Narrative Review Article

Ethanol Blend Fuels in Internal Combustion Engines: Effects on Performance, Fuel Stability, and Emissions: A Review

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ABSTRACT

Currently, internal combustion engines (ICE) utilize gasoline-based fuels to generate energy. These fuels have the tendency to emit products of incomplete combustion, as well as toxic and greenhouse gases. Ethanol can be used as an additive to gasoline fuels to limit these downsides. The objective of this study is to evaluate the impact of ethanol–gasoline blends on engine performance, emissions, corrosion, and blend stability. To evaluate whether the addition of ethanol is beneficial, the impacts of the alcohol on engine performance, engine emissions, blend stability, and corrosion were reviewed. This review indicates increases in power, torque, and efficiency by 5%, 3%, and 2% respectively; decrease in hydrocarbon (HC) and carbon monoxide (CO) emissions by roughly 30% and 40% respectively; increase in nitrogen oxides (NO_X) and carbon dioxide (CO_2) emissions by roughly 50% and 5% respectively; and mixed results for toxic emissions. These results were all compared to the data from base gasoline. It is also noted that temperature is a major factor for the stability of ethanol-gasoline blends and that corrosive properties of the fuel depend on the fuel's water content.

Keywords: ICE; Ethanol; Gasohol; Gasoline; Sustainability; Power; Emissions; Stability

INTRODUCTION

Many countries rely on internal combustion engine (ICE) vehicles as the main mode of transportation for people and goods. However, ICEs have significant negative consequences on the environment due to their operating mechanism. The main mechanism of an ICE is combusting fuel to create power. The ICE is designed as an air-tight cylinder with valves on top to draw in air and expel exhaust gases. Inside the cylinder sits a piston that travels vertically. The piston is connected to a crankshaft which translates the vertical motion of the cylinder into rotational motion (1). An ICE functions based on a 4-stroke cycle, with the cycles being intake, compression, combustion, and exhaust. The intake stroke pulls in air and combines it with fuel. Subsequently, the piston compresses this mixture in preparation for the next stroke. The combustion stroke ignites the compressed air and fuel, providing a powerful downward force onto the piston. The exhaust stroke expels the ignited fuel and air mixture (1). This process emits large amounts of greenhouse gases, such as carbon dioxide (CO_2) and nitrogen oxides (NO_X), and also toxic gases for humans, such as formaldehyde (2, 3). The impact of using this system creates a substantial build-up of CO_2 leading to

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global warming and consequences on human health such as respiratory issues (4).

Within the context of sustainable development, fossil fuels are exhaustive and current energetic demands lead to complete fossil fuel depletion within roughly 155 years (5). This is not sustainable as it compromises the ability of future generations to meet their needs (5). Governments have been encouraging the development of renewable energy sources, one example being bioethanol, to decrease reliance on fossil fuel feedstocks (5). A significant policy that prompted the increase in ethanol production was one implemented by the Brazilian Federal Government, mandating the mixing of anhydrous ethanol in gasoline, which led to an increase in production of ethanol (5). This review examines the impact of blending ethanol with gasoline on engine performance, emissions, blend stability, and corrosion by synthesizing existing literature.

INFLUENCE OF ETHANOL ON ENGINE PERFORMANCE

Many studies have been conducted on the influence of using ethanol blends on engine performance. Various authors have tested the impact of using different ethanol-gasoline blends on spark ignition engines. The main parameters and findings of the studies discussed here are summarised in Table 1.

Table 1. Engine performance outcomes in each study mentioned, with a focus of reporting the ethanol blend as a % vol, the power, torque and efficiency generated

