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A Review of automotive green technology: Potential of butanol as biofuel in gasoline engine

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This article contributes to:

7 AFFORDABLE AND CLEAN ENERGY

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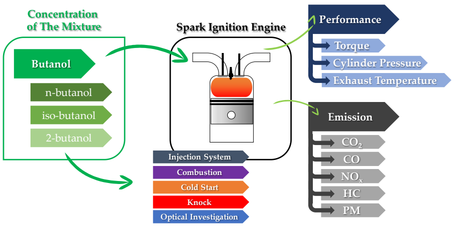

Highlights:

- A comprehensive review of butanol as biofuel in gasoline engines was discussed.
- The comparison of butanol and other biofuel and its advantages was reviewed.
- The effect of butanol on engine performance, combustion, and emission was critically discussed.
- Research gaps and possible further contributions were highlighted, such as the research of an optical engine.

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Abstract

In comparison to ethanol biofuel, butanol is considerably less corrosive, permitting the utilization of existing infrastructures used to ship gasoline or diesel for its distribution. Less corrosive also means that butanol can be utilized with no engine alteration. If butanol is mixed with water, it is less likely to split from the main fuel, thus facilitating the storage and distribution of blended fuels. Butanol also comprises a comparable energy content to gasoline fuel, with 25% more energy density/liter as opposed to ethanol. All these excellent qualities have led to higher engine performance, enabling the vehicles to achieve higher mileage using butanol with no significant issue. Several challenges and future research directions are discussed and in the last section of this review article, we emphasize the importance of an optical engine to diagnose engine combustion in more detail. The consequence of using butanol on spark ignition engine on cold start and knock phenomena are also worth investigating. Results on the spray, the pressure inside the cylinder, rate of heat release, and detonation are thus required.

Keywords: Butanol; Biofuel; Gasoline; Spark-Ignition engine; Performance; Combustion; Emission

1. Introduction

Environmental pollution, global warming, and oil-reserve exhaustion have driven research in internal combustion engines toward the improvement of fuel utilization [1]–[3]. Biofuels including biodiesel and bioalcohol are considered exceptional alternative fuels [4]–[12]. Alcohol-based fuels are of interest for a number of reasons, including being easily produced and able to be directly used without major engine modification [13], [14]. Currently, there are four alcohols commonly used as fuel for internal combustion engines: methanol, ethanol, propanol, and butanol. These fuels can be produced from renewable sources and are often referred to as biofuels. Ethanol, for example, can be produced from sugar cane, potato, corn and is known as bioethanol.

The main advantage of using renewable sources of alcohol fuels is that it can significantly reduce net carbon dioxide (CO_2) emissions [15]. Despite its rising popularity, growing concerns have emerged about increasing food prices as ethanol, produced from edible sources, often competes with the human food supply, resulting in higher food prices. In addition to that, ethanol has several other disadvantages. First, it is corrosive to plastics and rubbers in most cars, resulting in vehicle modification. Furthermore, this also means that ethanol should be shipped by truck, as it will corrode pipes and tubing if it is delivered using the current pipeline system. From a thermodynamic point of view, higher alcohols generally offer better calorific value (better volumetric fuel consumption), improved water tolerance, volatility control, and lower Reid vapour pressure. Higher alcohols, however, reduce both the availability of the hydrogen bonding effect and latent heat (charge cooling) thus reducing knock resistance. As a result, higher alcohols are usually to be added in a low to medium percentage.

Stringent emissions regulations have been pushing gasoline engines toward downsizing using direct injection and turbocharging. Direct injection offers increased charged density and knock resistance and is even more pronounced when using alcohol fuels such as methanol, ethanol, and butanol. This is because such fuels have higher heat vaporization and a lower air-to-fuel (AFR) ratio. To investigate the performance as well as emissions characteristics of methanol, ethanol, and butanol, Sileghem et al. [16] used these three alcohol fuels in a 4-cylinder DISI engine and compared them with pure gasoline fuel. The results show that the alcohol fuels gave a significant improvement in brake thermal efficiency, as well as lower exhaust emissions. In another study, Yang et al. [17] compared the performance of different butanol/gasoline blends on a gasoline engine. What caused the differences in performances was analysed using Chemical Reaction Dynamics Theory. Other factors that influenced engine performance parameters were also discussed. The results showed that butanol was a promising efficient fuel that could reduce 14% of brake-specific energy consumption while also producing fewer emissions.

In comparison to ethanol, butanol has a greater calorific value as well as lower latent heat vaporization. The properties butanol is comparable to gasoline, thus making it more suitable as an alternative fuel in a gasoline engine. A study carried out by Golke et al. [18] compared four fuels: n-butanol, n-butanol and ethanol mixture (B73E27), gasoline as well as ethanol mixture (G73E27), and hydrous ethanol. The tests are carried out on a single-cylinder naturally aspirated engine with port fuel injection. Engine performance was assessed through an experiment, while combustion parameters were evaluated using a reverse computation on GT-Power. The calculation was based on the intake, exhaust, and in-cylinder pressures collected from the experiments. The results showed that gasoline gave the worst indicated efficiency, while hydrous ethanol, despite its relatively lower indicated efficiency compared to B73E27, offered the best combustion phase. The lower indicated efficiency resulted from the larger quantity of injected fuel needed to get the same engine load.

Butanol has two competitive advantages over ethanol: its energy density and its miscibility with diesel. These benefits have attracted several research groups to evaluate all four butanol isomers. The traditional process of bio-butanol fermentation mostly utilises corn liquefaction, semi-continuous fermentation, as well as product distillation (**Figure 1**). Note that feedstock along with utilities make up the biggest costs of the entire process, 66% and 16%, respectively as shown in **Figure 2**.

Earlier studies investigating the combustion of butanol isomers in laminar premixed flames showed that each isomer revealed comparable combustion characteristics such as adiabatic flame temperature and speed. However, pollutant formation was strongly influenced by the chemical structure of every isomer. Regalbuto et al. [19] investigated the impact of three of the four isomers of butanol, namely n-butanol, iso-butanol, and 2-butanol, on engine performance as well as emissions characteristics. These fuels were examined in a single-cylinder port injection spark ignition engine with 30% butanol and 70% blends for each isomer. The air-fuel ratios and spark timing were constant, while the engine loads were measured at three different values.

