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Comparative Analysis of the Engine Performance and Emissions Characteristics Powered by Various Ethanol–Butanol–Gasoline Blends

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Abstract: Although many biofuel blends have been proposed recently, comparisons of such blends are rarely investigated. Currently, it is extremely difficult to recommend one biofuel blend over another since comparisons are not carried out under the same engine conditions. In the current study, different biofuel blends in dual and ternary issues are compared together, as well as with conventional gasoline under the same engine conditions. Five different biofuel blends are considered, i-butanol (iB), n-butanol (nB), bio-ethanol (E), n-butanol–bio-ethanol (nBE), and i-butanol–bio-ethanol–gasoline (iBE) blends, at two different engine speeds (2500 and 3500 rpm/min). Additionally, the blends are compared in the average bases through wide engine speeds. The comparisons of blends are carried out via engine performance and emissions. The performance includes engine power, torque, and volumetric efficiency, while the emissions include CO, CO_2, and UHC. Results showed that the E blends presented higher performance than the pure/neat gasoline by about 6.5%, 1.5%, and 25% for engine power, torque, and volumetric efficiency, respectively. Nevertheless the other four blended fuels (nB, iB, nBE, and iBE) presented lower levels of engine performance than the pure gasoline by about −3.4%, −2.6%, −5.2%, and −2.3% for engine power, −1.48%, −0.9%, −1.9%, and −1.7% for torque, and −3.3%, −3%, −2.4%, and −2.7% for volumetric efficiency, respectively. Regarding emissions, the E blends presented the highest CO_2 (by about 4.6%) and the lowest CO (by about −20%), while both nB and iB showed the lowest CO_2 (by about −35% and −36%, respectively) and the highest CO emissions (by about −10% and −11.6%, respectively). Lastly, iB and nBE introduced, respectively, the highest and the lowest UHC emissions (by about −6.8% and −17%, respectively) among all blends.

Keywords: butanol; ethanol; blends; comparative; dual; ternary

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1. Introduction

The kingdom of Saudi Arabia is one of the countries that produce waste in large quantities, as the amounts of solid waste are about 15 million tons annually, with an average of 1.4 kg per person daily. This is in addition to large quantities of industrial and agricultural wastes. Most of such wastes are valuable to produce renewable energies, such as biofuels [1–4]. Among the valuable biofuels generated from municipal solid waste (MSW), bio-ethanol, n-butanol, and i-butanol are some of the most encouraging. Studies have been carried out to examine and evaluate the combustion, emissions, and performance of such biofuels in neat and blended issues. In the blended issues, bio-ethanol–gasoline [5,6], n-butanol–gasoline [7,8], and i-butanol–gasoline [9,10] blends have been assessed, and the studies revealed that the combustion, emissions, and characteristics of fossil fuel (gasoline) are meaningfully enhanced by the addition of biofuels. Yousif [11] examined butanol blended with gasoline at high rates (25% and 50% butanol in gasoline). The study studied the influence of such blend ratios on the performance and exhaust emissions, concluding that the butanol led to lower exhaust emissions and higher engine performance. Hosseini [12] applied the effect of using ethanol–gasoline blends in four rates (E5, E10, and E15) on engine performance and emissions. E10 produced the highest torque, while E15 produced the highest power and the lowest CO and HC emissions compared with other fuels. Qadiri [13] computationally checked the effects of 85% ethanol blended with 15% gasoline on the performance, combustion, and emission characteristics. Results showed better emissions and performance when compared with 100% gasoline. Mohammed et al. [14] studied ethanol mixed with gasoline in different proportions (10–40% ethanol) and results showed an improvement in emissions and engine performance (brake-specific fuel consumption and thermal efficiency) but a negative effect on volumetric efficiency. Iodice et al. [15] presented a review on the effects of using ethanol/gasoline fuel blends on engine emissions. The study concluded, in agreement with the literature, that ethanol can reduce CO and HC exhaust emissions. Dehhaghi et al. [16] presented a review on emissions and engine performance when adding nanoadditives to gasoline. The study showed an enhancement of the combustion characteristics and thermophysical properties of the fuel. However, the use of biofuels in neat issues, on the other hand, is still not encouraging because of their high costs and necessary modifications for the globe automotive industry.