Ethanol Blend (% vol)	Power	Torque	Efficiency	Notes	Ref.
0	20.8 kW	N/A	12.7 kg/100 km		(2)
10	22.1 kW	N/A	12.8 kg/100 km	Power at 65 km/h	
15	22.1 kW	N/A	12.8 kg/100 km	Efficiency = fuel consumption at 65 km/h	
20	22.1 kW	N/A	12.2 kg/100 km		
0	52.1 kW	101 N m	13.1 MJ kWh^{-1}		(6)
5	52.0 kW	+1.4%	12.4 MJ kWh^{-1}	Power at 5500rpm	
10	52.3 kW	+2.2%	11.4 MJ kWh^{-1}	Torque at 3000rpm	
20	52.1 kW	+2.5%	13.2 MJ kWh^{-1}	Efficiency = BSEC at 3500rpm	
0	N/A	7.08 N m	N/A		(8)
5	N/A	7.48 N m	N/A	Torque at 8000 rpm	
10	N/A	7.43 N m	N/A		
15	N/A	7.45 N m	N/A		
5 + additive	N/A	7.50 N m	N/A		
10 + additive	N/A	7.60 N m	N/A		
15 + additive	N/A	7.53 N m	N/A		
21	N/A	430 N m	N/A		(9)
100	N/A	310 N m	N/A	Torque at 1100 rpm	
91 RON	N/A	N/A	31.0 %	Efficiency = Brake Thermal Efficiency at 1200rpm	(4)
E85	N/A	N/A	36.1 %		
0.0	27.8 kW	N/A	N/A	Power at 4000rpm	(7)
2.5	27.8 kW	N/A	N/A		
5.0	28.1 kW	N/A	N/A		
7.5	28.9 kW	N/A	N/A		
10.0	29.5 kW	N/A	N/A		
12.5	29.9 kW	N/A	N/A		
15.0	30.1 kW	N/A	N/A		
17.5	30.6 kW	N/A	N/A		
20.0	31.1 kW	N/A	N/A		
22.5	30.4 kW	N/A	N/A		
25.0	30.1 kW	N/A	N/A		

Engine Power

Pham *et al*. tested the effect of 10% ethanol by volume (E10), 15% ethanol by volume (E15), and 20% ethanol by volume (E20) on the performance and emissions of a carbureted and fuel-injected engine car (2). They used the steady state method–at full throttle and full load–at gears 3, 4, and 5 to test for the power and fuel consumption of each fuel. The results from the experiment found that the power delivery between the blends did not differ in the carbureted engine but on average had 6% higher power delivery than pure gasoline. The authors associated this effect to the higher Reid vapor pressure and higher Lower Heating Value of the blends with respect to pure gasoline. These properties lowered the manifold temperatures and led to a better volumetric efficiency when using the blends, leading to the higher power delivery. The results for the injected engine revealed minimal difference in power between all fuel types. This was associated with the equal amount of fuel injected, which was controlled by the intake air flow rate and engine speed.

Similarly, Singh also conducted an experiment to find the relation between ethanol blends and power (6). The experiment made use of a multipoint gasoline fuel injection engine with a displacement of 1196 cc (6). The results of the study indicated a 2.5% increase in power using the ethanol blends. The properties of ethanol, such as higher octane, higher heat of evaporation, and higher laminar flame speed (fuel combusts faster, increasing power), were suggested to help in improving the power output of ethanol blends regardless of the lower calorific value in ethanol.

A similar result was obtained by Hasan's study (7). In this study, an experiment using unleaded gasoline and ethanol of 99% purity was conducted. The results indicated that as the ethanol blend percentage increases, the brake power output also increases. They attributed this result to the method of calculating brake power. The brake power is calculated as the product of torque and engine speed. In their experiment, they found that brake torque increases with ethanol blends up to 20% ethanol, then decreases. The brake power results reflected this trend, with brake power increasing up to 20% ethanol then slightly falling beyond 20% ethanol.

These studies indicate that utilizing ethanol in gasoline fuel usually results in an increase in the power output. The general consensus is that the power increases because the heat energy absorbed by the fuel from combustion is lower and instead used to deliver power to the output of the engine.

Engine Torque

Some studies have also been conducted to research the impact of ethanol blends on the torque produced by the engine. One study by Singh found that the torque output peaked at 3000 rpm engine speed–an increase in rpm beyond this point yielded a drop in torque (6). This is because at full throttle, the mass of air remains the same, however the fuel required is different to maintain stoichiometry, which is controlled by the lambda sensor. Since ethanol is leaner, less fuel was injected. The torque using ethanol was higher for all speeds relative to the base gasoline. 5% ethanol by volume (E5) , E10, and E20 reached higher torque outputs by 1.4%, 2.2%, 2.5% relatively. This was attributed to the higher octane and oxygen content in the fuel which improves the combustion.

