altered. In contrast to situations involving pure diesel or a mixture of gasoline and ethanol blend fuel, as explained below, the piston transforms a greater percentage of the available heat into mechanical work, leading to a higher output power.

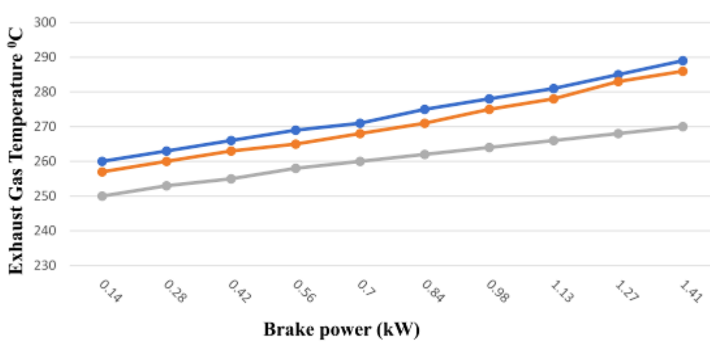


Figure 3. Exhaust gas temperature versus brake power.

Results and Discussion

Deposit Formation of Spark Plug Baseline Fuel and Blend Fuels

An endurance test was conducted on a spark ignition engine to evaluate deposit formation on engine parts, particularly the spark plug nap. The fuels used in the testing were ethanol (G80E20), gasoline (G100), and blend fuels with varying proportions of ethanol and gasoline (G90E10). A long-term endurance test was performed by replacing the engine spark plug in each sample for a deposition study. Following the completion of the warm-up phase, the locomotive to ensure consistency throughout the test. Since there is no petroleum extraction involved, the E100 product system in biofuels exhibits the least potential for acidification of all. "Sugarcane production" and "Steam, in the chemical industry" together account for 97% of this product system, with "transport, tractor, and trailer" making up the remaining 3%. Ammonium sulphate, a chemical fertilizer that provides Sulphur, is the primary fertilizer used in sugarcane farming in India. Although using these fertilizers increases agricultural output, the release of sulfur compounds like SO_2 during soil biogeochemical processes causes sulfur emissions (Harde & Ojha, 2025)

Table 3: Previous study on biofuels.

Engine type	Ethanol blend	Main results	Investigator
Single cylinder Hydra spark ignition engine	E10, E20, E40 and E60	↑Brake torque, BSFC and ↓HC CO	Costagliola et al. (2012)
A single-cylinder, 4- stroke spark ignition engine	E10, E15, E25 and E35	↓BTE, CO and CO_2	Topgül et al. (2006)
Hydra one-cylinder, four stroke, gasoline engine	E10, E20 E40 and E60	↑Brake torque, HC and ↓BSFC, CO	Elfasakhany (2014)
A single-cylinder, 4- stroke SI engine	E50 and E85	↑Brake torque, BSFC and ↓ CO, HC, NOx	Kothare et al. (2016)

In a long-term endurance test, elements deposition was visible on the surface of three distinct spark plug naps. A deposition study was carried out utilizing microscopic and visual inspection tests at various spark plug naps. The test also monitored the decrease of film viscosity to determine the impact of gasoline on engine performance.

Compared to the gasoline and alcohol blended fuel, the gasoline sample containing the ethanol mixture contained greater residue. Additionally, there was more deposit on the spark plug's exhaust side than its intake side. Additionally, the deposit was found to be irregularly distributed throughout the spark plug nap under a microscope, with more deposition in certain areas than others.

Due to localized combustion and greater deposition in certain areas, it was found that the unequal distribution of fuel in the engine cylinder was the source of the unequal deposition. Moreover, alcohols were shown to lose more cinematic viscosity than the other two fuels, indicating that fuel viscosity affects both deposition on the spark plug nap and engine performance.