Because of encouraging dual biofuel blends, researchers recently moved into investigating biofuels in ternary blended issues. Nazzal [17] evaluated a bio-methanol–bio-ethanol–gasoline blend, and the results showed an enhancement of gasoline combustion and emissions due to the bio-methanol/bio-ethanol additions. Elfasakhany [18] also evaluated the addition of bio-methanol/bio-ethanol to fossil gasoline, and the study recommended ternary biofuel blends. Balaji et al. [19] evaluated bio-ethanol/i-butanol addition to fossil gasoline; the results discovered that all blends increased the fuel consumption, but improved exhaust emissions and performance. Sileghem et al. [20] evaluated bio-ethanol/bio-methanol addition to fossil gasoline, and the authors highlighted improvements in emissions/performance of fuel blends compared to gasoline. Elfasakhany and Mahrous [21] applied the addition of n-butanol/bio-methanol to fossil gasoline, and the results showed promising fuel blends under certain operating conditions. Turner et al. [22] evaluated bio-ethanol/bio-methanol addition to fossil gasoline, and the study somewhat recommended ternary blends over the fossil gasoline. Andersen et al. [23] evaluated the emissions of n-butanol/bio-methanol blended in fossil gasoline, and the results confirmed the superiority of ternary fuel blends over neat gasoline. Elfasakhany [24] evaluated i-butanol/bio-methanol additions to fossil gasoline and compared the emissions and performance of biofuel blends with fossil gasoline; the study declared that ternary biofuel blends are promising alternatives to commercial gasoline fossil fuel.

In addition to investigating the ternary blends compared to gasoline, some studies compared ternary and dual blends of fuel. Elfasakhany [25] evaluated n-butanol/i-butanol addition to fossil gasoline, and the study compared the volumetric efficiency, brake power, and torque of blended fuels with those of pure fossil gasoline and dual blends (i-butanol and/or n-butanol in gasoline); additionally, the study compared UHC, CO_2, and CO engine releases between blended fuels and gasoline, and results recommended the ternary blended fuels as alternatives to fossil gasoline rather than dual blend issues (i-butanol and/or n-butanol in gasoline). Siwale et al. [26] evaluated n-butanol/bio-methanol addition to fossil gasoline with rates of 17%, 53%, and 30% for n-butanol, bio-methanol, and gasoline, respectively. The study compared such blends with bio-methanol–gasoline, and the study highlighted that the ternary blends presented higher CO, CO_2, and NOx emissions, but lower UHC emissions and thermal efficiency, compared to dual blends (bio-methanol–gasoline).

Despite the many advantages of bio-ethanol, n-butanol, and i-butanol as promising alternatives to commercial gasoline fuel, as clarified above, they show some drawbacks [27–30]. The negative aspects of bio-ethanol, for example, are that it has low carbon content, which causes low fuel energy content and high fuel consumption; it also has a high volatility aspect, which causes high cavitation and, in turn, requires special precautions for use in different weather conditions (hot or cold). The bio-ethanol also needs high vaporization heat, which leads to combustion difficulty in a cold environment. It has a low flash point, e.g., it burns easily in a hot environment and, in turn, self-ignites in hot weather. It also has lower kinematic viscosity, which causes wear problems and a short life of the fuel system. It has distribution difficulties, since it is transported using only rails, barges, or trucks. Lastly, it is toxic even in small doses. On the other hand, n-butanol and i-butanol also show some drawbacks such as very high emissions per unit motive energy and lower oxygen content in the chemical structures [31,32].

Both i-butanol and n-butanol have valuable characteristics to resolve/moderate the drawbacks of bio-ethanol fuel. For example, i-butanol and n-butanol contain a couple more carbon atoms than bio-ethanol in their chemical structures, leading to higher energy content and stumpy fuel consumption; specifically, i-butanol/n-butanol produced from biomass (using the same quantity) has a ~18% higher energy yield than bio-ethanol. Furthermore, i-butanol/n-butanol have low saturation pressures, e.g., low volatility, causing low cavitation and, in turn, doing away with any special precautions when using i-butanol/n-butanol in different weather conditions (hot or cold). Their high flash points and low vapor pressure make i-butanol/n-butanol suitable and safe fuels for hot environments. Additionally, i-butanol/n-butanol have high kinematic viscosity and can be dissolved into fossil fuels without cosolvents, thereby avoiding/limiting any wearing problems in the fuel system. Lastly, i-butanol/n-butanol are less corrosive in general and more appropriate than bio-ethanol for use in existing fossil fuel pipeline systems.

In the discussion presented above, one can easily notice that the advantages of i-butanol/n-butanol address the drawbacks of bio-ethanol, whereas the advantages of bio-ethanol address the drawbacks of i-butanol/n-butanol biofuels. In the current study, we aimed to investment/exploit the advantages of i-butanol/n-butanol/bio-ethanol biofuels, seeking to establish high/strong promising alternatives to fossil fuels by overcoming or limiting their drawbacks. In the current study, i-butanol/n-butanol are blended with bio-ethanol to provide novel and promising blended fuels (n-butanol–bio-ethanol and i-butanol–bio-ethanol) as alternatives to gasoline. In the study, the proposed biofuel blends are compared together, as well as with the related dual blends, e.g., bio-ethanol–gasoline, n-butanol–gasoline, and i-butanol–gasoline. It is important to highlight that the current study is dedicated to a comparison of such biofuel blends rather than a determination of the detailed combustion and chemical/physical characteristics, which would require a separate study for each blend.