Likewise, In Abikusna's study, the torque when using ethanol fuels also increased. Using a 150 cc engine with ethanol blends of 5%, 10%, and 15% by volume, and also additional test fuels with oxygenated additives, the study found that the maximum torque was achieved at 5400 rpm with 10% ethanol and additives (8). Additionally, all torque values were higher using ethanol in general. This trend was attributed to the higher oxygen in ethanol, which results in higher complete combustion leading to increased torque. The additives increased torque because at 5400 rpm, the fuel ratio approaches stoichiometry, but the additive makes the fuel richer which slows down engine rotation. Slow engine rotation improves torque.

Bottazi *et al*., conducted a computational study in which they observed torque output decreasing with increasing ethanol content (9). This result was attributed to the product of the density and the lower heating value (LHV) of each blend. After conducting an experiment with 21% ethanol by volume (E21) and 100% ethanol by volume (E100) under the same operating conditions, the torque output was found to have decreased. This is because of the lower energy amount in each cycle. This reduced the engine power, and they concluded that this also led to the decrease in torque (9). The ratio of the torque between E100 and E21 was found to be very close to the ratio between product of the density and lower heating value for E100 and E21.

The majority of studies here imply that torque output will increase with the addition of ethanol in the blends. This is because of the higher oxygen content in the fuel. The higher oxygen content in ethanol improves combustion which leads to the higher torque output (9). However, Bottazi's study suggested an opposite result, where torque decreases when using ethanol. This may be due to the differing ethanol-gasoline ratio in the fuel. Singh and Abikusna used similar ratios, between 5%-20% ethanol by volume, while Bottazi used 21% and 100% (6-9). This stark difference in ratios may have resulted in the different results for torque output.

Engine Efficiency

The efficiency of the engines when using ethanol blends were also compared with the base efficiency when using pure gasoline in the following studies. Singh's study found a decrease in brake specific energy consumption (BSEC) by up to 2.5% and reduction in the BSCE with increase in ethanol content (6). Despite the calorific value of the fuel being lower, the higher octane compensates for this downside, helping it achieve a lower BSEC. The lower BSEC was also claimed to be the result of a higher air fuel ratio, which improves combustion and the combustion peak pressure.

A similar result in a study by Stein was conducted with modern engines using ethanol blends (4). Their experiments yielded improved efficiency using Toyota and GM engines, attributed to reduced heat transfer losses. This conclusion was supported by the lower burned gas temperatures because of the charge cooling effect. The charge cooling effect is influenced by the higher heat of vaporization of the blends, leading to lower charge temperatures at the start of combustion. Utilization of ethanol also results in greater heat capacity and lower adiabatic flame temperatures.

In consistency, Pham's study found that the fuel consumption was only significantly higher for E20 fuel in the injected engine which was attributed to its lower heating value (2). The fuel consumption for all ethanol fuels decreased, specifically, by 1.8%, 3.8% and 5.1% with E10, E15 and E20 respectively, in the carbureted engine. The fuel consumption decreased by 0.8%, 0.925%, and 0.34% for E10, E15 and E20 respectively in the injected engine.

All the studies investigated report an increase in the efficiency of the engine when using ethanol fuel, attributing the result to the lower heat absorbed by the fuel during combustion, resulting in a higher amount of energy transferred to the output. The overall findings from the studies were higher engine performance because of the increased volumetric efficiency, greater torque values because of the higher oxygen content in the fuel, and improved efficiency because of the lower specific energy consumption.

INFLUENCE OF ETHANOL ON ENGINE EMISSIONS

Engine emissions were also an important factor studied in many investigations exploring the effect of using ethanol blends as fuels. The main parameters and finding of the studies discussed here are summarised in Table 2.

Hydrocarbon and Carbon Monoxide Emissions

Hydrocarbon (HC) and carbon monoxide (CO) emissions are regulated emission products that form due to incomplete combustion. Studies have been done on the impact of ethanol on the production of these harmful gases.