Spark Plug Comparison Baseline Fuel and Blended Fuels Visual Inspection

The long-term endurance test was passed by the gasoline fuel G100 and the ethanol blend fuels G90E10 mixes. Following a partial disassembly of the engine, each spark plug's deposit formation was examined. Higher temperatures near plug nap depositions, which might result in deposits that are especially difficult to remove, are a characteristic of advanced gasoline (Solangi et al., 2024).

When the G100, G90E10, and G80E20 mix were put through a lengthy running endurance test, spark plug pictures were collected, as shown in Fig. 4. The head surfaces and spark plug liners of both fuel types showed some deposit deposition after different operation hours, as shown in Fig. 4 (a-c).

Carbon deposits on several important engine parts were qualitatively analyzed (photographically). In order to guarantee that the engine ran at the same speed and under the same load circumstances during both experiment phases, the engine power output was kept constant throughout the endurance test (Anand et al., 2018). As shown in Fig. 4, spark plugs were captured on camera during an endurance test on the baseline and blend gasoline samples G100, G90E10, and G80E20 mix.

As seen in Figure 4, pictorial examine the following dissimilar operation hours showed deposit in the spark plug nap of all test gasoline samples. However, compared to G80E20, utilizing G100 baseline fuel produced a dirtier spark plug nap surface. Additionally, the plug nap exposed to the G80E20 blend exhibited dry deposits, while the plug nap exposed to the G100 blend had greasy/oily deposits.

(a) (b) (c)

Figure 4: Visual inspections of a) gasoline G100, b) Ethanol G90E10 10% and c) Ethanol 20% G80E20.

Carbon dioxide is one byproduct of burning. Incomplete fuel combustion and lubricating fluid contamination contribute to some of the carbon deposition. However, the spark plug nap operating on G90E10 was dirtier than the one operating on G100 76.46%. Similar results have been documented. The amount of deposit formation in the spark plug nap was discovered in another investigation by Birgel et al. (2022). Additionally, deposits were discovered to be greasy and oily on the spark plug nap running with G100 and dry on the spark plug nap running with the G90E10 21.16% mix. Reduced deposit on the spark plug nap is the outcome of using the mix fuel sample G80E20 17.75%.

The analysis of deposit formation on the intake and combustion chamber surfaces revealed a significant reduction when using the G80E20 ternary blend. Energy-dispersive X-ray spectroscopy (EDX) quantification showed that carbon deposits decreased by approximately 28% compared to the baseline gasoline (G100), with error margins of ±2–3% based on triplicate measurements. This reduction is attributed to the higher oxygen content in ethanol, which promotes in-cylinder oxidation of carbonaceous species, thereby mitigating deposit accumulation. Additionally, the presence of ethanol improves fuel atomization and combustion completeness, further contributing to lower surface deposits. These findings provide both quantitative evidence and mechanistic insight into the effectiveness of ethanol-enriched blends in reducing engine deposits, enhancing the reliability and interpretability of the experimental results.

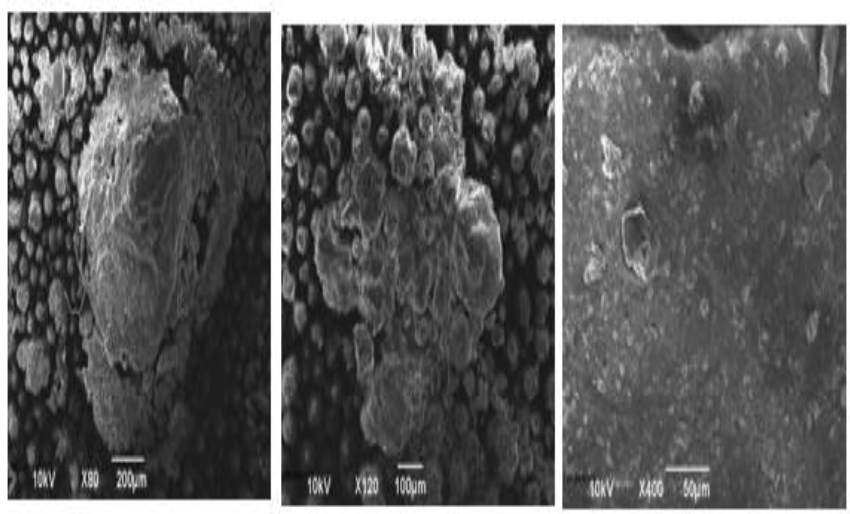
Scanning Electron Microscopy of Gasoline and Ethanol Blend Fuels