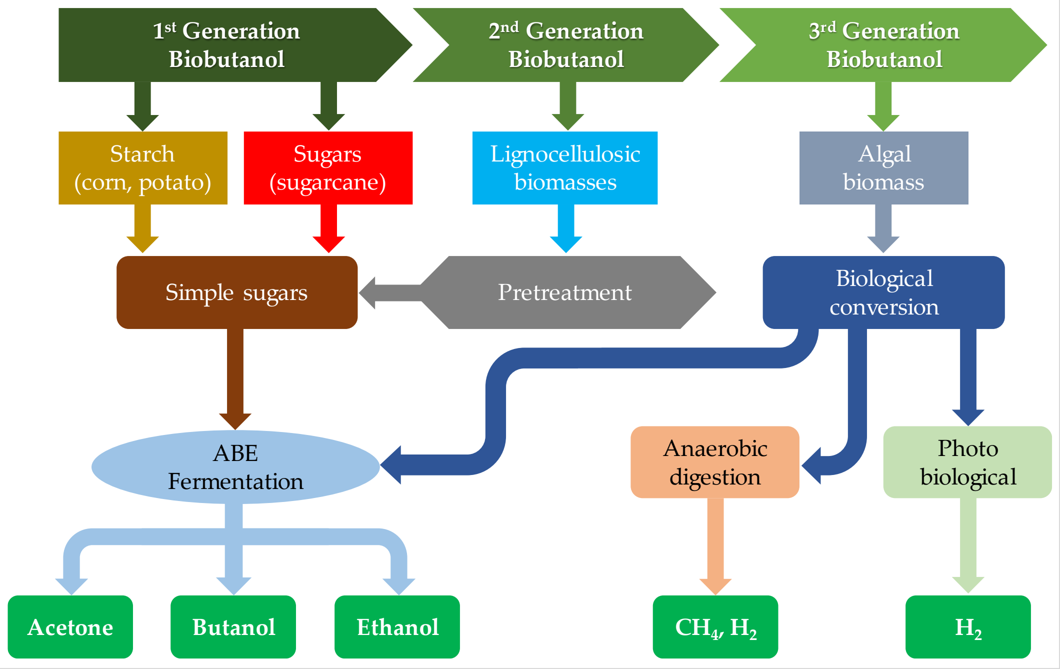

Figure 1. 1st, 2nd, and 3rd generation biobutanol routes and their microbial fermentation pathway, reproduced from [20]

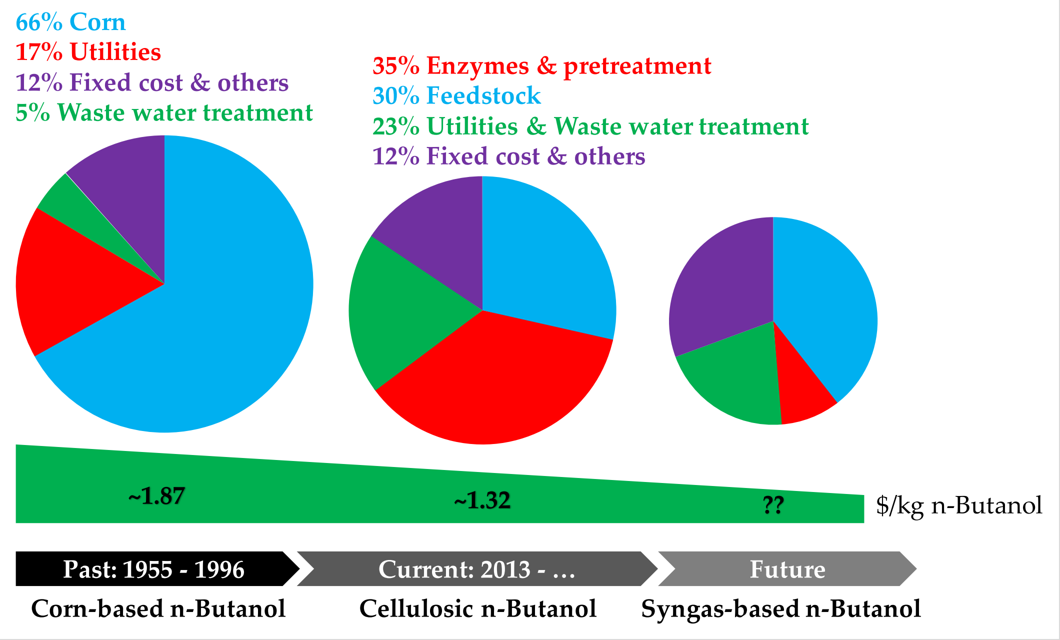

Figure 2. Cost distribution of bio-butanol according to percentage and total cost, reproduced from [20]

2. Mixture Concentration

Alasfour [21], [22] conducted one of the first studies using butanol and gasoline blends using 30% isobutanol and published two parts. Both articles investigated NOx emission, with the first part [21] focusing on the effect of preheating the inlet air, while the second article [22] focused on the effect of ignition timing. The butanol production method was still in its infancy, and its production cost was still expensive. Therefore, the addition of 30% iso-butanol at that time was considered high. Wallner and Frazee [23] conducted another study that compared the use of butanol and ethanol by comparing ethanol/gasoline (E0, E10, E50) and butanol/gasoline blends (Bu0, Bu16, Bu83). Note that this study used butanol addition up to 83%, while maximum ethanol addition was only 50%. Ethanol was chosen as a comparison because it has long been used on a large scale as a renewable alcohol fuel.