A drop in HC and CO emissions was found in Pham's study for the carbureted car following the ECE15+EUDC driving cycle for Euro 2 emissions (2). They found a drop in HC emissions by 25.0%, 42.3% and 48.2% for

Table 2. Engine emissions outcome in each study mentioned, with a focus on ethanol blends as % vol of ethanol to HC, CO, NOX, CO2, and HCHO emissions

Ethanol Blend (% vol)	HC	CO	NOX	CO2	HCHO	Notes	Ref
0	3.8 g km^{-1}	31 g km^{-1}	2.2 g km^{-1}	152 g km^{-1}	N/A	N/A	(2)
10	2.9 g km^{-1}	22 g km^{-1}	3.1 g km^{-1}	155 g km^{-1}	N/A		
15	2.2 g km^{-1}	19 g km^{-1}	3.3 g km^{-1}	160 g km^{-1}	N/A		
20	2.0 g km^{-1}	16 g km^{-1}	2.5 g km^{-1}	156 g km^{-1}	N/A		
(injected)							
0	11.6 g km^{-1}	38 g km^{-1}	2.9 g km^{-1}	169 g km^{-1}	N/A		
10	10.2 g km^{-1}	35 g km^{-1}	3.2 g km^{-1}	174 g km^{-1}	N/A		
15	11.7 g km^{-1}	44 g km^{-1}	3.5 g km^{-1}	177 g km^{-1}	N/A		
20	11.9 g km^{-1}	46 g km^{-1}	2.6 g km^{-1}	171 g km^{-1}	N/A		

Continued Table 2. Engine emissions outcome in each study mentioned, with a focus on ethanol blends as % vol of ethanol to HC, CO, NOX, CO2, and HCHO emissions

Ethanol Blend (% vol)	HC	CO	NOX	CO2	HCHO	Notes	Ref
0	2500 ppm	0.4 %	1300 ppm	12.7 %	N/A	HC emissions relative to gasoline at 3000rpm	(6)
5	-13%	-12%	+4%	+1%	N/A		
10	-30%	-50%	+78%	+10%	N/A		
20	-34%	-65%	+109%	+14%	N/A	CO emissions relative to gasoline at 6000rpm NOX emissions relative to gasoline at 6000rpm CO2 emissions relative to gasoline at 6000rpm	
50% load							(3)
0	N/A	N/A	N/A	N/A	40-50 ppm		
10	N/A	N/A	N/A	N/A	50-60 ppm		
100% load							
0	N/A	N/A	N/A	N/A	60-70 ppm		
10	N/A	N/A	N/A	N/A	70-80 ppm		

E10, E15, and E20 respectively. The CO emissions dropped by 29.6%, 40.8% and 52.4% for E10, E15, and E20 respectively. As the ethanol content increased, lower HC and CO emissions were obtained. The results for the injected car had slightly different results. They found that E10 had reduced HC emissions by 3.88% while E15 and E20 had increased HC emissions by 1.06% and 3.09% respectively. The CO emissions for E10 had also dropped, by 7.76%, but increased when using E15 and E20, by 16.03% and 22.3% respectively. They state that this is possibly because of the improved combustion from the higher oxygen content in the ethanol fuel.

However, Stein's study noticed that engines also perform tasks off cycle, such as reducing exhaust temperatures to protect aftertreatment systems (4). This example relies on enrichment to reduce temperatures, but when doing so, it increases HC and CO production due to incomplete combustion. This suggests that enrichment should be avoided to reduce these emissions and using ethanol can help as it enables the opportunity to maintain stoichiometry for longer.

In accordance with Pham's research, Singh's study investigated the emissions when using ethanol blended fuels (6). They found that CO emissions decreased overall and fell with increasing concentrations of ethanol. This is due to the higher oxygen content in ethanol which reduces the chances of incomplete combustion and carbon atoms unable to bond to 2 oxygen atoms. The CO emissions fell by 12%, 50%, 65% relative to neat gasoline for E5, E10, and E20 respectively. HC emissions were also reduced when using ethanol fuels. Significant improvements in HC emissions are noticed at higher engine speeds. The higher oxygen content improved complete combustion of ethanol reducing the HC emissions when using this fuel.