The locomotive was moderately disassembled and the deposit on each locomotive spark plug was examined following the completion of the long-term durability test for the G100, G90E10, and G80E20 mix. Li et al. (2019) state that increased gasoline PFI systems are characterized by high temperatures around the spark plug nap.

In this study, the carbon deposits on engine heads were measured and photographed. When the G100 was utilized in damp and dirty conditions, a thick carbon deposit was discovered on the spark plug, in contrast to petroleum gasoline, as shown in Figure 5 (a-c). This could be the consequence of the lighter fuel content evaporating and deteriorating (Hagos et al., 2015).

There is less carbon deposit in the G90E20 engine. When burning G80E20 cleaner in an atmosphere with higher oxygen concentrations, less clean deposits may form. As seen in figure 5, test gasoline G80E20, however, had less deposition.

Figure 5 displays SEM micrographs of deposits on the spark plug of a SI engine that is powered by G90E10 and G80E20, respectively. It is evident that deposits with G100 are substantially lower than those with the G90E10 combination. Figure 5 (a-c) shows the SEM of deposits on a spark plug driven by gasoline (G), ethanol low per volume (G90E10), and ethanol (G80E20). On G100, the top layer of the piston crown had a carbon concentration of 89.68%, while on gasoline, it was 76.42%. Elemental analysis showed that the equivalent oxygen concentrations were 17.75% and 21.16%, respectively, and that carbon levels were often greater in darker places.



(a) (b) (c)

Figure. 5 SEM running on gasoline fuel and blend fuels a) G100, b) G90E10 and c) G80E20.

However, the carbon content of G80E20 was found to be 31.29 percent. On the other hand, their respective oxygen concentrations were 42% and 32.21%. Several other metal elements were also included in the spectrum of this investigation. This illustrates that the carbon layer that develops during deposition is not necessarily dense in the case of baseline fuel. There are two primary processes by which carbon deposits form at high temperatures: either hydrocarbons combine and condense into higher polynuclear aromatic hydrocarbons (PAHs), which are the building blocks for the development of carbonaceous deposits, or hydrocarbons decompose into elemental carbon and hydrogen. Several metallic elements were detected in the spectra of the resultant deposition.

Conclusion and Future Work

The experiment results were used to evaluate the exhaust gas temperature, deposition properties, and operation of a single-cylinder horizontal gasoline engine that runs on a blend of gasoline and alcohol. The stability and solubility of the blended gasoline fuel are enhanced by the addition of ethanol. The G90E10 and G80E20 exhibit great potential for usage in unmodified SI engines based on their physical and chemical characteristics. This study examined the exhaust gas temperatures of blend fuels G90E10 and G80E20 with gasoline fuel. Under engine operating circumstances, the exhaust gas temperature was lowered by using G80E20 rather than G100 and G90E10. This study compared gasoline fuel to blend fuels like G100, G90E10, and G80E20 in order to examine the spark plug nap endurance test. Visual examination of the spark plugs of the G100, G90E10, and G80E20 fuel-running engines showed trace amounts of deposit deposition. In contrast, the spark plugs that used G90E10 and G80E20 were found to be cleaner than the spark plug that used G100. Spark plug nap substantially fewer deposits when G100 and G80E20 were used in place of the G90E10 combination. No uniformly thick coating of carbon developed. Deposits on mix fuel samples also did not significantly damage the spark plug.

Future research will build on these findings by extending the analysis to other engine speeds and load circumstances, assessing long-term engine longevity, and performing a thorough emissions assessment that includes CO, HC, NOx, and particulate matter. To supplement the mechanistic and quantitative results presented here, additional research into different mix ratios will provide light on the environmental impact and practical usability of ethanol-enriched ternary fuels.