Some researchers have increased the butanol addition to a high percentage. To be used on a large scale and to evaluate its maximum usage, butanol needs to be investigated as a pure fuel in an SI engine without any addition of gasoline fuel. Irimescu [24] used a 100% isobutanol when developing a simple thermodynamic model to study the cold start characteristics of the PFI gasoline engine fuelled with isobutanol blends. The model calculates the parameters of the air-fuel mixture to identify an ideal concentration. This was done to ensure excellent cold start performance and emissions comparable to those of gasoline. To validate the model, an experimental test using a port injection engine was used. The model was found to show good agreement between the theoretical and experimental tests.

Broustail et al. [25] compared the addition of butanol and ethanol to the PFI-SI engine. The gasoline surrogate fuel, i.e. iso-octane, was selected as the reference fuel. It was found that both alcohol, butanol and ethanol increased fuel consumption. However, butanol only increases fuel consumption by 30% compared to a significant increase of 60% by adding ethanol. This was because butanol has a higher LHV than ethanol. Yacoub et al. [26] performed another study that conducted a comprehensive investigation of various alcohol fuels. They investigated the knocking combustion of several alcohols. They studied the knock characteristics of butanol, focusing on the knock-limited spark timing (KLST). A similar study was performed by Gautam et al. [27].

Several studies have also reported improved engine performance using hydrogen. The hydrogen enrichment is known to improve torque and IMEP of spark ignition engine at lean environments [28]. At both idle and lean conditions, better thermal efficiencies with lower emissions were described in Ref. [29]. As the hydrogen fraction increased, higher cylinder peak pressure and temperature were observed, while the development of flame and durations of propagation decreased [30].

Gu et al. [31] investigated 10%, 30%, 40% and 100% n-butanol combined with hot EGR on PFI SI engine. The results indicated that n-butanol was able to decrease specific CO emissions. This emission also decreased when the spark timing was advanced. However, when the n-butanol was increased to 100% n-butanol, the specific CO emissions were found to increase. The application of EGR also gave a slight increase in CO emissions. Gu et al. [31] investigated 10%, 30%, 40% and 100% n-butanol combined with hot EGR on PFI SI engine. The results showed that n-butanol along with the assist of EGR was able to decrease SI engine-specific HC emissions. However, this emission became higher as the spark timing was advanced. Moreover, specific HC emissions were also found to increase when n-butanol increased to 100%. Similarly, the application of EGR gave a slight increase in HC emissions.

Alasfour [32] used 30% iso-butanol to investigate its effect on HC emissions. He found that lower HC emissions were significantly influenced by ignition timing, cooling water temperature, and engine speed variables. Moreover, it was found that HC emissions largely depended on fuel/air equivalence ratio with its lowest level was at maximum brake torque (MBT) and at lean mixture with ϕ = 0.85. Furthermore, delaying the ignition time by 6 degrees from MBT could reduce the HC emissions level by 12%, while increasing the cooling water temperature by 35 ^{o}C from 55 ^{o}C to 90 ^{o}C could reduce the HC emissions level by 30%. Retarding ignition timing was accompanied by increased exhaust temperature caused by post reaction of HC oxidation. It was also reported that by increasing the engine speed from 1500 to 2000 rpm at MBT was more likely to lower the HC emissions level. **Figure 3** shows the typical representation gasoline engine test bench run with butanol.

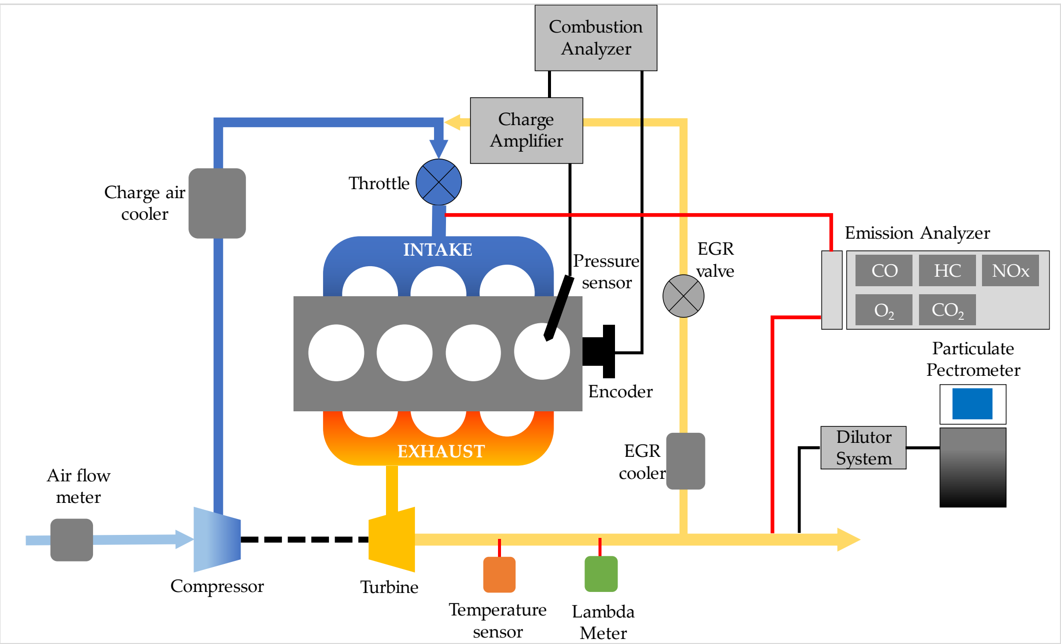

Figure 3. Schematic diagram of SI engine fuelled with butanol, reproduced from [33]

3. Injection System

Since the injection system plays a substantial part in the combustion process, brief insight into both port fuel injection (PFI) and direct injection (DI) systems will be discussed first. Throughout this paper, most experiments reported were conducted either in PFI or DI. Port injection and direct injection systems use computer-controlled electric injectors to spray fuel into the engine. The difference lies at the location where the system sprays the fuel. Port injection sprays the fuel into the intake ports before it blends with the incoming air and come as an air-fuel mixture into the cylinder, while direct injection sprays the fuel directly into the combustion chamber with the injectors being mounted in the cylinder head. Only air passes through the intake manifold.