The general trend for HC and CO emissions is that they fall when using ethanol. Most of the authors agree that the decrease is associated with the higher oxygen content in the fuel which improves complete combustion, reducing the emissions of products of incomplete combustion, such as CO and HC. Some authors found that certain ethanol fuels increased HC and CO emissions, but this is likely due to the off-cycle tasks that Stein mentioned (4).

NO_X and CO_2 Emissions

The impact of using ethanol blends on greenhouse gas emission were studied. The gases that were heavily studied were nitrogen oxides (NO_X) and carbon dioxide (CO_2). Pham *et al*. explored the production of greenhouse gases when using ethanol blended fuels. The study found that NO_X emissions, instead of decreasing, increased by 43.7%, 52.7%, and 13.3% for E10, E15, and E20 (2). The CO_2 emissions also increased for all ethanol blends by 2.2%, 4.7%, and 2.5% with E10, E15, and E20 respectively.

NO_X had increased emissions using E10 and E15 (10.70% and 21.63% increases respectively) but reduced by 10.58% for E20, because of the lower combustion temperatures achieved with E20 in the injected car. CO_2 emissions for the injected engine, similar to the carbureted engine, had increased emissions compared to pure gasoline by 3.41%, 3.90%, and 1.90% for E10, E15, and E20, respectively.

This trend was also observed in the NO_X emissions of Singh's study, finding that the emissions were higher when using ethanol blends (6). A large difference between the emissions for the fuels was noticed at higher engine speeds. NO_X was higher by 4%, 78%, 109% for E5, E10, E20 respectively. Since the experiment used a rich mixture for maximum power, it increased the combustion temperatures which increased the production of nitrogen oxides, providing a possible explanation for the increased NO_X emissions. CO_2 emissions also increased when using ethanol fuels. Greater blend proportions increased the CO_2 emissions where, at maximum power, CO_2 emissions for E5, E10, E20 were 1%, 10%, 14% higher than gasoline respectively. The higher oxygen content in ethanol resulted in the increased emissions of CO_2 and NO_X.

These reports indicate that NO_X and CO_2 generally increase when using ethanol. The reason for this is because of the higher oxygen content which increases products of complete combustion like CO_2.

Toxic Emissions

The rate of toxic emissions emitted was also researched with respect to ethanol content in blends. A significant product is formaldehyde, which is a human carcinogen, and was studied in numerous papers (4). Stein's paper discusses the magnitude of toxic emissions when using ethanol fuels. They state that alcohol fuels are cleaner and less harmful for humans because they are not composed of complex chemical compounds such as benzene (4). 1,3-butadiene is a by-product of complex combustion, and utilizing ethanol reduces the likelihood of complex combustion since it is a simpler fuel. Formaldehyde and acetaldehyde are also human carcinogens, but unlike benzene and 1,3-butadiene, they are formed and emitted using ethanol fuels, mainly during cold starts. They are products of incomplete combustion when using ethanol fuel.

Agarwal's study indicates an increase in formaldehyde when using gasohol (10% ethanol by volume) (3). They state that formaldehyde is formed mainly as a product of incomplete combustion and occurs in low temperature zones of combustion (3). Since ethanol has a higher latent heat of vaporization, the in-cylinder temperatures fall making it harder to oxidize the products of incomplete combustion. Another reason that was attributed to this was the presence of the hydroxyl group in ethanol. This makes it easier to oxidize ethanol to form formaldehyde, doing the same for HC (3).

Stein's study suggests that carcinogens should decrease when using ethanol fuel because they are products of incomplete combustion and ethanol reduces the chances of incomplete combustion in the engine (4). Agarwal's study indicates the opposite, where formaldehyde emissions increase, but this is because of the lower combustion temperatures which make it hard to oxidize the products of incomplete combustion (3). Therefore, ethanol use should decrease carcinogen emissions, if combustion temperatures are increased.