2. Experimental

The experimental setup contained two main components: the engine and gas analyzer. The engine was a spark ignition type with four strokes and a single cylinder, as specified in Table 1 [33–35]. The engine was connected with a dynamometer and a desktop computer; the dynamometer was used to control and measure different engine parameters, such as speed and torque, while the computer was connected to collect the measured data from the dynamometer and other sensors, enabling analysis and sorting of the measured data. Figure 1 shows an image of the engine experimental setup. The gas analyzer, on the other hand, was used to measure and analyze the exhaust emissions from the engine. The analyzer weighed about 9 kg and worked in an exhaust gas temperature range of 5 to 45 °C, as shown in Figure 1. It took about 10 min to warm up before measuring the concentrations of CO, CO_2, and UHC emissions in the range of 0–10 vol.% for CO, 0–20 vol.% for CO_2, and 0–2000 ppm for UHC (considered as C_6H_{14} in the measurement of the analyzer system). The complete specifications of the gas analyzer are shown in Table 1. Further details of the experimental setup and analyzer errors are presented in Section 3.

After warming up the engine and the gas analyzer, different fuel blends were separately inserted into the fuel system of the engine, including i-butanol, n-butanol, bio-ethanol, and conventional gasoline. Such fuels are typically from Saudi Arabia, and the complete fuel properties are shown in Table 2 [36–40]. The fuels were prepared and blended at a rate up to 10 vol.%, and then inserted into the engine tank. Five blends were prepared on a dual and ternary basis: i-butanol–gasoline (iB), n-butanol–gasoline (nB), bio-ethanol–gasoline (E), n-butanol–bio-ethanol–gasoline (nBE), and i-butanol–bio-ethanol–gasoline (iBE). The engine was operated at two different speeds during the experiments (2500 and 3500 rpm/min), representing low and high speeds. Additionally, the engine was operated at intermediate speeds, and the measured data were averaged.

Table 1. Gasoline engine and pollutant gas analyzer specifications [33–35].

Gas Analyzer		*Engine*	
Weight	9 kg	*Type*	*SI (spark ignition)*
Warm-up period	10 min	*No. of cylinders*	1
Exhaust gas temp. range	5–45 °C	*No. of valves*	2
Apparatus heating range	0−130 °C, resolution ±1 °C	*Bore (mm)*	65.1
Voltage	230 V (+10%/−15%)	*Stroke (mm)*	44.4
Frequency	50 ± 1 Hz	*Compression ratio*	7:1
Power consumption	Max. 45 VA	*Displacement (cm^3)*	147.7
Pollutant range	CO 0–10 vol.% CO_2 0–20 vol.% UHC 0–2000 ppm	*Maximum power (kW)*	1.5
		Weight	17 kg

Figure 1. Experimental setup showing engine (bottom) and gas analyzer (top).

Table 2. Fuel properties [36–40].

Property \ Fuel	Gasoline	Bio-Ethanol	i-Butanol	n-Butanol
Formula	C_8H_{15}	C_2H_6O	$C_4H_{10}O$	$C_4H_{10}O$
C, H, O value (wt.%)	86, 14, 0	52, 13, 35	65, 13.5, 21.5	65, 13.5, 21.5
LHV (MJ/kg)	43.5	27	33.3	33.1
Heat of evap. (kJ/kg)	223.2	725.4	474.3	582
Stoich. A/F ratio	14.6	9	11.1	11.2
Oxygen wt.%	0.0	34.7	21.6	21.6
Density (kg/m^3)	760	790	802	810
P sat. at 38 °C (kPa)	31	13.8	2.3	2.27
Flash temp. (°C)	−45 to −38	21.1	28	35
Ignition temp. (°C)	420	434	415	385
Boiling temp. (°C)	25–215	78.4	108	117.7
Solubility in water (mL/100 mL H_2O)	<0.1	Fully miscible	10.6	7.7
Vapor toxicity	Moderate irritant	Toxic even in small doses	Moderate irritant	Moderate irritant

Before measurements were made, the errors and uncertainties of the measurements were assessed and calibrated, as defined in our previous study [41]. They were estimated to be within the range of ±2%. The temperature sensor accuracy was around ±1 °C. Other sensor errors were calculated and found to be within acceptable ranges. When it came to the reproducibility of the measures, the standard deviation (SD) was between ±0.5% and ±0.1% SD, and the measurements were practically repeated approximately three times, revealing 90–95% consistency [41].

