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Research on Bioethanol/Gasoline Ratios and Engine Spark Ignition Control for Energy and Environmental Sustainability of Vehicles

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Abstract: This article presents an experimental study focused on the impact of supplementing pure gasoline (E0) with bioethanol, gradually increasing the biofuel concentration up to 70% (E10, E50, and E70). The research was conducted in two phases: In the first phase (Part I), the engine's operation involved varying engine speeds (n = 2000 rpm, n = 2500 rpm) and adjusting throttle openings (15%, 20%, 25%) to analyze changes in brake torque, thermal efficiency, and ecological indicators. The second phase (Part II) aimed to complement and clarify the study data. Here, the engine was maintained at a constant speed (n = 2000 rpm) and brake torque (M_B = 80 Nm) while altering ignition timing. The findings revealed that increasing the bioethanol concentration up to 70% led to modest enhancements in engine brake torque and thermal efficiency. However, the most significant impact was observed in the reduction of greenhouse gas emissions and incomplete combustion byproducts. The study also established that achieving higher thermal efficiency requires compensating for the extended ignition delay phase resulting from bioethanol addition by advancing ignition timing. Nevertheless, this approach is constrained by the escalating emissions of carbon dioxide and hydrocarbons. These findings provide valuable insights into optimizing the balance between bioethanol supplementation, engine performance, and environmental sustainability in spark ignition engines.

Keywords: engine; spark ignition; bioethanol; gasoline; fuel mixture; throttle opening; ignition timing; engine performance; emissions

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1. Introduction

The Paris Agreement, a landmark agreement in the global fight against climate change, has set out an imperative: countries must develop and implement strategies to reduce emissions across all sectors, with transport under particular scrutiny [1]. As nations strive to meet their commitments under this agreement, the spotlight is increasingly on the transport industry. This sector is not only a significant contributor to global emissions, but also a critical focus for pioneering sustainable and environmentally responsible solutions [2,3]. In this context, the use of cleaner and more sustainable fuels [4–6], increased energy efficiency [7,8], and the incorporation of cutting-edge technologies to reduce the environmental impact of transport have emerged as central pillars in the transition to a greener future. Among these solutions, bioethanol stands out as a keystone, offering a multi-faceted approach to addressing the common challenges of sustainable transport [9–11].

The use of ethanol in transport can significantly reduce CO_2 emissions. The use of 15-30% ethanol petrol blends can reduce CO_2 emissions by between 7.2 and 13.4% [12]. Increasing the ethanol content of petrol is therefore necessary to increase the CO_2 neutrality of transport, but unfortunately it is currently limited to 10% in many countries.

Ethanol can be used in both spark-ignition and compression-ignition engines [13]. However, while spark-ignition engines use a wide range of petrol/ethanol blends, from very low percentages to pure ethanol, compression-ignition engines can only add a relatively small percentage of ethanol [14–16].

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The other scientists from China present an innovative method for bioethanol production using apple wood residue [17]. Their research not only demonstrates the potential of apple wood residue as a sustainable source of bioethanol, but also the adaptability and versatility of bioethanol in different production contexts.

As the global movement towards sustainable fuels continues to gain momentum, scientists in the US are looking at the escalating emissions from the transport sector [18]. Their comprehensive analysis assesses the environmental impact of producing bioethanol from different feedstocks, with a focus on global availability. The results paint a compelling picture for the use of waste-based feedstocks, which have minimal environmental impact and offer a potential solution to the perennial food versus fuel debate. Not only do waste feedstocks reduce material consumption and land use compared to agricultural feedstocks, they also fit seamlessly with the broader goals of sustainability and emissions reduction.

The addition of ethanol as a gasoline additive in spark-ignition engines, where the air-fuel mixture is prepared in the carburettor, leads to a slight reduction in engine power and torque due to the air-fuel mixture becoming leaner [19]. However, engines equipped with a multi-point fuel injection system exhibit the opposite effect, resulting in a slight increase in engine torque and brake power [20]. The brake specific fuel consumption increases in both cases due to the lower calorific value of ethanol. Nevertheless, when taking into account the fuel mass and calorific value, the energy consumption among all mixtures and pure petrol appears to be remarkably similar [21].

Otto engines with a carburettor show a significant reduction in NO_x emissions that is directly proportional to the percentage of ethanol in the ethanol/petrol mixture. This is influenced by the decreasing combustion temperature [19]. However, this leads to increased emissions of CO and HC. Engines equipped with a multi-point fuel injection system, utilizing an ethanol/petrol mixture, demonstrate diminished emissions of CO and HC. Notably, the emissions of CO_2 exhibit an increase in this context. NO_x emissions in such engines remain relatively stable at lower revs and torque levels; however, under elevated loads, there is a discernible rise in NO_x emissions [20].

The aim of this paper is to highlight the potential of bioethanol in the widest possible transport context, including aviation. Some work has shown that ethanol can affect the spray characteristics of fuels [22]. For example, a blend of 20% ethanol and aviation kerosene is an ideal alternative fuel for aircraft engines that improves atomisation performance and therefore has a high potential for use in aircraft engines. Bioethanol (or bioethanol/kerosene blends) can be used not only in jet engines, but also in pulse engines for aerospace applications [23].

The work of Liu and others illustrates how ethanol biofuel uniquely addresses two pressing challenges: oil security and CO_2 emissions [24]. Given the aviation industry's heavy reliance on imported kerosene, securing a stable and sustainable supply of oil is of paramount importance. At the same time, reducing carbon emissions is of paramount importance to meet stringent environmental sustainability targets. Biofuel ethanol, derived from renewable biomass, is emerging as a viable solution that offers a twofold remedy by reducing dependence on finite petroleum resources and reducing greenhouse gas emissions. These findings are equally promising for the road transport sector, where ethanol-based fuels can serve as a viable option to reduce reliance on fossil fuels and reduce emissions from spark ignition engines.