Compared to direct injection system, the injectors in port injection system are not exposed to the high heat and pressure of the combustion chamber thus cheaper to produce. The injectors of port system also do not have to deliver the high fuel pressures. Handling relatively lower fuel pressures means that support system such as fuel pumps are less expensive. Port injection systems spray the fuel behind the intake valve. Consequently, the fuel has to wait until the valve opens to enter the combustion chamber, causing fuel to leave the air. However, as the engine is running faster, this drawback can be minimized. Although it is relatively better than the old carburettor, port injection system is not able to achieve the power and economy comparable to direct injection.

Improved fuel economy is the biggest benefit offered by direct injection system. By altering from port to direct injection, significant reduction in fuel consumption can be achieved. In addition to reduced fuel consumption, direct injection also gives better performance. To obtain optimum engine performance, direct injection measures the exact quantity of fuel needed into every cylinder. This fuel is then sprayed under very high pressure thus better fuel atomization and instant ignition can be achieved. The advancement in computer and control technology has allowed the injectors to be pulsed for every combustion stroke. As a result, the fuel was able to be injected in a relatively longer interval to increase the power output.

Despite the advantages in terms of fuel economy and performance, direct injection is more expensive than port injection system as the injector tips is mounted exactly into the cylinder. This requires high quality materials and consequently increases the production cost. Moreover, as the direct injection requires high pressure to inject the fuel directly into the cylinders, more expensive and more complicated high-pressure fuel pumps are needed since the pumps are mechanically driven from the engine. Lastly, it is more difficult to control emissions using direct injection system. Although the fuel is injected under high pressure, it has little time to mix with the air. To direct the fuel accurately, precise nozzles with multiple holes is one of the solutions. Another solution to meet emission standards of direct injection is to design piston and cylinder head that are able to swirl the intake air. This approach will mix the fuel and the air relatively better since the air will swirl rapidly when it is forced coming into the cylinders.

In port fuel injection (PFI) and direct injection (DI) gasoline engines, most publications using n-butanol focus only on the combustion and emission. Wang et al. [34] aimed to investigate the combustion as well as particle emission attributes of gasoline blended with n-butanol at various injection methods and conditions. The main goal was to obtain the best fuel injection method according to combustion and particle emission attributes. This study used three different fuel injection strategies; gasoline and n-butanol using DI with various volume mixing ratio, n-butanol utilizing PFI combined with gasoline fuel using direct injection and gasoline using PFI combined with n-butanol using direct injection. To describe particle emission traits such as particle number (PN), particle matter (PM) and particle distribution, the tests were conducted at stoichiometric as well as rich mixture condition.

The results showed that when the n-butanol blending volume ratio for GNDI was increasing, the indicated mean effective pressure (IMEP) was also increasing but it then decreased subsequently. Furthermore, total particle matter (TPM) was found to decrease continuously, while the APN intensified constantly. The total particle number (TPN) and nucleation mode particle number (NPN) reduced first and increased afterward. The best NBr was considered to be 20% as this percentage gave the highest IMEP with decreased TPN and TPM by 8.63% and 30.88%, respectively compared to GDI at stoichiometric condition. Among the investigated injection strategies, N-GxDI with 40% Dir was considered the best since it gave the lowest TPN in which its value was reduced by 51.07%. The value of TPM was also insignificant and could be neglected compared to GDI under stoichiometric condition. This strategy, however, decreased the IMEP by 1% than that of PFI gasoline, but the value was still better than DI gasoline.

4. Performance and Emissions

For engine performance evaluation, engine torque and cylinder pressure were compared between the isomers. As for the emissions, NOx, HC, CO_2 and CO were assessed. The results showed that the three isomers (n-butanol, iso-butanol and 2-butanol) gave similar performance characteristics for the brake torque as well as the peak pressure inside the cylinder. Their emissions, however, showed different results with n-butanol giving the highest average NOx emissions. Iso-butanol and 2-butanol exhibited the highest average of CO and HC emissions, respectively.

It is important to evaluate the engine performance as well as emissions of pure n-butanol with those of gasoline and ethanol fuels. The brake torque, exhaust gas temperature and in-cylinder pressure traces need to be measured to examine the engine performance, whereas unburned hydrocarbons, CO and NOx were examined to investigate the combustion by-products. Butanol is expected to give comparable performance to gasoline fuel but possibly with less brake torque. The exhaust gas temperature and NOx are predicted to reduce, indicating that the combustion of butanol will occur at a lower peak temperature. It is important to note that butanol may not atomize as effective as gasoline and ethanol where the unburned hydrocarbons may increase by two and three times than gasoline.

Vojtisek-Lom et al. [35] examined the gasoline, E85, and B85 on typical gasoline engine vehicle using fuel injection as well as three-way catalyst. The vehicle was fitted with an on-board emission examining system. The tests were carried out in city and rural roads such as hills. Numerous tests on every fuel were conducted to validate the repeatability of the experiment. At more than tens of km driving, the ECU adapted to both E85 and n-butanol by raising the pulse width of injector thus achieving stoichiometric ratio on all fuels. The results showed that the tailpipe temperatures were similar for the whole fuels. Compared to gasoline, E85 and n-butanol blends produced lower CO, higher NOx emissions. This may be resulted from the variations in AFR. Moreover, no consequences on particle mass were observed for E85, but its particle length, an indicator of nanoparticles, was found to reduce, whereas the use of n-butanol was observed to rise particle mass without giving no adverse effects on particle length.

Compared to ethanol, butanol is less corrosive with higher energy density, lower vapour pressure and lower solubility in water. Furthermore, the use of an intermediate product in ABE fermentation known as ABE is less expensive to produce than butanol. This study [36] investigated three high-alcohol fuels i.e. E85, B85 and ABE85 in a PFI gasoline engine. The ABE had a component ratio of 3:6:1 for the acetone, butanol, and ethanol, respectively. Moreover, pure gasoline was also used and tested as a baseline fuel for comparison. The experimental investigations for all fuels were performed at constant value of 1200 RPM, $\Phi = 0.83-1.25$, and BMEP = 3 bar.