3. Results and Discussion

Comparisons of five different biofuel blends (dual and ternary) are presented and discussed in terms of engine performance and pollutant emissions. The performance included brake power, torque, and volumetric efficiency, while the emissions included CO, CO_2, and UHC. The comparisons were performed at two engine speeds, low (2500 rpm/min) and high (3500 rpm/min), along with an average across intermediate speeds. Figure 2 shows the comparison of brake power (BP) for i-butanol (iB), n-butanol (nB), bio-ethanol (E), n-butanol–bio-ethanol (nBE), and i-butanol–bio-ethanol–gasoline (iBE) blends, as well as pure gasoline (baseline), at the two applied engine speeds (2500 and 3500 rpm/min). As shown, the greatest power was achieved by E dual blends at both engine speeds. The BP of E was greater than that of pure gasoline (baseline); however, all other biofuel blends showed a lower BP than the pure gasoline. The lowest power was recorded for iB at high speed and by nB at low speed. The ternary blends (iBE and nBE) showed a moderate level of power among the fuel blends.

Figures 3 and 4 show comparisons of the engine torque (Tq) and volumetric efficiency (VE), respectively, for the tested fuels, i.e., for iB, nB, E, nBE, and iBE blends, as well as the pure gasoline (baseline), at two engine speeds (2500 and 3500 rpm/min). Similar to the BP results, the E dual blends showed the greatest Tq value (greater than pure gasoline) at both speeds, but all other blends showed lower levels than pure gasoline. The lowest Tq was introduced by iBE at high speed and nBE at low speed. The dual blends of nB and iB introduced moderate levels between E and the ternary blends (nBE and iBE). On the other hand, E dual blends presented the greatest VE (greater than pure gasoline) at both speeds, but all others (iB, nB, nBE, and iBE) presented lower levels than pure gasoline.

However, it was difficult to define the best fuel blends at all speeds, as shown in the figure; consequently, comparisons using the average principle were carried out.

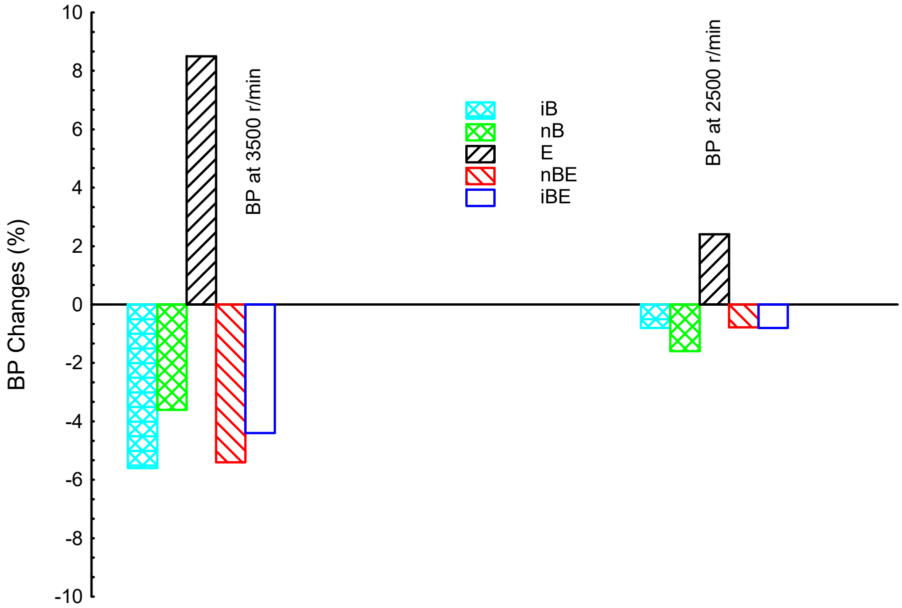

Figure 2. Comparison of brake power (BP) for i-butanol (iB), n-butanol (nB), bio-ethanol (E), n-butanol–bio-ethanol (nBE), and i-butanol–bio-ethanol–gasoline (iBE) blends, as well as pure gasoline (baseline), at two engine speeds (2500 and 3500 rpm/min).

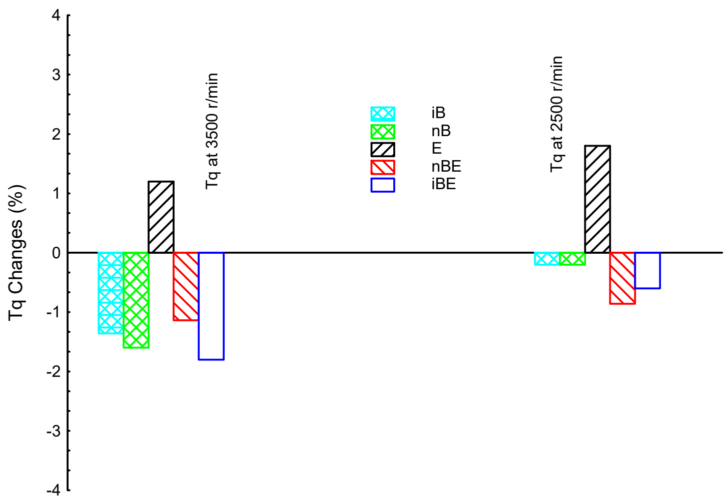

Figure 3. Comparison of engine torque (Tq) for i-butanol (iB), n-butanol (nB), bio-ethanol (E), n-butanol–bio-ethanol (nBE), and i-butanol–bio-ethanol–gasoline (iBE) blends, as well as pure gasoline (baseline), at two engine speeds (2500 and 3500 rpm/min).