Research by scientists at Tianjin University presents innovative ethanol-to-jet fuel processes that combine corncob gasification, syngas fermentation and ethanol conversion. A life cycle assessment underlines the benefits of corncob gasification combined with fermentation, highlighting the potential for reduced emissions and cleaner production methods [25].

As we embark on this journey towards sustainability, it is crucial to consider the compatibility and feasibility of different bioethanol concentrations within existing systems. The use of different bioethanol concentrations provides an opportunity to identify optimal blend ratios that balance performance, fuel economy and emissions [26]. This knowledge is crucial not only for developing guidelines for the use of higher bioethanol blends, but also for optimising engine performance, ultimately contributing to improved overall efficiency in sustainable transport.

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In conclusion, despite previous research in this area, ongoing testing with different bioethanol concentrations remains relevant and critical. Such investigations provide the basis for a deeper understanding of combustion processes with alternative fuels, compatibility assessments with existing systems and the development of cleaner and more sustainable transport solutions. Collectively, these studies are influencing the ongoing development of bioethanol as a viable and environmentally friendly fuel source, offering a promising future for sustainability in sustainable transport.

Nevertheless, notwithstanding the enumerated favorable attributes of ethanol and its positive impact on fuel emissions and efficiency, recent scientific review articles reveal inconsistencies in the findings of certain studies [26,27]. Therefore, the objective of our study is to reassess and substantiate the influence of ethanol-gasoline mixtures on emissions, brake thermal efficiency and other parameters in spark ignition engines.

2. Research methodology

The influence of bioethanol on the performance of an internal combustion engine was evaluated by conducting bench tests on the HR 16DE spark ignition engine from Nissan Qashqai (refer to Table 1). Experimental tests were conducted in two distinct stages, each designed to evaluate various engine performance parameters under controlled conditions: Stage I: During this phase, the engine's throttle opening was fixed at three different positions (15%, 20%, 25%). The engine's shaft rotation speed (n) and ignition timing (Θ) were set to specific values. Specifically, when the engine speed was set to n = 2000 rpm, the ignition timing was maintained at Θ = 20° Crank Angle (CA) before Top Dead Center (bTDC). Similarly, when the engine speed was adjusted to n = 2500 rpm, the ignition timing was set at Θ = 24° CA bTDC. This allowed for the assessment of key parameters, including Brake Torque (M_B), Brake Specific Fuel Consumption (BSFC), and both energy and ecological indicators, while keeping the throttle opening constant. Stage II: In the second stage of testing, the engine operated at a consistent engine load, maintaining a Brake Mean Effective Pressure (*BMEP*) of 0.62 MPa by adjusting the Brake Torque (MB) to 80 Nm. Within this stage, the ignition timing (Θ) was systematically altered, ranging from Θ = 16° CA bTDC to Θ = 32° CA bTDC. This phase enabled the assessment of the engine's energy and ecological performance indicators while keeping the engine load fixed.

Table 1. Engine data.

Specifications of the Nissan HR 16DE engine	Value
Number of cylinders	4
Piston stroke	83.6 mm
Cylinder bore	78 mm
Number of valves per cylinder	4
Displacement	1598 cm^3
Compression ratio	10.7
Nominal power	84 kW at 6000 rpm
Maximum engine torque	156 Nm at 4400 rpm

The engine testing setup, as illustrated in Figure 1, comprises essential components for precise control and measurement. The engine is under the command of the MoTeC M800 programmable electronic control unit (ECU). Engine load is generated using an eddy current-type AMX 200/100 load stand, boasting a maximum speed of 6000 rpm and a peak torque capacity of 480 Nm, with a remarkable accuracy of ±0.9 Nm. Fuel consumption is meticulously quantified using an electronic-gravitational fuel consumption weight, the AMX 212F, which provides measurement capabilities within the range of 0.01 to 50 kg/h and ensures precision at ±0.1%. To measure air consumption accurately, an air mass meter of the BOSCH HFM 5 variety is employed, capable of measuring within limits of 8 to 370 kg/h, with an accuracy of ±2%. The temperature of exhaust gases is precisely monitored through the utilization of a K-type thermocouple sensor, offering measurement

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capabilities ranging from 0 to +1250°C and delivering results with an accuracy of ±0.5%. Emissions analysis is performed using the AVL DiCom 4000 emission analyzer, offering accurate measurement limits for CO_2 (0 to 20%, with an accuracy of ±0.1%), CO (0 to 10%, with an accuracy of ±0.01%), HC (0 to 20000 ppm, with an accuracy of ±1 ppm), NO_x (0 to 5000 ppm, with an accuracy of ±1 ppm), and O_2 (0 to 25%, with an accuracy of ±0.01%). This comprehensive suite of instrumentation ensures rigorous and precise data acquisition for this type of research.