Kalita et al. [37] used commercial gasoline with EURO-IV as the main fuel with 5%, 10% and 20% of n-butanol being utilized as the mixing element. The passenger car in this study was tested on chassis dynamometer so that the fuel consumption, both regulated and un-regulated emissions could be evaluated at standard driving cycle of NEDC. The outcomes showed that the fuel economy reduced between 0.6 to 3% with 5-20% n-butanol addition compared to pure gasoline under transient condition. Furthermore, by adding n-butanol, CO levels were observed to be increasing, while CO_2 and NOx emissions was decreasing under NEDC driving cycle. In addition to that, unregulated emissions i.e. formaldehyde and benzaldehyde decreased, whereas acetaldehyde, acrolein, acetone, etc increased. It was important to note that high content of n-butanol/gasoline blends resulted in misfiring/engine stalling. This study indicated that n-butanol can be used up to 10% and 20% without any engine modification.

Butanol has been received much attention as an alternative fuel [38]. Despite its promising proposition, concern has been given to alcohol fuel's non-regulated emissions especially aldehydes. Wallner and Frazee [23] investigates three different alcohol isomers in a DI gasoline engine. To avoid emission changes caused by slight changes in EGR ratio, EGR was deactivated. This was done to give direct comparison of the emission results. Moreover, to characterize the exhaust stream, a standard emissions bench coupled with a Fouried Transform Infrared (FTIR) analyser were used. The tested fuels were ethanol, n-butanol and iso-butanol which were blended in gasoline fuel. As the alcohol percentage was increasing, the results showed that NOx emissions were decreasing. As for the unregulated emissions namely formaldehyde and acetaldehyde, both emissions were also observed to be decreasing. The reduction of aromatic hydrocarbon emissions with the increasing of alcohol content was not caused by the changes in the fuel chemistry, but by high percentage dilution of aromatics in gasoline. Moreover, the PM emissions from iso-butanol was produced via C_3/C_3 route to produce benzene, while that of n-butanol was produced via C_4/C_2 route.

Most published papers reveal that by increasing EGR-rate, soot particle could be reduced. The reduction is achieved because the increase of EGR rate can reduce the combustion temperature thus decreasing soot particle. However, in locally rich combustion, different results were observed. On the hand, the sources of soot formation including the particle formation and oxidation rates need to be understood thoroughly. Such information is still limited and an alternative method to quantify the soot formation as well as oxidation rates is needed. Most studies were conducted using particle sizer metal engines. Investigating the quantitative volumetric of soot distribution in the combustion chamber for the duration of the combustion cycle is one viable method to limit soot formation as well as oxidation rates.

Koegl et al. [39] investigated the volumetric soot distribution in an optically accessible DISI engine. The soot formation as well as soot oxidation were analysed using the volumetric extinction measurement technique under low gas along with soot particle temperatures for gasoline-ethanol and -butanol combinations. A fuel mixture that consists of 65% isooctane in addition to 35% toluene known as Toliso was used. The impact of exhaust gas recirculation on soot formation and fuel oxidation was also considered under part-load operation. The running point was distinguished by an initial injection timing resulting in wetting of the piston along with a sooting pool-fire. The experiments without EGR gave a minimal soot formation for Toliso, whereas that of with EGR gave higher soot formation.

Different trends were found in sooting tendencies of butanol isomers in diesel engines. In addition to that, those four isomers effect on the particulate emissions of DISI engines had not been reported. For all isomers, the results showed that the particle number concentration decreased significantly, while the particle mean diameter (PMD) slightly with the increasing of butanol percentage. The tert-butanol/gasoline blends gave the highest particle number concentration followed by iso-butanol, n-butanol and 2-butanol. Similar tendency was also observed for the particle mean diameter with tert-butanol/gasoline blends giving the largest particle size and 2-butanol giving the smallest. Since the decrease of the particle mean diameter was not as substantial as that of particle number concentration, the variation in the particle size of the isomers was not substantial.

A number of three-dimensional, computational fluid dynamics coupled with one dimensional engine models are available for ethanol or ethanol-gasoline blends. For computer simulation of butanol addition on SI engine, obtaining the necessary data such as its properties values to be used for engine modeling is difficult. Furthermore, to validate the simulation results, obtaining correctly measured data is also problematic. There is limited information regarding butanol’s engine performance making it hard to assess its benefits. To overcome this constraint, 1D model was used to characterize the full engine and to simulate engine performance of various fuels by adjusting the physico-chemical fuel properties up to the numerical outcomes agree with experiments scores. Roberto and Gonçalves [40] aimed to investigate properties of an n-butanol-gasoline blend using 1D simulation model.

Another interesting approach in the research of butanol in SI engine is proposed by using hydrogen addition. Hydrogen is considered as an ideal fuel since it emits zero pollutants and has excellent combustion properties [41]. It also has high diffusion coefficient thus achieving proper air-fuel mixture in the cylinder. Backfiring is a significant problem when hydrogen is used in internal combustion engine. Therefore, instead of using hydrogen as the only fuel, it could offer better results when used as an additive to hydrocarbon fuel to take the advantage of its superior combustion properties.

The exhaust gas recirculation or EGR is often utilized to improve knock resistance in SI engine by diluting the air-fuel mixture thus reducing the temperature of combustion and delaying the autoignition. Despite its advantage in reducing the knock, the effect of EGR combined with the addition of butanol fuel is rarely investigated. Few studies have investigated the effects of EGR of n-butanol/gasoline blends of SI engines thereby more in-depth information is needed. Furthermore, the sensitivity of knock phenomena to factors including intake pressure as well as compression ratio need to be explored.

Gu et al. [31] investigated n-butanol and discovered that the n-butanol was able to decrease SI engine specific NOx emissions. However, when the spark timing was advanced, the combustion occurred early, and the cylinder peak pressure increased. Therefore, the peak temperature increased and raised the NO_x emissions for all blends (Bu0, Bu10, Bu30, Bu40 and Bu100). However, Bu100 gave the lowest specific NOx emissions of all blends. This is because n-butanol has lower adiabatic temperature and heat value compared to gasoline fuel; 2340 K vs 2370 K and 33.0 MJ/kg vs 42.9 MJ/kg, respectively. Therefore, higher n-butanol concentration in the blends could lower the NOx emissions.