Figure 5 shows the comparisons of average brake power, engine torque, and volumetric efficiency for iB, nB, E, nBE, and iBE blends. As shown, the greatest BP, Tq, and VE were introduced by E dual blends. However, the lowest BP and Tq were introduced by nBE, and the lowest VE was introduced by nB. The four fuel blends (nB, iB, nBE, and iBE) showed lower levels of all engine performance parameters (BP, Tq, and VE) than pure gasoline, whereas E blends showed higher performance parameters than pure gasoline. In particular, the BP changed by −2.6%, −3.4%, 6.5%, −5.2%, and −2.3%, the Tq changed by −0.9%, −1.48%, 1.5%, −1.9%, and −1.7%, and the VE changed by −3%, −3.3%, 25%, −2.4%, and −2.7% for iB, nB, E, nBE, and iBE, respectively, compared to pure gasoline.

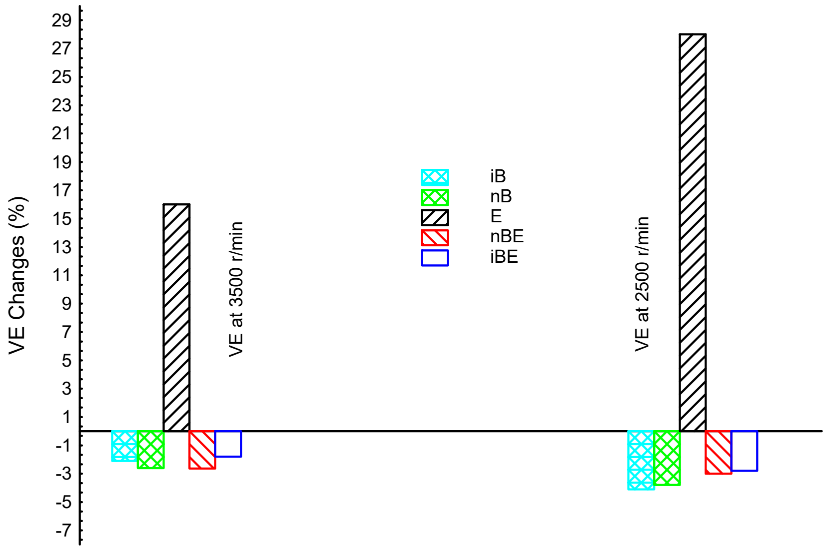

Figure 4. Comparison of volumetric efficiency (VE) for i-butanol (iB), n-butanol (nB), bio-ethanol (E), n-butanol–bio-ethanol (nBE), and i-butanol–bio-ethanol–gasoline (iBE) blends, as well as pure gasoline (baseline), at two engine speeds (2500 and 3500 rpm/min).

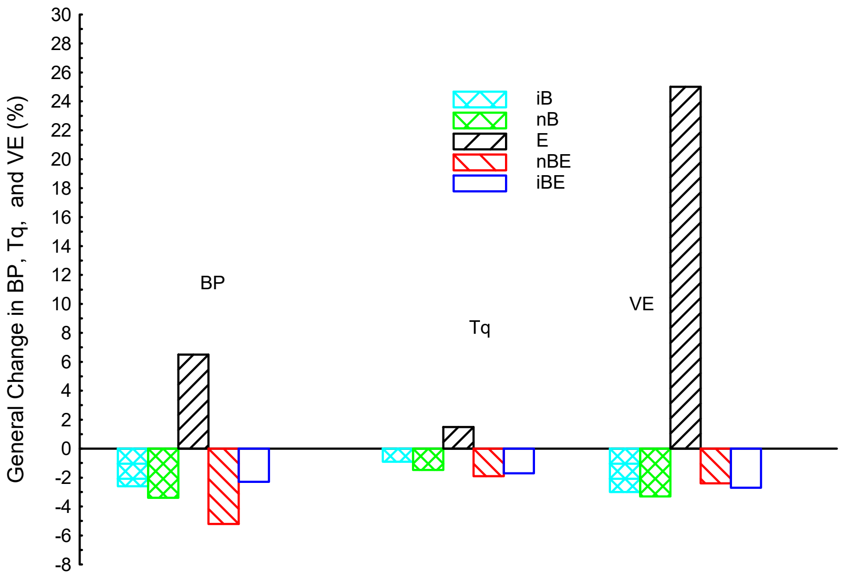

Figure 5. Comparison of average brake power (BP), engine torque (Tq), and volumetric efficiency (VE) for i-butanol (iB), n-butanol (nB), bio-ethanol (E), n-butanol–bio-ethanol (nBE), and i-butanol–bio-ethanol–gasoline (iBE) blends, as well as pure gasoline (baseline).