References

Abomohra, A. E. F., Elsayed, M., Esakkimuthu, S., El-Sheekh, M., & Hanelt, D. (2020). Potential of fat, oil and grease (FOG) for biodiesel production: A critical review on the recent progress and future perspectives. *Progress in Energy and Combustion Science*, *81*, 100868.

Abdullah, N., Mohamed Zaharin, M. S., Bin Mamat, A., Nawi, M., & Sharudin, H. (2015). Effects of ethanol blends on gasoline engine performance and exhaust emissions. *Jurnal Teknologi, 76*.

Agarwal, D., Singh, S. K., & Agarwal, A. K. (2011). Effect of exhaust gas recirculation (EGR) on performance, emissions, deposits, and durability of a constant-speed compression ignition engine. *Applied Energy, 88*(8), 2900–2907.

Algayyim, S., Saleh, K., Wandel, A., Fattah, I. M. R., Yusaf, T., & Alrazen, H. (2024). Influence of natural gas and hydrogen properties on internal combustion engine performance, combustion, and emissions: A review. *Fuel, 362*, 130844.

Ben Hassen, T., & El Bilali, H. (2022). Impacts of the Russia–Ukraine war on global food security: Towards more sustainable and resilient food systems? *Foods, 11*(15), 2301.

Burda, C., Chen, X., Narayanan, R., & El-Sayed, M. A. (2005). Chemistry and properties of nanocrystals of different shapes. *Chemical Reviews, 105*(4), 1025–1102.

Cai, T., & Zhao, D. (2022). Temperature dependence of laminar burning velocity in ammonia/dimethyl ether–air premixed flames. *Journal of Thermal Science, 31*(1), 189–197.

Cai, T., Zhao, D., Sun, Y., Ni, S., Li, W., Guan, D., & Wang, B. (2021). Evaluation of NOx emissions characteristics in a CO_2-free micro-power system by implementing a perforated plate. *Renewable and Sustainable Energy Reviews, 145*, 111150.

Costagliola, M. A., De Simio, L., Iannaccone, S., & Prati, M. V. (2013). Combustion efficiency and engine-out emissions of a spark-ignition engine fueled with alcohol/gasoline blends. *Applied Energy, 111*, 1162–1171.

Elfasakhany, A. (2014). The effects of ethanol–gasoline blends on performance and exhaust emission characteristics of spark ignition engines. *International Journal of Automotive Engineering, 4*, 1–8.

Hagos, F. Y., Aziz, A. R. A., & Sulaiman, S. A. (2015). Investigation of deposit formation in a direct-injection spark-ignition engine powered by syngas. *International Journal of Automotive Technology, 16*(3), 479–485.

Harde, C. K., & Ojha, D. K. (2025). Are ethanol–gasoline blends sustainable in India? A life cycle perspective on benefits and trade-offs. *Sustainable Chemistry for Climate Action, 7*, 100128.

Hasan, A. O., Al-Rawashdeh, H., Abu-Jrai, A., Gomaa, M. R., & Jamil, F. (2023). Impact of variable compression ratios on engine performance and unregulated HC emissions from a single-cylinder research engine fueled with commercial gasoline. *International Journal of Hydrogen Energy, 48*(68), 26619–26628.

Heydari-Maleney, K., Taghizadeh-Alisaraei, A., Ghobadian, B., & Abbaszadeh-Mayvan, A. (2017). Evaluation of carbon nanotube additives in diesohol–B2 fuels on diesel engine performance and emissions. *Fuel, 196*, 110–123.

Kalam, M. A., Masjuki, H. H., Jayed, M. H., & Liaquat, A. M. (2011). Emission and performance characteristics of an indirect injection diesel engine fueled with waste cooking oil. *Energy, 36*(1), 397–402.