The effect of EGR rate on NOx emission was also investigated by Gu et al. [31]. With higher EGR rate, the specific NOx emissions were observed to decrease. The main reason why increasing the EGR rate could decrease the NOx is that EGR decreases the in-cylinder temperature by recirculating the exhaust gas. Thus, the supply of fresh air and fuel was reduced, and the ignition delay was prolonged, thus postponing the combustion phasing and decreasing the heat release. Gu et al. [31] also found that PN concentration reduced with higher percentage of n-butanol. Moreover, the use of EGR could concurrently lower PN concentration engine as well as the specific NOx emissions. PN concentration emission was, however, found higher when the spark timing was advanced. Overall, this study showed that using n-butanol could successfully reduce the PN concentration emissions.

Another study on particle number was conducted by Arsie et al. [51]. They examined the impact of AFR and spark advance. It was found that lean mixtures gave a sharp decrease in PN concentration compared to that of stoichiometric. At advanced spark timing, particles smaller than 20 nm were found to increase. As for the effect of using EGR, Alger et al. [52] revealed that EGR could potentially lower particulate matter (PM) emissions. Results on the PM emissions from Arsie et al. [51] and Alger et al. [52] were in line with findings from Gu et al. [31] mentioned above. Those studies, however, were performed on PFI engines. More investigations should be carried out in DI-SI engines to evaluate why a direct injection system produces relatively more PM emissions [53].

Wallner and Frazee [23] investigated both regulated and non-regulated emissions. They compared ethanol (E0, E10, E50) with butanol (Bu0, Bu16, Bu83). The results showed that formaldehyde and acetaldehyde became higher as the butanol ratio increased, while formaldehyde did not increase substantially with ethanol addition. Propene, 1,3-butadiene, and acetylene emissions also increased with butanol addition but not with ethanol. It was also found that ethanol addition gave lower CH_4 and C_2H_2 emissions compared to pure gasoline, while no change was observed with butanol addition. Furthermore, the addition of ethanol gave an increase in CH_2O and CH_3CHO emission, while the addition of butanol had different results.

Broustail et al. [25] compared the regulated and non-regulated of iso-octane/butanol and iso-octane/ethanol. The results showed that the non-regulated pollutants of ethanol and butanol addition decreased significant methane emissions. The addition of both alcohol fuel was also found to stimulate a decrease in acetylene and a rise in formaldehyde emissions. Furthermore, ethanol brought a considerable reduction of ethylene up to 100%, while butanol, on the other hand, gave a substantial increase in ethylene. The effects of acetaldehyde were negligible for both ethanol and butanol addition.

5. Combustion

To have improved understanding of in-cylinder events using butanol-gasoline blends, Tornatore et al. [42] studied the combustion process of such blends in a PFI SI boosted engine via optical diagnostics. They investigated the effect of 40% of n-butanol addition through cycle resolved visualization working at low speed, medium boosting and wide-open throttle. They found that butanol blend induced advanced spark timing without irregular combustion. Butanol addition has enabled the spark timing to be more advanced without abnormal combustion being reported. A stoichiometric mixture was obtained for the mix BU40 by increasing the duration of injection (DOI). To minimize abnormal combustion effects including the emission of ultrafine carbonaceous particles such as NOx and HC, open valve injection system was used.

Nearly similar results were also reported in another study. Merola et al. [43] tried to present better understanding of in-cylinder events under various engine operating conditions using pure gasoline (BU00) and butanol-gasoline blend (BU20). Previous studies mostly examined the development of combustion progression using cycle resolved visualization as well as UV-visible digital imaging. In their study, Merola et al. [43] used UV-visible natural emission spectroscopy to understand the formation as well as evolution of the principal compounds & radical species. These two, principal compounds and radical species, are important to understand as they characterise the normal and abnormal combustion such as knocking. For BU20, the flame kernel was identified earlier than BU00 possibly owing to the greater oxygen content that accelerated the initiation of the flame. Moreover, a number of bright spots were discovered in the burnt gas prior to the flame front reaching the combustion chamber walls, with the BU20 spots being less evident than that of

Bu00. These bright spots were believed to be caused by the fuel deposits on the optical window. In addition to that, the presence of OH radical emission observed at 325 nm could be an indication of knocking.

Tornatore et al. [42] studied the combustion of butanol in via optical diagnostics. Open valve injection system was used to minimise irregular combustion. They found that butanol blend induced advanced spark timing without irregular combustion. A stoichiometric mixture was obtained for 40% butanol by increasing the duration of injection (DOI). This study suggested that the open intake valve injection system was able to reduce ultrafine carbonaceous particles, i.e. HC emissions without sacrificing the performance of SI engine.

To understand butanol's combustion process, a number of models for its chemical reaction kinetics were suggested. These models have allowed the computer simulations to forecast the heat release rate and emissions of butanol more accurately. Sarathy et al. [44] developed a detailed chemical kinetic combustion for four isomers of butanol. This model was later simplified by Wang et al. [45] who inserted it into a reduced n-heptane-PAH mechanism. In doing so, they tried to examine the consequences of oxygen content on combustion process by adopting the multi-dimension CFD. The progress in computer simulations such as CFD has improved the predictions of heat release and exhaust emissions in internal combustion engine.

A number of studies have been conducted using butanol-gasoline blend. Yet, limited research groups had investigated the detailed oxidation mechanism of 1-butanol or commonly known as n-butanol. Dagaut and Togbe [46] investigated the combustion of n-butanol/gasoline by means of both theoretically and experimentally study using a jet-stirred reactor. The outcomes revealed that the simulation and experimental results were in good agreement. For the advantage of combustion study, the finding from this study provided valuable and usable data for future kinetic modelling using n-butanol-gasoline blends.