In summary, the greatest BP, Tq, and VE were introduced by E, and the lowest BP and Tq were presented by nBE, while the lowest VE was introduced by nB. These results may be due to bio-ethanol containing oxygen in its chemical structure (35%, as shown in Table 2). However, both i-butanol and n-butanol contained an oxygen content of about 21.5%, which enhanced blended fuel combustion. Consequently, E blends, which contained the greatest oxygen value, produced the greatest performance (BP, Tq, and VE). All other blends showed lower performance than pure gasoline despite a reasonable oxygen content, due to the incompatibility of such blends with gasoline fuel engines without any sort of tuning/modification. In other words, the four blends (iB, nB, nBE, and iBE) were more sensitive to operation in gasoline fuel engines without adjustments than the E blends. Another reason may have been the blend quality; when mixing different biofuels, blends may not be completely homogenized, e.g., fuel separation problems. This can lead to combustion of separate fuels in the combustion chamber, i.e., nonhomogeneous combustion, reducing the engine performance of such fuels.

Figure 6 compares CO emissions for iB, nB, E, nBE, and iBE blends, as well as pure gasoline (baseline), at two engine speeds (2500 and 3500 rpm/min). As shown, all blended fuels presented lower CO emissions than pure gasoline; the lowest CO was presented by E at high speed, but nBE at low speed. One interesting note in the CO results of all fuel blends is that the emissions increased with engine speed, except for the E blends, where they decreased. Figure 7 compares UHC emissions for iB, nB, E, nBE, and iBE blends, as well as pure gasoline (baseline), at two engine speeds (2500 and 3500 rpm/min). As shown, all blended fuels presented lower UHC emissions than pure gasoline, similar to the CO results. The lowest UHC was shown by nBE at low speed, but nB at high speed. Figure 8 compares CO_2 emissions for iB, nB, E, nBE, and iBE blends, as well as pure gasoline (baseline), at two engine speeds. As shown, unlike the results for CO and UHC emissions, the E blends introduced higher CO_2 than pure/neat gasoline, whereas the other four blends (iB, nB, iBE, and, nBE) introduced lower levels than pure gasoline. The lowest emissions were recorded for iB at low speed but nB at high speed. The highest CO_2 emissions were recorded for E blends at all speeds, while the ternary blends introduced moderate CO_2 levels.

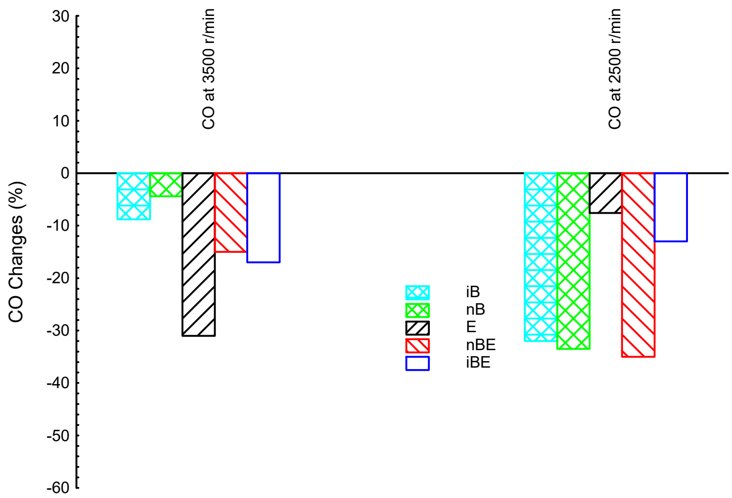

Figure 6. Comparison of CO emissions for i-butanol (iB), n-butanol (nB), bio-ethanol (E), n-butanol–bio-ethanol (nBE), and i-butanol–bio-ethanol–gasoline (iBE) blends, as well as pure gasoline (baseline), at two engine speeds (2500 and 3500 rpm/min).

Figure 9 compares the average CO, UHC, and CO_2 emissions for iB, nB, E, nBE, and iBE blends. As shown, the lowest CO emissions were presented by the E dual blend followed by nBE ternary blend, while the highest CO emissions were presented by nB followed by iB. In terms of UHC emissions, the lowest were presented by nBE followed by nB, while the highest were presented by iB followed by E. In terms of CO_2 emissions, the lowest were presented by iB followed by nB, while the highest were presented by E followed by iBE. Specifically, the CO emissions for iB, nB, E, nBE, and iBE changed by about −11.6%, −10%, −20%, −18%, and −14%, respectively, compared to pure gasoline. The UHC emissions for iB, nB, E, nBE, and iBE changed by about −6.8%, −16.2%, −10%, −17%, and −14%, respectively, compared to pure gasoline. The CO_2 emissions for iB, nB, E, nBE, and iBE changed by about −36%, −35%, 4.6%, −27%, and −14%, respectively, compared to pure gasoline. One exciting note from the results is that the iBE ternary blends presented the same level of CO, UHC, and CO_2 emissions (−14%); however, all other blends showed different levels of emissions. Additionally, all blends showed a lower level of emissions (CO, UHC, and CO_2) than pure gasoline except for the E dual blends (for CO_2). Both iB and nB showed the highest CO and the lowest CO_2 emissions among all fuel blends. On the other hand, the ternary blended fuels (nBE and iBE) showed moderate levels of emissions compared to the dual blended ones (E, nB, and iB).