Particulate matter (PM) emission also causes health problems like respiratory issues (4). A few factors influence PM production in engine emissions. Stein's paper discusses that low vapor pressure of fuel will result in a higher boiling point of the fuel, which will result in liquid fuel remaining after combustion (4). When liquid fuel remains in the combustion chamber, it will remain in contact with the wall or piston leading to poor air-fuel mixing and diffusion flames, which result in higher PM production. Double bond equivalent (DBE) values are numbers that indicate the number of double bonds and rings in the fuel and are defined by the number of hydrogen atoms required to saturate it. Additionally, Stein's research found that using ethanol fuels reduce PM emissions (4). Ethanol fuel has a very low DBE value (value of 0) which significantly reduces PM emissions when using the fuel. Ethanol also has a higher vapor pressure and a much lower boiling point which increases the fuel's volatility and makes it a near azeotrope-like mixture (4). Finally, ethanol is an oxygenated molecule, producing less soot because oxygenates limit the formation of aromatic precursors that produce soot.

These studies indicate a general trend of drops in CO and HC emissions when using ethanol. They hypothesized that the reason for this observation is because of the higher oxygen content in ethanol which improves combustion and lowers the chances of incomplete combustion. The trend for NO_X and CO_2 emissions in the studies are that they increase when using ethanol. The NO_X increase was likely the result of higher combustion temperatures while the CO_2

emissions were likely the result of increased complete combustion because of the higher oxygen content in ethanol. The studies also agree that the carcinogens form from incomplete combustion, however Agarwal's study experienced higher incomplete combustion in their study at 50% and 100% loads, leading to a finding with higher formaldehyde emissions. The PM emissions are stated to have been reduced because of the low DBE value, higher vapor pressure, lower boiling point, and the oxygenated characteristic of ethanol.

INFLUENCE OF ETHANOL ON FUEL STABILITY

When using ethanol blends, the stability of the fuel is an important factor to determine whether the blend is a viable alternative to pure gasoline. The stability section discusses the phase separation characteristic of the fuel. The main parameters and findings of the studies discussed here are summarised in Table 3.

For instance, Singh et. al. reported that the ethanol gasoline blends are relatively stable, arguing that ethanol and gasoline are completely miscible (6); The fuel will separate, however, in the presence of water. This is also important for anhydrous blends. Similarly, Zhang's study indicates that the stability of ethanol and gasoline depend on its phase separation temperature, water content, and the ethanol content. Zhang indicates that the temperature of the fuel will affect the interfacial tension between the oil and water. When the interfacial tension is high, phase separation is likely to occur. At higher temperatures, the interfacial tension decreases, which reduces the likelihood of phase separation and improves the fuel stability.

When the water content is high, the phase separation temperature of the fuel increases. This means that the fuel is likely to separate at higher temperatures like room temperature. This will reduce the stability of the fuel, suggesting that the water content must be low for a stable blend (10). Another major factor is the ethanol content of the fuel. This study found that as the ethanol content was raised, the phase separation temperature was lowered, at a constant water content (10). This suggests that as the ethanol content rises, the stability of the fuel increases. They claimed that the rise in ethanol content promotes the oil to become a homogeneous system, increasing the stability of the oil (10).

Likewise, Amine's study indicates that temperature is an important variable when considering the stability of a fuel (11). The phase separation temperature indicates the temperature when the fuel splits into two phases. They found that as the ethanol content increased at a constant water content of 5% by volume, the phase separation temperature decreased (11). The stability is increased because of the hydrogen bonding between the ethanol molecules and the water molecules (11).

In the same way, Mužíková's study investigated the phase stability of ethanol in petrol (12). The findings

Table 3. Fuel stability measurements of ethanol blends in each study, focusing on the ethanol blend as % vol of ethanol to the phase separation temperature and water solubility

Ethanol Blend (% vol)	Phase Separation Temperature	Water Solubility	Notes	Ref
7.7	8 °C	N/A	Phase separation temperature measured at 0.4% water content	(10)
10	6 °C	N/A		
15	-28 °C	N/A		
0	N/A	N/A		(11)
15	-12 °C	N/A		
(-10 °C)				(12)
5	N/A	0.23 wt%		
10	N/A	0.54 wt%		
(0 °C)				
5	N/A	0.24 wt%		
10	N/A	0.67 wt%		
(10 °C)				
5	N/A	0.28 wt%		
10	N/A	0.78 wt%		

from this study indicate that an increase in ethanol content, done by increasing the volume of ethanol, will result in greater water solubility. The water solubility is a measurement of the percentage of water in the fuel until it reaches phase separation. They found that the water solubility of E10 by volume was three times higher than E5 at 0 °C. However, they noted that E10 had a greater change in water solubility when the temperature decreased from 10 °C to -10 °C. The water solubility reduced by roughly 30% for E10, while only by 14% for E5. They stated that the water solubility is influenced by the presence of oxygen containing compounds (12). They also found that the phase separation temperature decreased to below -30 °C when the ethanol content was increased from 5% to 10% volume.