In DI-SI engines, understanding the effects of new bio-components on spray formation is challenging as direct injection system is very sensitive to fuel properties. More in-depth investigations are needed to study the DI-SI engine injector nozzles using alternative fuels such as butanol. The cavitation evaluation, Reynolds along with Weber numbers are important parameters to understand its atomization systems. Aleiferis et al. [47] initiated the study to examine the consequences of fuel temperature along with gas pressure on cavitation as well as spray formation from a actual-size optical-accessed nozzle of butanol. This was the first study investigating the relations between cavitation combined with flash-boiling under extremes pressures-temperatures of various fuels; gasoline, iso-octane, n-pentane, ethanol and butanol. The results showed that the flow regime of in-nozzle in addition to spray formation were sensitive to the fuel temperature as well as gas pressure caused by the vapour pressure and temperature relationships.

Serras-Pereira et al. [48] examined the spray growth as well as combustion using optical investigations in a one cylinder DI gasoline. This investigation employed crank-angle resolved imaging studies with batches of images from 100 successive cycles were obtained using synchronized in-cylinder pressure logging. To achieve homogeneous mixture formation, the injection timing was set early in the intake stroke, while the engine was motored and fired at 1500 rom stoichiometrically under part load of 0.5 bar intake pressure. The tested fuels were gasoline, iso-octane, ethanol and butanol with engine coolant temperatures being 20^{o}C and 90^{o}C. To gather the information regarding the atomization and evaporation process for each fuel, projected spray areas noticed via the piston crown were determined. Furthermore, to analyse the combustion process, flame areas and centroids were determined using calculation.

Another study also reported that the butanol addition could advance the ignition timing without the occurrences of knocking. Deng et al. [49] were successful in increasing the combustion efficiency of gasoline engine powered by butanol-gasoline blend by adjusting the ignition timing. As a result, higher combustion efficiency was achieved. Deng et al. [50] continued their previous study and performed the heat release analysis of bio-butanol/gasoline blends on a high speed single cylinder spark ignition engine. The tests were conducted twice for butanol/gasoline blends. The first one was tested without any modification of the engine and represented as B35-Without CIT (changing ignition timing), whereas another test was completed at the ignition timing of maximum brake torque, and represented as B35 -With CIT.

Similar characteristics are observed for the ROHR and in-cylinder pressure. It indicates that the profile of ROHR at low speed (3000 rpm) is narrower and higher compared to those of 6000 and 8500 rpm. This means that the ROHR of 3000 rpm occurs earlier and reaches higher value, resulted from the advance of its ignition timing. Furthermore, it was found that the peak of ROHR falls with the increase of engine speed. As the speed rises, the degrees of crank angle also increase.

It is important to note that at relatively higher speed, the difference between PG and Bu35 is getting smaller. Another noteworthy feature is that the ROHRs of Bu35 is less oscillating than that of PG. The same trend was observed by another study in which it demonstrated that the coefficient of variance of net IMEP for butanol was slightly lower than for gasoline. The less fluctuation of COV implied that butanol addition could successfully stabilize the in-cylinder combustion.

6. Cold Start

The cold start has been a main problem of alcohol fuel in SI engines. It is important to evaluate the butanol addition in SI engine in terms of cold start performance. In ambient temperatures below 0°C, a vehicle fuelled with alcohol fuel blends such as ethanol and gasoline should increase its gasoline composition to improve its cold start characteristics. To reduce the drawbacks of using alcohol at cold start, butanol has been proposed to replace ethanol due to its closer heating value to gasoline. Given the butanol has a lower octane rating compared to gasoline, the iso-butanol, one isomer of n-butanol, was used.

Irimescu [24] developed a simple thermodynamic model to study cold start characteristics of iso-butanol. The model calculates air-fuel mixture parameters to identify an ideal composition of iso-butanol. This was done to ensure excellent cold start performance and emissions comparable to gasoline. The mixture formation was assumed to be adiabatic since engine was on ambient temperature at cold starts. The temperature was found to drop caused by two conditions; the breaking up of the fuel into droplets and the evaporating process. The key aspect that influenced the blend temperature after the evaporation of the fuel was considered to be the ambient air temperature.

To validate the model, an experimental test using a port injection engine was used. The model was found to show similarity between the theoretical and experimental tests. The results showed that for pure iso-butanol (Bu100), the engine could not be started at ambient temperatures lower than 20°C. Although the composition had been reduced to Bu70, the same problem still occurred. For Bu50, however, the engine was able to run even at 5°C. When higher iso-butanol such as Bu70 was used, the engine was able to start but then stop afterwards. In this case, the adiabatic condition was not achieved. The component contributing to the majority of heat transfer was the intake valve. This was because the intake valve warmed up quickly resulted from the in-cylinder combustion. Another reason was that the fuel was sprayed directly on to the intake valve by the injector. Iso-butanol, in conclusion, gave poor cold start performance during cold seasons like other alcohol fuels. However, the thermodynamic model established from this study provides a valuable insight into the cold start behaviour of butanol. The errors were within an acceptable interval so that the model can be further applied for more comprehensive research. Related studies by the same author using gasoline-iso-butanol blends can be found in Refs. [54], [55].

7. Knock

Previous study conducted alcohol fuel such as ethanol was found successfully eliminate the knock phenomena. Koc et al. [56] found that the addition of ethanol into gasoline fuel could increase the compression ratio without knocking. Their study indicated that using fuels that have high octane number can potentially avoid knock occurrence and increase the thermal efficiency resulted from increased compression ratio. Compared to methanol and ethanol, butanol has lower research octane number (RON) number. Smaller RON number means that butanol encompasses higher knock resistance.

Currently, findings on butanol's detonation combustion characteristics are still limited. Yacoub et al. [26] investigated the knocking of various alcohols varying from methanol to pentanol. They focused on anti-knock ability, knock intensity as well as knock limited spark timing (KLST). It was found that n-butanol was more than likely to produce knock compared to gasoline. The addition of lower carbon alcohols was observed to provide better knock resistance. Different results were observed by Gautam et al. [27]. They investigated several alcohol-gasoline blends including methanol, ethanol, propanol, butanol, pentanol and RON 96 gasoline and found that the higher the oxygen content, the better the knock endurance and the faster the burning velocity.