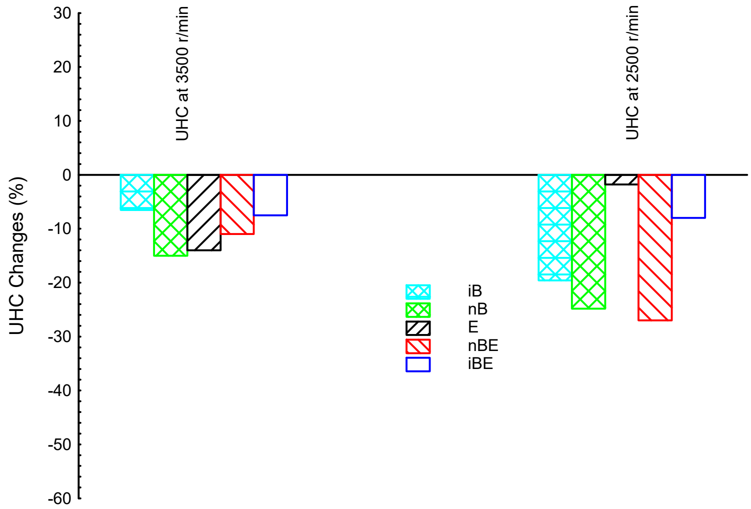

Figure 7. Comparison of UHC emissions for i-butanol (iB), n-butanol (nB), bio-ethanol (E), n-butanol–bio-ethanol (nBE), and i-butanol–bio-ethanol–gasoline (iBE) blends, as well as pure gasoline (baseline), at two engine speeds (2500 and 3500 rpm/min).

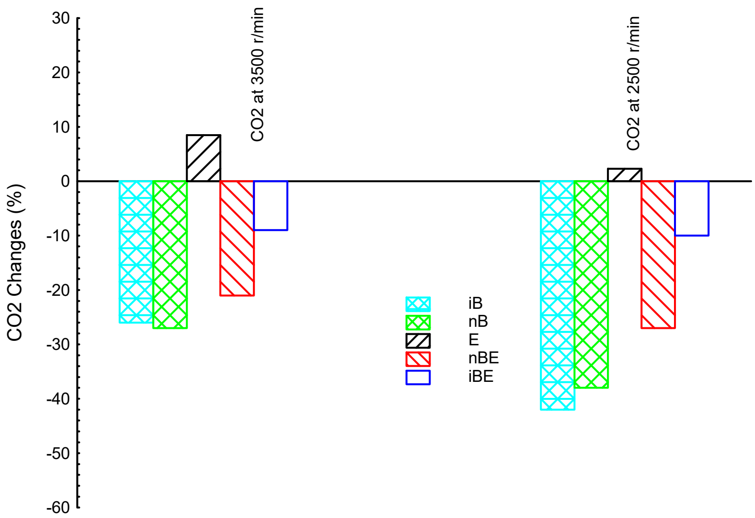

Figure 8. Comparison of CO_2 emissions for i-butanol (iB), n-butanol (nB), bio-ethanol (E), n-butanol–bio-ethanol (nBE), and i-butanol–bio-ethanol–gasoline (iBE) blends, as well as pure gasoline (baseline), at two engine speeds (2500 and 3500 rpm/min).

In summary, the E blends presented the highest CO_2 and the lowest CO emissions, while both nB and iB presented the lowest CO_2 and the highest CO emissions. On the other hand, iB and nBE presented the highest and the lowest UHC emissions, respectively. The E blends may have introduced the lowest CO emissions because of their more complete combustion due to their great oxygen content, as shown in Table 2, consequently introducing the highest CO_2 emissions. On the other hand, iB and nB may have introduced the highest CO emissions due to somewhat incomplete combustion, as supported by their lowest CO_2 emissions (high CO and low CO_2 due to low oxidation). Ternary blends underwent more complete combustion than nB and iB, albeit not as complete as E blends. This outcome is supported by the CO_2 results of both ternary blends, which mirrored complete/incomplete combustion. Accordingly, to gain low CO emissions from engines, one should use E dual blends, whereas, to gain low UHC emissions, one should use nBE; however, in the case of iB and nB dual blends being unavoidable, one should add bio-ethanol, e.g., using nBE and iBE ternary blends, to avoid high CO emissions.