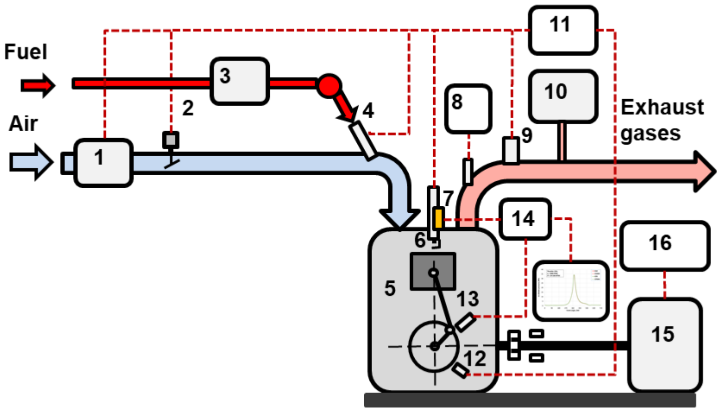

Figure 1. Engine test scheme: 1 – air meter; 2 – throttle control; 3 – fuel mass meter; 4 –injector; 5 – engine; 6 – spark plug; 7 – pressure sensor; 8 – temperature sensor; 9 – oxygen (lambda) sensor; 10 – exhaust gas analyser; 11 – engine ECU; 12 – crankshaft encoder; 13 – crankshaft sensor; 14 – in-cylinder pressure data processing module; 15 – engine load stand; 16 – load stand data processing module.

Throughout both stages of testing, a range of fuels was employed, including pure gasoline (E0) and various gasoline-bioethanol mixtures (E10, E30, E50, E70). It's important to note that a stoichiometric mixture with an excess air ratio of $\lambda = 1.0$ was consistently maintained to ensure standardized conditions and reliable data collection during the bench tests. In the formulation of fuel mixtures E10, E30, E50, and E70, gasoline was blended with bioethanol and the properties of the pure fuels are presented in Table 2. Bioethanol sets itself apart with a significantly lower carbon content, resulting in a reduced carbon-to-hydrogen (C/H) ratio compared to gasoline. This unique biofuel also contains a notable amount of oxygen, serving as an effective oxidizer during combustion, ultimately enhancing combustion efficiency. Bioethanol exhibits a considerably lower heating value compared to gasoline, burning at slightly lower temperatures but with an accelerated rate. Moreover, when bioethanol is introduced into the intake manifold, it imparts a heightened cooling effect within the cylinder during the evaporation process, owing to its significantly higher latent heat of evaporation (2 – 3 times greater). Additionally, bioethanol exhibits greater resistance to detonation during combustion, contributing to improved engine safety and performance.

Table 2. Fuel properties.

Indicator	Fuel	
	Gasoline (100%)	Bioethanol (100%)
Chemical formula	C_nH_{2n+2} (C_4 … C_{12})	C_2H_5OH
Molecular weight	100 … 105	46.07
Elemental composition %:		
Carbon (C)	86.00	52.14
Hydrogen (H)	13.98	13.13
Oxygen (O)	0.02	34.73
C/H	6.15	3.97

Density (20°C), kg/m³	736	790
Viscosity (40°C) (mm²/s)	0.4 … 0.8	1.13
Boiling point, °C	27 … 225	78
Latent heat of evaporation, kJ/kg	364	840
Auto-ignition temperature, °C	257	422
Laminar flame speed, cm/s	51	63
Adiabatic flame temperature, °C	2307	2247
Freezing point, °C	-40	-114
Stoichiometric air to fuel ratio (*A/F*), kg air/1 kg fuel	14.84	9.10
Flammability limits by volume in air, %:		
lower limit	~ 0.6	~ 3.5
upper limit	~ 8	~ 15
Octane number	88 … 98	109
Lower heating value (mass) ($LHV\__m$), MJ/kg	43.5	27.0

The primary properties of the experimentally used mixtures (E10, E30, E50, and E70) were determined with careful consideration of the bioethanol concentration. It's worth noting that the properties of E70 closely resemble those of E0, as outlined in Table 3.

Table 3. Bioethanol and gasoline mixture properties.

Mixture	E0	E10	E30	E50	E70	ΔE70, %
Density, kg/m³	736.00	741.75	753.01	763.96	774.59	5.24
C	86.00	82.39	75.33	68.47	61.80	-28.14
H	13.998	13.91	13.73	13.55	13.38	-4.41
O	0.002	3.70	10.94	17.98	24.82	1240900
C/H	6.14	5.92	5.49	5.05	4.62	-24.76
A/F	14.84	14.23	13.03	11.87	10.74	-27.63
LHV, MJ/kg	43.50	41.74	38.30	34.96	31.71	-27.10

3. Results and Discussion

Following the initial stage of our study, which involved varying throttle openings, we observed a marginal increase in engine brake torque (M_B) and Brake Mean Effective Pressure (*BMEP*) as we heightened the bioethanol concentration in the fuel mixture (Figure 2). Specifically, when the engine ran on the E70 fuel blend, M_B and *BMEP* exhibited a consistent rise of up to 1% compared to E0. This outcome stems from multiple factors. On one hand, the introduction of bioethanol lowers the Lower Heating Value (*LHV*) of the fuel mixture, delivering approximately 27% less energy per unit of fuel mass to the cylinder, as indicated in Table 3. Conversely, biofuels contain a substantial oxygen content that actively participates in combustion, and bioethanol requires significantly less air per 1 kg. Our tests maintained a stoichiometric mixture, leading to approximately 27.6% more fuel injection for the same volume of intake air with the increased concentration of bioethanol. Another noteworthy factor is the latent heat of evaporation—bioethanol enhances the cooling effect on intake air, increasing its density and intake mass during the cycle, thereby facilitating an additional boost in fuel mass and energy. In summary, the rise in M_B and *BMEP* is due to better cylinder filling with fuel energy, but is also influenced by more efficient combustion of bioethanol. It's worth noting that when we elevated the engine's rotational speed from 2000 rpm to 2500 rpm, we observed a decrease in both

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M_B and *BMEP* due to reduced volumetric efficiency. However, this phenomenon became less pronounced with wider throttle openings, as the mixture of intake air and fuel gained greater inertia, ultimately improving volumetric efficiency. In the second phase of our study, we varied the ignition timing (Θ), while maintaining constant engine load (M_B = 80 Nm) and consistent *BMEP* (0.62 MPa).