The majority of the papers agree that water content in ethanol fuel impacts the stability of the fuel, where the higher water content means that the fuel is less stable because of phase separation. The water content of the fuel influences the temperature at which the two may separate which will reduce the fuel's stability. The studies also agree that the ethanol content can influence the stability of the fuel, and as ethanol rises, the stability increases.

INFLUENCE OF ETHANOL ON METAL CORROSION

The impact of ethanol on corrosion was also investigated by authors. It was found that some metals experience greater corrosion than others when ethanol is used. The data gathered from the studies on corrosion rates of different metals with respect to ethanol-blend percentages are displayed in Table 4.

For example, Jafari's study investigates the impact of ethanol-gasoline fuels on the corrosion of metals (13). They found that low carbon steel faced high amounts of corrosion from the water contaminated ethanol-gasoline blends (13). They attributed this to the slight separation of ethanol into anions and cations when mixed with water, resulting in electrochemical activity, causing corrosion. They found that as the water and ethanol content increases, the corrosion rate of the fuel delivery system also increases. Aluminum 6061 had a low corrosion rate, and was addressed to the passivation of the metal when in contact with oxygen from the water, forming a layer of Al_2O_3 (13). Copper and Aluminum 6061 have high resistance to corrosion in water containing ethanol-gasoline blends, compared to plain carbon steel. However, as the volume of ethanol rises beyond 10%,

Table 4. Corrosion rates when using ethanol blends in each study, focusing on ethanol blends as % vol of ethanol to the corrosion rates of different metals

Ethanol Blend (% vol)	Corrosion Rate	Ref
(Low carbon steel)		(13)
0	77 mpy	
5	82 mpy	
10	86 mpy	
15	149 mpy	
(Medium carbon steel)		
0	36 mpy	
5	44 mpy	
10	87 mpy	
15	149 mpy	
(Al 6061)		
0	9 mpy	
5	10 mpy	
10	19 mpy	
15	17 mpy	
(Copper)		
0	8 mpy	
5	10 mpy	
10	11 mpy	
15	36 mpy	
(Mild steel)		(14)
40	3.8 $\mu m \cdot year^{-1}$	
60	4.4 $\mu m \cdot year^{-1}$	
85	6.8 $\mu m \cdot year^{-1}$	
100	2.4 $\mu m \cdot year^{-1}$	
(Aluminum)		
40	7.3 $\mu m \cdot year^{-1}$	
60	9.2 $\mu m \cdot year^{-1}$	
85	10.3 $\mu m \cdot year^{-1}$	
100	2.9 $\mu m \cdot year^{-1}$	
(Copper)		
40	5.2 $\mu m \cdot year^{-1}$	
60	5.4 $\mu m \cdot year^{-1}$	
85	7.2 $\mu m \cdot year^{-1}$	
100	7.7 $\mu m \cdot year^{-1}$	
(Brass)		
40	3.7 $\mu m \cdot year^{-1}$	
60	4.5 $\mu m \cdot year^{-1}$	
85	4.7 $\mu m \cdot year^{-1}$	
100	27.1 $\mu m \cdot year^{-1}$	

the corrosion rate of carbon steel (both medium and low) increases significantly (13). This was because the conductivity of ethanol increases as the water content is increased.

Matějovský also conducted a similar study investigating corrosion and ethanol-gasoline fuels (14). They found that the corrosion rate of aluminum was 4-5 times higher than that of mild steel using oxidized fuels, while it was 3-5 times higher when using unoxidized fuels (14). This results from the greater corrosion resistance of mild steel than that of aluminum. This may have been a reason for the large difference in corrosion rates. They also noted that the formation of acidic substances' rises as the fuel oxidizes, which increases the corrosion rate of aluminum.