Adding alcohol to fossil fuels can raise the fuel octane rating and the power of spark ignition engine. Merola et al. [57] investigated the influence of butanol addition to gasoline using experiments conducted in an optical PFI single-cylinder gasoline engine. The engine was equipped with external boosting device and the head of a gasoline turbocharged engine that had comparable geometrical designs in terms of bore, stroke as well as compression ratio. This study examined the impact of 20% n-butanol addition to gasoline (BU20). The timing of spark and phasing of fuel injection were changed. The spark timing was altered to determine the maximum brake torque and the knocking limit. Furthermore, the flame luminosity and the combustion pressure data were compared. It was found that butanol can be used in earlier spark timing with no irregular combustion phenomena.

8. Optical Investigation

To achieve higher efficiencies and less emissions, the basic concept of spark ignition process in gasoline engine needs to be understood thoroughly. One stage in the combustion process that provides an essential information is the early stages of spark ignition process. The formation of flame kernel in the cylinder has a great influence in the development of combustion. A study by Merola et al. [58] analysed the evolution of spark-ignited flame kernel with in depth detail on the cycle-to-cycle differences. The butanol addition was 40% and the blends were tested at stoichiometric and lean mixture conditions. Moreover, the tests were performed at 2000 rpm using both conventional and optical diagnostics. UV-visible natural emission spectroscopy was used to examine the formation and the evolution of the main compounds describing the spark ignition and combustion process. Furthermore, a post-detection procedure was used to examine the flame kernel areas evolution and its correlation to the MFB.

Ethanol has long been used as a blending component in gasoline engine [59]. Like ethanol, n-butanol is also an oxygenated fuel with the potential to improve engine performance and to reduce emissions [60]. The fuels tested in this study [61] were ethanol, n-butanol, along with gasoline fuel with no oxygen substance. The alcohol fuel had maximum blend rate of oxygenates of 10% by volume. The tests were conducted at different equivalence ratio between 0.7 and 1.3 with pressure and temperature being at 10 bar and 373 K, respectively.

Tornatore et al. [62] investigated butanol-mix combustion in a gasoline engine using in-cylinder optical diagnostic. To compare normal and knocking conditions, spark timing as well as fuel injection mode were altered. focus was given to OH and CO_2 evolution as well as the spectral evidence of soot precursors resulted from fuel deposits burning. The OH was observed to be the best indicator of normal and abnormal combustion.

Direct-injection technology have been widely applied in internal combustion engines both in gasoline and diesel engines [53]. It can not only improve engine's performance, but it also can reduce harmful emission. Despite its growing popularity, detailed combustion process of direct-injection engines is not entirely understood. Irimescu et al. [63] investigated the effects of a number control parameters on the combustion process. These parameters include ignition timing and EGR.

Breda et al. [64] compared the combustion behavior of gasoline and n-butanol using both experimentations and 3D-CFD simulations. The experiments were conducted on a single-cylinder DI gasoline engine equipped with an optically accessible flat piston. The analysis of experimental results was then performed at stoichiometric undiluted and lean-diluted mixture for both pure fuels. To predict laminar flame speed for gasoline and n-butanol at selected engine-relevant conditions, a dedicated set of detailed chemistry simulations was performed.

The use of alcohol fuel such as butanol is often proposed to diverse the energy sources [65]. In addition to that, control strategies for spark-ignition engine are also used to increase fuel economy and reduce harmful emissions. To improve the stability of spark-ignition operating points, Irimescu et al. [66] used plasma assisted ignition (PAI) at lean conditions along with cooled EGR for n-butanol and gasoline blends. The UV-visible 2D chemiluminescence measured the flame morphology, whereas the natural emission spectroscopy gave insight into the active chemical species of combustion. The results show that PAI, the proposed different ignition system, can increase the engine stability of butanol blends. The in-cylinder data were observed to be different among the tested fuels and influenced by the flame speed and movement, particularly during the initial steps of kernel formation and propagation.

9. Conclusion

Understanding the combustion process of butanol is a crucial step in the study of alcohol fuel in internal combustion engine. However, very few studies are conducted on the use of butanol in an optical engine. Its effect on cold start and knock phenomena are also rarely investigated.

Therefore, more experimental, and numerical investigations are needed to clarify the difference between butanol-gasoline blends and pure gasoline. This paper highlights some important approaches and findings on the use of butanol addition in SI engine, as shown in **Table 1**.

Table 1. Results for gasoline usage

Fuel	Engine	Operating Condition	Novelty/Contribution	Reference
Iso-butanol	A port injection engine, with an integrated injection and ignition system	Cold start, 3500–4000 rev/min.	Developing a simple thermodynamic model to calculate air-fuel mixture parameters.	Irimescu [24]
Butanol, ethanol, gasoline, iso-octane, n-pentane	Elevated-pressure multi-hole injectors direct injection	Using real-size optical nozzles	The first study investigated the relations between cavitation along with flash-boiling under extremes pressures and temperatures of various alcohol fuels.	Aleiferis et al. [47]
Iso-octane/ butanol and iso octane/ ethanol	A single-cylinder port-fuel injection	Two homogeneous operating points at 1700 and 2000 rpm	Providing new experimental data on engine performance, regulated and non-regulated pollutants for various butanol/iso-octane blends.	Broustail et al. [25]
Bu0, Bu10, Bu30, Bu40, Bu100	Port fuel injection	Various spark timings and EGR rates	Report on the number and size distribution of particulate emissions from butanol addition	Gu et al. [31]
Bu40	Single-cylinder port fuel injection with an external boosting equipment	Low speed, medium boosting and WOT. Fuel was injected at closed valve (CV) and open intake valves (OV)	Improved understanding of in-cylinder events of butanol-gasoline blends and one of the earliest studies focusing on butanol addition in SI engine using optical diagnostics.	Tornatore et al. [42]

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript

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