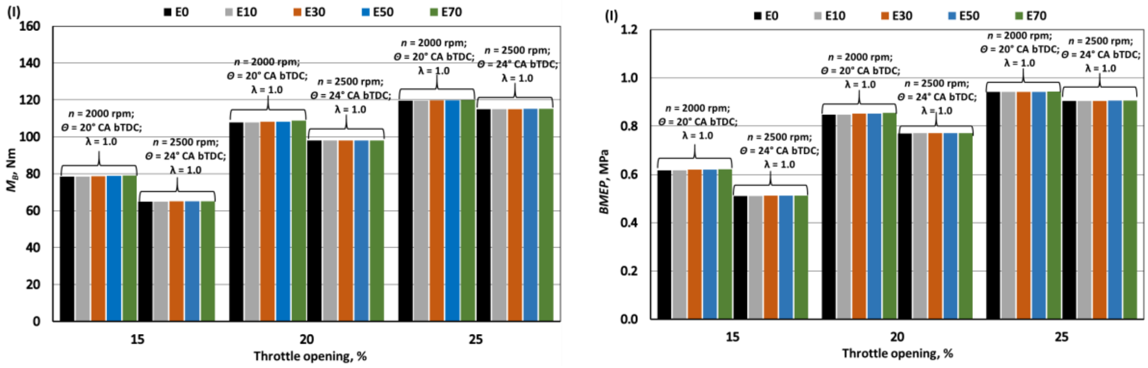

Figure 2. Dependencies of M_B (I) and *BMEP* (II) on fuel type, throttle opening and engine speed.

Significant variations in performance indicators become evident when analyzing specific fuel mass consumption (*BSFC_m*). In initial phase, gradually increased the bioethanol concentration to 10%, 30%, 50%, and 70%, resulting in consistent *BSFC_m* increases of approximately 3.5%, 11%, 19%, and 26% compared to E0 (Figure 3). The primary driver behind these changes is the diminishing *LHV* of the fuel mixture. Moreover, expanding the throttle, specific fuel consumption gradually decreased, a consequence of enhanced engine power output and improved efficiency. In the second stage, it was determined that *BSFC_m* for all tested fuels reached its minimum when the ignition timing Θ was set between 24 – 26° CA bTDC. Despite bioethanol's faster combustion characteristics (Table 2.), there was no necessity to delay combustion when incorporating bioethanol as an additive. This is attributed to bioethanol's cooling effect on the fuel-air mixture, accounting for one of the longer ignition delays within the gasoline-bioethanol blend [28].

Specific fuel volume consumption *(BSFC_V)* holds significance, especially considering fuel procurement is based on volume measurement. In the initial study phase, the incremental increase in bioethanol concentration (E10, E30, E50, and E70) consistently resulted in *BSFC_V* increments of approximately 3.1%, 9.3%, 15.8%, and 22.5% compared to E0 (Figure 4). Notably, with higher bioadditive concentrations, the specific volume consumption exhibited a more moderate increase due to the higher density of pure bioethanol, which surpasses that of gasoline by approximately 7.3%.

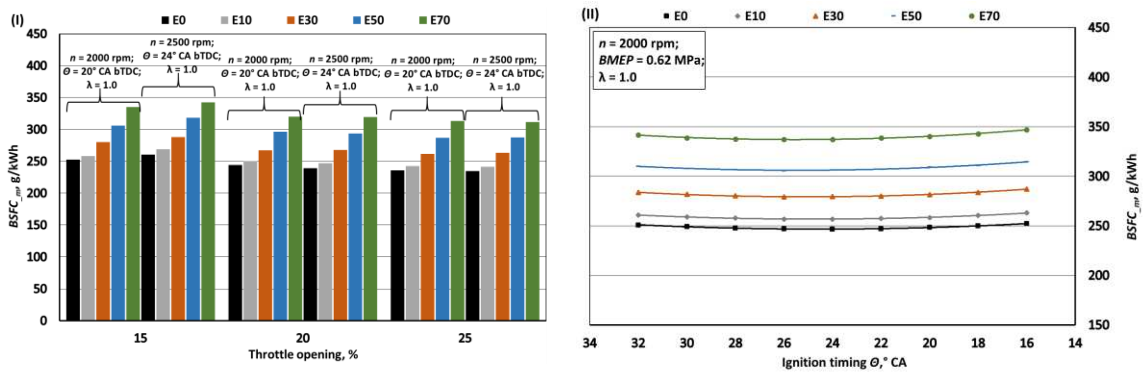

Figure 3. Dependencies of *BSFC_m* on fuel type and: I – throttle opening and engine speed; II – ignition timing.

The results from Phase II of the study reaffirm the differences in fuel consumption and the combustion characteristics of bioethanol-enhanced fuels discussed earlier. Importantly, the higher combustion speed of ethanol does not necessitate a reduction in ignition timing, as it leads to an increase in ignition delay [29].