Khan, T. M. Y., Atabani, A. E., Badruddin, I. A., Badarudin, A., Khayoon, M. S., & Triwahyono, S. (2014). Recent scenario and technologies to utilize non-edible oils for biodiesel production. *Renewable and Sustainable Energy Reviews, 37*, 840–851.

Khond, V. W., & Kriplani, V. M. (2016). Effect of nanofluid additives on performance and emissions of emulsified diesel and biodiesel-fueled stationary CI engines: A comprehensive review. *Renewable and Sustainable Energy Reviews, 59*, 1338–1348.

Kothare, C., Kongre, S., & Bhope, D. (2016). Experimental investigation of gasoline–higher alcohol blends on performance characteristics of a four-stroke spark-ignition engine at variable compression ratio. *International Journal of Engineering Research & Technology, 5*(5), 1–6.

Li, X., Guan, C., Yang, K., Cheung, C. S., & Huang, Z. (2019). Impact of lower and higher alcohol additions to diesel on combustion and emissions of a direct-injection diesel engine. *Environmental Science and Pollution Research, 26*, 25991–26002.

Lin, C.-Y., & Li, R.-J. (2009). Engine performance and emission characteristics of marine fish-oil biodiesel produced from discarded fish parts. *Fuel Processing Technology, 90*(7), 883–888.

Lv, J., Wang, S., & Meng, B. (2022). Effects of nano-additives added to diesel–biodiesel fuel blends on combustion and emission characteristics of diesel engines: A review. *Energies, 15*(3), 1032.

McCarthy, P., Rasul, M. G., & Moazzem, S. (2011). Analysis and comparison of performance and emissions of an internal combustion engine fueled with petroleum diesel and biodiesels. *Fuel, 90*(6), 2147–2157.

Mohadesi, M., Hojabri, Z., & Moradi, G. (2014). Biodiesel production using alkaline earth metal oxide catalysts synthesized by sol–gel method. *Research Journal of Seed Science, 1*, 1–7.

Moustafa, E. B., & Hussein, H. (2025). Enhancing automotive performance: A comparative study of spark plug electrode configurations on engine behavior and emission characteristics. *Vehicles, 7*(2), 55.

Parlak, A., İslamoğlu, Y., Yaşar, H., & Erişoğut, A. (2006). Application of artificial neural networks to predict specific fuel consumption and exhaust temperature for a diesel engine. *Applied Thermal Engineering, 26*, 824–828.

Shaafi, T., Sairam, K., Gopinath, A., Kumaresan, G., & Velraj, R. (2015). Effect of dispersion of various nano-additives on performance and emission characteristics of a CI engine fueled with diesel, biodiesel, and blends: A review. *Renewable and Sustainable Energy Reviews, 49*, 563–573.

Solangi, F., Memon, L., Samo, S., Luhur, M., Memon, I., Ansari, A., & Mastoi, S. (2024). Comparative assessment of head deposition, exhaust gas temperature, and sound emission in a CI engine using blended fuels. *Jurnal Kejuruteraan, 36*, 1321–1327.

Soudagar, M. E. M., Nik-Ghazali, N.-N., Kalam, M. A., Badruddin, I. A., Banapurmath, N. R., Bin Ali, M. A., Kamangar, S., Cho, H. M., & Akram, N. (2020). Influence of aluminium oxide nano-additive and honge oil methyl ester on engine performance, combustion, and emission characteristics. *Renewable Energy, 146*, 2291–2307.

Topgül, T., Yücesu, H. S., Çınar, C., & Koca, A. (2006). The effects of ethanol–unleaded gasoline blends and ignition timing on engine performance and exhaust emissions. *Energy Conversion and Management, 47*(15–16), 2534–2542.

Wang, Z., Liu, H., & Reitz, R. D. (2017). Knocking combustion in spark-ignition engines. *Progress in Energy and Combustion Science, 61*, 78–112.

Yu, W., Zhang, Z., & Liu, B. (2021). Performance enhancement and emission reduction of a biodiesel-fueled diesel engine using an improved engine simulation model. *Processes, 9*(1), 104.