The results from the two studies indicate contrasting results for corrosion, highlighting that the metals used will face different rates of corrosion based on the properties of the metal. The second study also indicates that the oxidation of the fuel can influence the corrosiveness of the metals, and could be a reason the aluminum had a higher corrosive rate than steel compared to Jafari's study.

DISCUSSION

Through this study, general trends were found for the influence of ethanol on the engine performance, emissions, and blend stability. The overall power output of the engines was greater when using ethanol fuel. The investigations attributed this outcome to the increased volumetric efficiency of the fuel when ethanol is used. The papers also found greater torque output when using ethanol. Most of the studies attributed the increase in torque to ethanol's higher oxygen content, improving combustion, and the higher octane content of the fuel. Bottazzi's research, however, indicates a contrasting result of lower torque because of the lower density and LHV of the fuel. The efficiency of the engines were also found to have been improved when using ethanol gasoline blends. This improvement in efficiency was mainly associated with the lower specific energy consumption overall.

The general impact of ethanol on emissions between studies found that CO and HC emissions dropped when using ethanol fuels. This is because of the higher oxygen content of blended fuel, improving combustion and lowering the chances of incomplete combustion. The studies also found that NO_X and CO_2 increase with ethanol addition in gasoline. The increase in NO_X is suggested to be due to the higher combustion temperatures while the increase in CO_2 is suggested to be because of increased complete combustion. The studies indicate contrasting results for toxic emissions, namely formaldehyde. Agarwal's paper had increased formaldehyde from 50% to 100% loads, mainly because of incomplete combustion while Stein only noted formaldehydes for cold starts. PM emissions, however, were found to have been reduced because of the low DBE, higher vapor pressure, lower boiling point, and oxygenated characteristics of ethanol fuels.

Finally, the research of ethanol on blend stability found that temperature was a major factor on the fuel's blend stability. Higher temperatures prevent phase separation of the fuel–mainly due to the presence of water–and can be avoided when ethanol content is increased. The corrosion rates between the papers researched had contrasting results. This could be because the fuels were tested based on the oxidation of the fuel for one study, which may have influenced the corrosion results.

These results are helpful in determining whether the use of ethanol in current gasoline engines will be beneficial for the environment and if they will require changes in the operating condition of the engine. The results suggest that the use of ethanol improves the running conditions of the engine while reducing toxic emissions. The fuel however emits greater CO_2 contributing to greater greenhouse gas emissions and can be hard to maintain sustainability.

CONCLUSION

The limitations of this literature review include discrepancies between test methods of the studies analysed. Engines have many variables that can be hard to control between tests. They can have drastically different designs, whether it is the displacement size, the injection timing, fuel injection method, etc. Such circumstances can result in various different outcomes when testing for the impact of ethanol on engine performance, emissions, and stability. The need to control multiple variables in engine operation and testing, such as fuel injection and carbureted engines, pose challenges with regards to comparing results from various studies. Another significant control variable between papers was the test fuel and their blend percentages. Though many used similar ethanol ranges, the type of ethanol and base gasoline used is likely to be different among studies. The test engines also have differing sizes which may have resulted in differences among the results between studies.

The implementation of a standardized testing protocol may help to improve the reliability of comparison among different research papers and authors.

In this paper, the effect of ethanol blends on engine performance, emissions, fuel stability, and corrosion were reviewed. For engine performance, particular focus was given on the power, torque, and efficiency. It was observed that as ethanol content increased power, torque, and efficiency improved. The emissions reviewed when using ethanol blends were HC, CO, NO_X, CO_2 and toxic emissions. HC and CO emissions were found to decrease, while NO_X and CO_2 were found to increase when using ethanol. The fuel stability was stated to be dependent on the phase separation temperature, and when using ethanol-gasoline blends, greater care is required to ensure the two fuels don't separate. It was observed that increasing ethanol content improves the stability of the fuel. It was also found that using ethanol blends causes greater corrosion because of the water content of ethanol.

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CONFLICT OF INTEREST

The authors declares that there are no conflicts of interest related to this work.

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