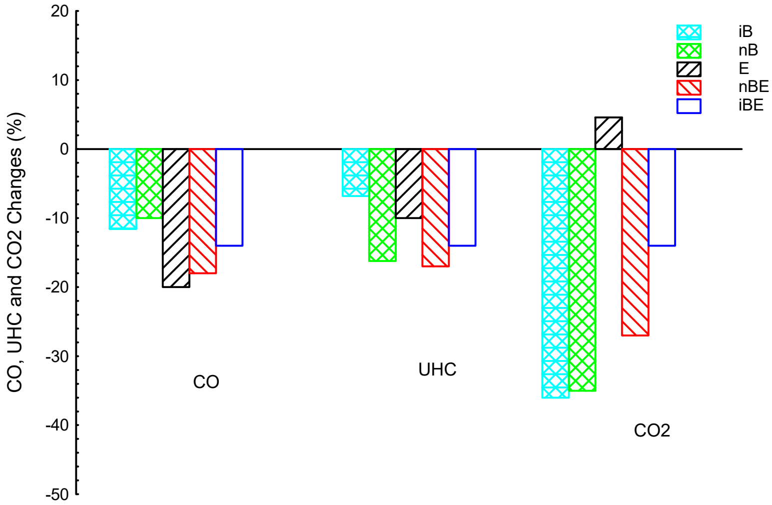

Figure 9. Comparison of average CO, UHC, and CO_2 emissions for i-butanol (iB), n-butanol (nB), bio-ethanol (E), n-butanol–bio-ethanol (nBE), and i-butanol–bio-ethanol–gasoline (iBE) blends, as well as pure gasoline (baseline).

A final observation, which may be useful for practical implications, is that the comparisons of different blended fuels were significantly influenced by the engine speed. The lowest BP was introduced by nB at low engine speed, but iB at high engine speed (i.e., one should avoid such speeds when using nB and iB blends). Similarly, the lowest Tq was presented by nBE at low speed, but iBE at high speed; the lowest VE was presented by iB at low speed, but nBE and nB at high speed. Accordingly, the fuel blends performed differently at certain engine speeds. Hence, one should define the engine speed according to the fuel blend and the best performance/emissions needed. Lastly, it is important to highlight that the average values of performance and emissions presented in Figures 5 and 9 were calculated at several intermediate speeds, thus differing from the values calculated in Figures 2–4 and 6–8.

4. Conclusions and Future Perspectives

Five different biofuel blends were compared in this study in terms of engine performance (power, BP, torque, Tq, and volumetric efficiency, VE) and emissions (CO, CO_2, and UHC). The biofuels were blended in dual and ternary issues: i-butanol (iB), n-butanol (nB), bio-ethanol (E), n-butanol–bio-ethanol (nBE), and i-butanol–bio-ethanol–gasoline (iBE). The comparisons were carried out at two engine speeds (2500 and 3500 rpm/min), as well as averaged across intermediate speeds. The results showed that the lowest BP was introduced by nB at low speed, but iB at high speed. The lowest Tq was presented by nBE at low speed, but iBE at high speed. The lowest VE was presented by iB at low speed, but nBE and nB at high speed. Across all speeds, the greatest Bp, Tq, and VE were presented by E blends.

In conclusion, the fuel blend performance was significantly influenced by engine speeds. On average, the four fuel blends (nB, iB, nBE, and iBE) showed lower levels of engine performance (BP, Tq, and VE) than pure gasoline, whereas the E blend showed higher performance than pure gasoline. The E blend also presented the highest CO_2 emissions among all blends. Both nB and iB showed the lowest CO_2 and the highest CO emissions. The E blends presented the lowest CO emissions, while iB and nBE introduced the highest and the lowest UHC emissions, respectively. The iBE ternary blends presented the same level of CO, UHC, and CO_2 emissions, whereas all other blends showed different levels of emissions. Additionally, all blends showed lower emissions (CO, UHC, and CO_2)

than pure gasoline except for E (for CO_2). Both nB and iB were subjected to incomplete combustion and, in turn, emitted low emissions. On the other hand, ternary blends underwent more complete combustion than the nB and iB dual blends. In summary, to obtain low CO emissions from the engine, one should use E dual blends. However, if the application of iB and nB dual blends is compulsort, one should consider introducing E (i.e., using nBE and iBE ternary blends). If interested in great BP and Tq, one should avoid using nBE (lowest BP and Tq), instead applying E blends. Lastly, more biofuel blends should be compared in the future to recommend the best in terms of overall performance.

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Abbreviations/Nomenclatures

CO	Carbon monoxide
CO_2	Carbon dioxide
UHC	Unburned hydrocarbon
BP	Brake power
Tq	Engine torque
VE	Volumetric efficiency
iB	i-Butanol–gasoline blend
nB	n-Butanol– gasoline blend
E	Bio-ethanol–gasoline blend
nBE	n-Butanol–bio-ethanol–gasoline blend
iBE	i-Butanol–bio-ethanol–gasoline blend

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