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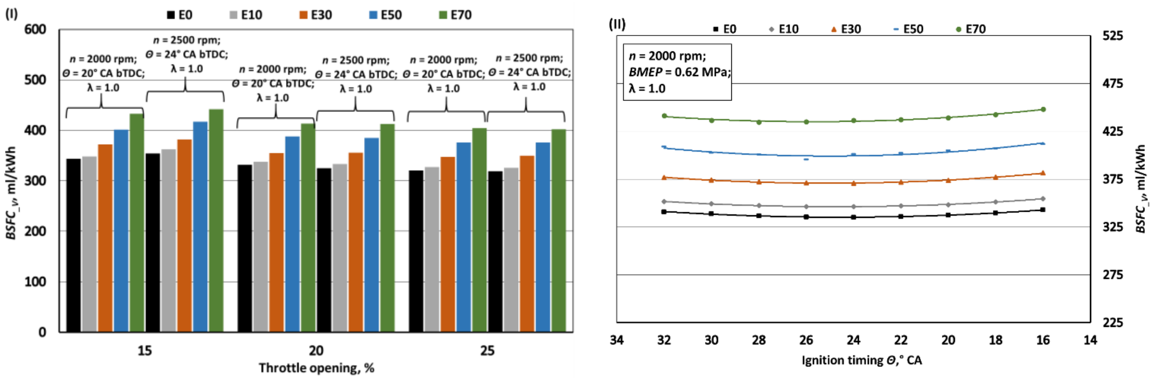

Figure 4. Dependencies of *BSFC_v* on fuel type and: I – throttle opening and engine speed; II – ignition timing.

Break Thermal Efficiency (*BTE*) serves as a key indicator of fuel thermal energy conversion into engine mechanical energy. (Figure 5) illustrates the notable enhancement in overall performance achieved by introducing higher bioethanol concentrations into fuel mixtures. This improvement is primarily attributed to the heightened oxygen concentration, facilitating a more efficient combustion process within the cylinder. In the initial stage of the study, a gradual increase in bioethanol concentration in the fuel yields incremental *BTE* improvements of approximately 0.6%, 0.9%, 1.3%, and 1.7% when compared to E0. In the second phase of the study, it becomes evident that fuel mixtures with elevated bioethanol content exhibit higher *BTE* values when ignition timing is advanced. This adjustment likely compensates for the prolonged ignition delay associated with the higher auto-ignition temperature of bioethanol (Table 2).

Exhaust Temperature (T_{ex}), as depicted in (Figure 6), demonstrates a noticeable decrease (~0.27%, ~0.72%, ~1.2%, and ~1.9%) with the introduction of bioethanol into the fuel blend. This reduction in exhaust gas temperature is associated with higher Break Thermal Efficiency (*BTE*), indicating improved energy conversion. The lower exhaust temperature is primarily attributed to bioethanol's slightly faster burning rate compared to E0, as well as its lower flame temperature, as outlined in Table 2.

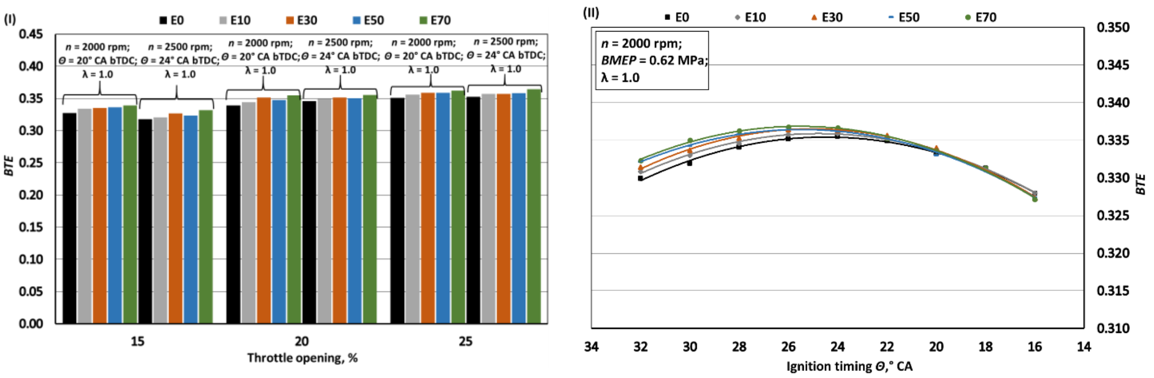

Figure 5. Dependencies of *BTE* on fuel type and: I – throttle opening and engine speed; II – ignition timing.

During the initial test phase, an increase in T_{ex} is observed with wider throttle openings, but this does not imply reduced thermal efficiency. Instead, it reflects the larger energy content within the cylinders. In all cases, the bioethanol additive consistently lowers T_{ex} across various throttle openings and engine speeds. During the second test phase, advancing ignition timing results in T_{ex} reduction, signifying an earlier combustion completion and greater conversion of combustion energy into useful work. However, excessively early ignition ($\Theta > 24 – 26°$ CA bTDC) leads to diminishing *BTE* as a significant portion of fuel combustion energy dissipates through the cooling system. In this scenario, the ethanol additive, which lowers combustion temperatures, becomes more influential [30].

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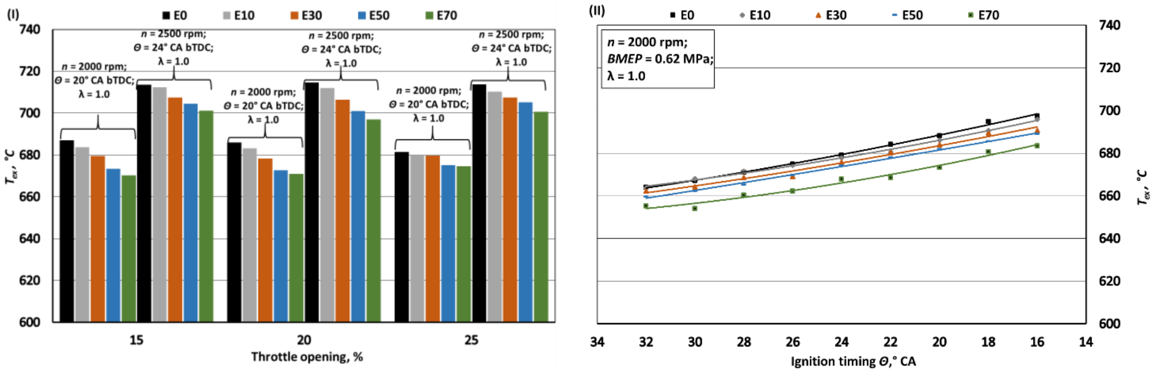

Figure 6. Dependencies of T_{ex} on fuel type and: I – throttle opening and engine speed; II – ignition timing.

As the bioethanol concentration gradually increases to 70%, specific CO_2 emissions decrease by approximately 0.5%, 0.7%, 0.8%, and 1.1%, respectively (Figure 7). It's worth considering that with the rise in bioethanol concentration to 70%, the E70 C/H ratio diminishes by around 25% (Table 2). One might expect a more substantial decrease in CO_2 emissions; however, the 26% increase in fuel consumption (Figure 3) exerts a counteractive effect. It's important to note that CO_2 is a product of complete combustion, and its emission increases as combustion efficiency improves. Understanding the intricate relationship between fuel composition and emissions is pivotal for optimizing both environmental sustainability and engine performance. In the initial phase of the study, a notable increase in specific CO_2 emissions is observed when the throttle opening is set at 15% and *n* = 2500 rpm. This can be attributed to reduced brake torque (Figure 2) owing to the engine's poorer volumetric efficiency. In such cases, the addition of bioethanol yields a more pronounced positive effect. During Phase II of the study, it becomes apparent that the lowest CO_2 emissions coincide with achieving the highest *BTE*. For E70, advancing ignition timing by approximately 2° CA compared to E0, due to the extended ignition delay phase, results in a more effective reduction in CO_2 emissions. Additionally, it's noteworthy that bioethanol qualifies as a renewable fuel, and in terms of its life cycle, E100 CO_2 emissions are approximately 60% lower compared to fossil-based gasoline [6].

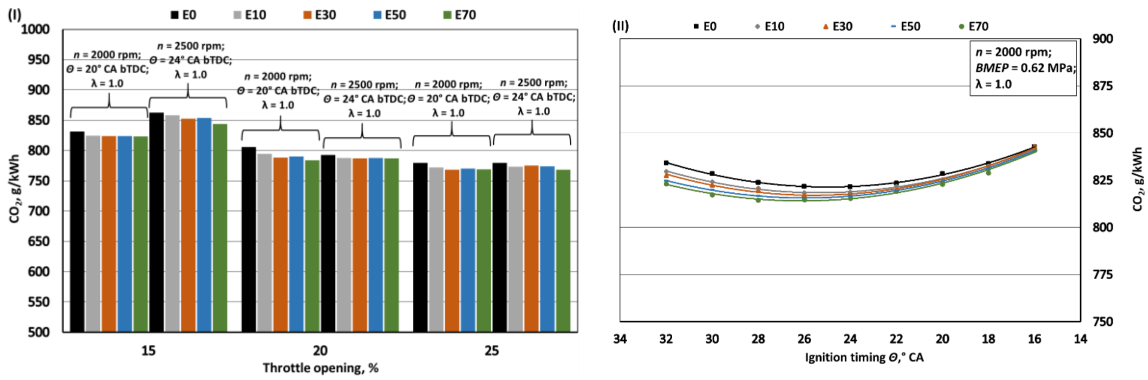

Figure 7. Dependencies of CO_2 on fuel type and: I – throttle opening and engine speed; II – ignition timing.

Carbon monoxide (CO) specific emissions, as illustrated in (Figure 8), serve as indicators of partial combustion. An inverse relationship is observed between bioethanol concentration in the mixture and CO production. Gradual increases in bioethanol concentration up to 70% yield reduced CO emissions of approximately 3.8%, 8.9%, 13.7%, and 16.7%, respectively. This correlation can be attributed to bioethanol's oxygen content, which enhances combustion efficiency as oxygen levels rise in the mixture. Additionally, a lower C/H ratio plays a role (Table 3). In the results of test I, it is evident that as the throttle opening increases, resulting in higher M_B and *BTE*, the specific CO emissions of E0 decrease more significantly compared to the reduction in CO emissions of the E70

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mixture. E70's higher *BSFC* and lower combustion temperature are likely contributing factors in this context. Test II demonstrates that, regardless of the bioethanol concentration in the fuel, the lowest CO specific emissions are achieved at the same ignition timing, corresponding to the point of maximum *BTE*.

Hydrocarbons (HC) are byproducts of incomplete combustion, typically arising from uneven fuel-air mixing and the extinguishing of the flame front in various zones of the combustion chamber. Bioethanol plays a crucial role in enhancing oxygen delivery during the combustion process, thereby optimizing combustion outcomes and reducing the emission of incomplete combustion products. With an increase in bioethanol concentration to 70%, specific HC emissions exhibit a significant decrease of approximately 8.2%, 19.7%, 32.0%, and 43.5% (Figure 9).

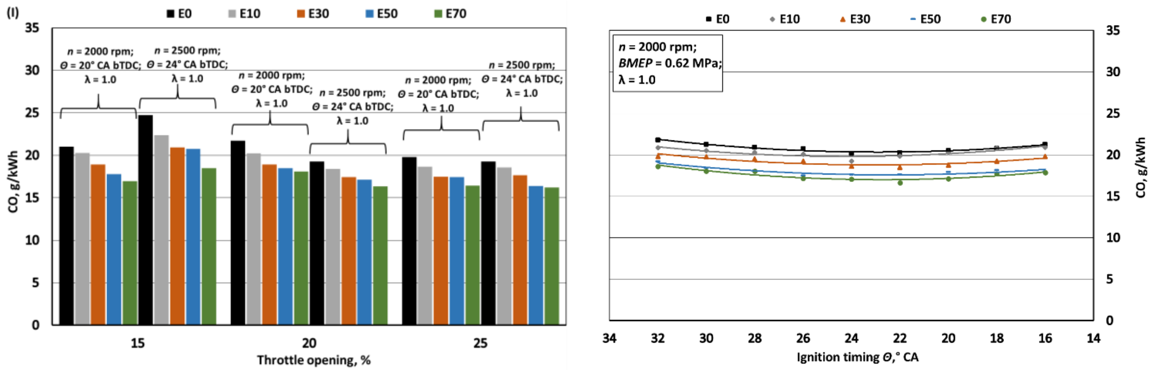

Figure 8. Dependencies of CO on fuel type and: I – throttle opening and engine speed; II – ignition timing.

During the first stage of the tests, it became evident that as the throttle opening and engine brake torque increase, the specific HC emissions decrease more pronouncedly in fuels with lower bioethanol concentrations. This observation correlates with CO emissions, suggesting that the greater reduction in emissions of these incomplete combustion products at higher throttle openings is constrained by the higher *BSFC* and lower combustion temperature of E70 fuel. In the second stage of the tests, it was established that when altering the ignition timing, the behaviour of specific HC emissions differs from that of CO emissions. Advancing the ignition timing from Θ = 16° CA bTDC to Θ = 32° CA bTDC leads to a gradual increase in HC emissions. Early combustion initiation results in elevated HC emissions, as combustion starts before the fuel-air mixture is fully homogenized. This pattern holds for all investigated fuel mixtures, but it is observed that with a higher concentration of bioethanol, the increase in HC emissions occurs with lower intensity, affirming bioethanol's role in facilitating the preparation of a more uniform and complete burning mixture [31].

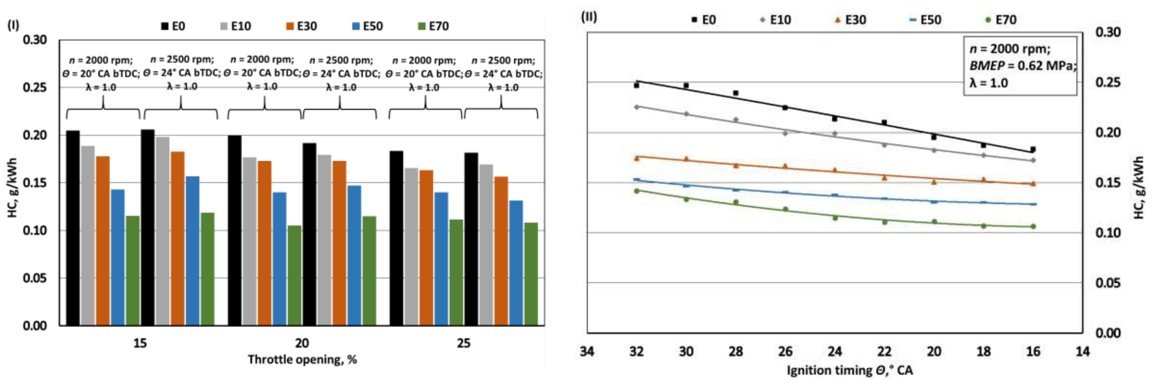

Figure 9. Dependencies of HC on fuel type and: I – throttle opening and engine speed; II – ignition timing.

Nitrogen oxide (NO_x), a significant pollutant known for its contribution to smog formation and its impact on tropospheric ozone and acid rain, is a byproduct of the combustion process. NO_x formation becomes particularly pronounced in engines operating at higher loads and elevated temperatures within the cylinder. Notably, the exclusive use of bioethanol tends to reduce NO_x emissions due to its lower flame temperature, as indicated in Table 2. Additionally, bioethanol exhibits a substantially higher latent heat of evaporation, leading to enhanced cooling of the intake air-fuel mixture when compared to pure gasoline. This cooling effect results in reduced temperatures in the cylinder during the intake and compression strokes, consequently lowering combustion temperatures and, in turn, the formation of NO_x compounds. Upon replacing pure gasoline (E0) with gasoline-bioethanol blends such as E10, E30, E50, or E70, specific NO_x emissions exhibited notable reductions of approximately 4.5%, 8.8%, 18.2%, and 23.5%, respectively (Figure 10). This significant decrease underscores the potential of bioethanol in mitigating NO_x pollutants, thus addressing environmental concerns related to combustion-related emissions. An examination of the first stage of the study reveals that while increasing the throttle opening from 15% to 25% and the engine speed from 2000 rpm to 2500 rpm tends to elevate specific NO_x emissions, the addition of bioethanol consistently counteracts this increase, resulting in reduced NO_x emissions across all tested conditions.

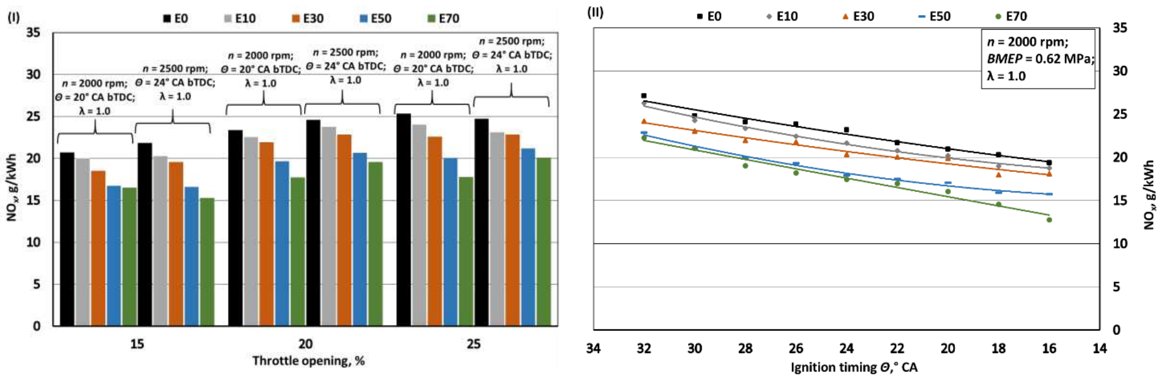

Figure 10. Dependencies of NO_x on fuel type and: I – throttle opening and engine speed; II – ignition timing.

The results of the II phase of the study demonstrate that advancing the ignition timing leads to a clear increase in specific NO_x emissions. This is primarily due to the intensified combustion occurring within a smaller volume and at higher temperatures. However, even in this scenario, the bioethanol additive continues to play a significant role in reducing NO_x emissions. Notably, at an ignition timing of approximately $\Theta \approx 24°$ CA bTDC, when the E70 fuel mixture reaches its maximum *BTE*, NO_x emissions remain lower compared to E0, especially when compared to situations with delayed ignition ($\Theta = 16°$ CA bTDC). This showcases the effectiveness of bioethanol in mitigating NO_x emissions even under conditions that typically promote their increase.

4. Conclusions

In conclusion, this extensive exploration into the impact of varying bioethanol concentrations (10%, 30%, 50%, and 70%) on both the energetic and ecological parameters of an engine operating under stoichiometric air-fuel conditions, as compared to using pure gasoline, has yielded valuable insights. The research encompassed two distinct phases: the first involving consistent engine speeds ($n = 2000$ rpm and $n = 2500$ rpm) and varying throttle positions (15%, 20%, 25%), and the second focusing on maintaining a constant engine brake torque of 80 Nm while investigating the influence of different ignition timing settings on engine performance. These findings provide crucial guidance for the optimization of engine performance and enhancement of environmental sustainability through the utilization of bioethanol/gasoline blends:

1. When bioethanol concentration in gasoline blend reaches 70%, the engine's M_B and *BMEP* increase by approximately 1%. This rise is influenced by factors like a 27.1% reduction in *LHV*,

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a 27.6% increase in fuel mass per 1 kg of air, and improved volumetric efficiency due to lower intake mixture temperatures from bioethanol's higher latent heat of evaporation. This also enhances *BTE* by around 1.7% by aiding hydrocarbon oxidation. However, bioethanol's lower *LHV* causes a 26% increase in $BSFC\__m$ and a 22.5% increase *in* $BSFC\__V$ compared to pure gasoline (E0).

2. The exhaust temperature of E70 decreases by approximately 1.9% due to lower initial combustion temperatures resulting from enhanced intake mixture cooling and the lower flame temperature of bioethanol. While bioethanol has a faster burning rate than gasoline, it experiences a longer ignition delay phase. To achieve maximum *BTE* and minimum *BSFC*, the ignition timing for E70 needs to be advanced by around 2° CA compared to the optimal timing for E0.
3. Increasing bioethanol concentration in gasoline blends leads to a reduction in greenhouse gas emissions, particularly CO_2 and NO_x. The decrease in specific CO_2 emissions when bioethanol concentration reaches 70% is approximately 1.1%, despite a 24.8% reduction in the fuel's C/H ratio. However, it's important to note that increased *BSFC* has a negative impact in this context. The reduction in CO_2 emissions, while not substantial, should be considered alongside the fact that bioethanol is a renewable fuel, with E100 having approximately 60% lower CO_2 emissions during its life cycle compared to E0. With the introduction of bioethanol, NO_x emissions decrease due to the lower combustion temperature, resulting in reductions of approximately 4.5%, 8.8%, 18.2%, and 23.5% when switching from E0 to E10, E30, E50, and E70, respectively. However, it's crucial to limit ignition timing as increasing it leads to higher NO_x emissions. The oxygen content in bioethanol reduces the emission of incomplete combustion products, resulting in decreases of approximately 3.8%, 8.9%, 13.7%, and 16.7% in CO emissions and 8.2%, 19.7%, 32.0%, and 43.5% in HC emissions when transitioning from E0 to E10, E30, E50, and E70, respectively. Advancing the ignition timing by +2° CA, which optimizes *BTE*, reduces specific CO emissions but increases HC emissions as combustion initiates before the air-fuel mixture is fully mixed.

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Abbreviations

A/F	Air to fuel ratio
BMEP	Brake mean effective pressure
$BSFC\__m$	Specific fuel mass consumption
$BSFC\__V$	Specific fuel volume consumption
bTDC	Before top dead center
BTE	Break thermal efficiency
C	Carbon
C/H	Carbon-to-hydrogen ratio
CA	Crank angle
CO	Carbon monoxide
CO_2	Carbon dioxide
E	Ethanol
ECU	Electronic control unit
H	Hydrogen
HC	Hydrocarbons

LHV	Lower heating value
M_B	Brake torque
n	Engine speed
NO_x	Nitrogen oxides
O	Oxygen
T_{ex}	Exhaust Temperature
Θ	Ignition timing
λ (lambda)	Excess air ratio

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