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THE EFFECT OF ETHANOL ADDITION TO GASOLINE FUEL: A COMPREHENSIVE ANALYSIS OF PERFORMANCE, EMISSIONS, AND MATERIAL COMPATIBILITY BASED ON LITERATURE STUDIES

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ABSTRACT

Background: Using bioethanol as an oxygenate additive in gasoline shows an increasing trend driven by the need for renewable fuels and efforts to mitigate exhaust emissions.

Purpose: This study aims to conduct a critical and comprehensive synthesis of the positive and negative impacts of ethanol addition, focusing on engine performance, exhaust emissions, and material compatibility.

Design/methodology/approach: The method used was a systematic literature review of primary scientific journals indexed by Scopus and SINTA.

Findings: The analysis results show a dualism of impacts: on the one hand, adding ethanol consistently increases engine torque and power and significantly reduces carbon monoxide (CO) and hydrocarbon (HC) emissions. On the other hand, this is offset by the potential for increased fuel consumption due to the lower energy density of ethanol, ambiguous effects on nitrogen oxide (NO_x) emissions, and the emergence of serious challenges related to corrosion of metal components and degradation of elastomer materials.

Implication: These findings imply that adopting ethanol blends requires a holistic approach, including engine design optimization and improved material specifications in fuel systems to ensure long-term durability and safety.

Paper type: Literature review

Keyword: *Corrosion; Engine Performance Ethanol; Exhaust Emissions; Gasoline*

A .*INTRODUCTION*

The context of global energy transition and pressure to reduce dependence on fossil fuels has driven the search for more sustainable alternative energy sources. In the transportation sector, ethanol, particularly bioethanol produced from biomass, has emerged as one of the most prominent and technically feasible renewable fuel candidates for blending with gasoline. The similarity of ethanol's physicochemical properties to gasoline makes it the preferred choice as an oxygenate additive or partial substitute. Ethanol as a fuel blend, known as gasohol, offers two main advantages that are often promoted: increased fuel octane ratings and the potential for reduced pollutant emissions. Higher octane ratings allow engines to operate more efficiently without *knocking*, while the oxygen content in ethanol molecules promises a more complete combustion process (Manikandan et al., 2013).

The push for ethanol adoption stems from environmental considerations, national energy security, and economic diversification strategies. Reducing dependence on fluctuating global crude oil supplies is a strategic priority for oil-importing countries such as Indonesia. Developing a

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domestic bioethanol industry, utilizing agricultural resources such as sugar cane and corn, offers a path to import substitution while creating added value in the agricultural sector. Mandatory biofuel blending policies, such as those successfully implemented in Brazil and the United States, serve as models for other countries to stimulate markets and investment in renewable energy. However, the success of such programs is highly dependent on the availability of sustainable feedstocks and adequate infrastructure, a challenge many developing countries still face.

Technically, integrating ethanol into an established gasoline fuel system presents a series of complex physicochemical considerations. The fundamental chemical properties of ethanol (C_2H_5OH) differ significantly from the complex hydrocarbons that make up gasoline. On the one hand, ethanol's research octane number (RON) of 108 provides superior anti-knock properties. On the other hand, its energy density is about 30% lower than gasoline, which theoretically means that a larger fuel volume is needed to produce the same energy output. This duality creates an engineering dilemma: how to leverage the high-octane advantage to improve engine thermal efficiency by increasing the compression ratio to compensate for the loss due to lower energy density(Samawa & Mufarida, 2022). Without appropriate engine optimization, the efficiency benefits of ethanol may not be fully realized, and may even lead to more wasteful fuel consumption.

However, behind this positive potential lies a series of complex technical challenges. The lower calorific value or energy density of ethanol than gasoline raises concerns about increased fuel consumption to cover the same distance. Furthermore, the hygroscopic (water-absorbing) and more electrically conductive chemical properties of ethanol create an aggressive environment for fuel system components, triggering the risk of corrosion in metal materials and degradation in polymer and elastomer components. The conflict between the benefits of improved performance and reduced emissions and the disadvantages of reduced fuel efficiency and material durability is at the heart of the debate over the widespread adoption of ethanol (Yücesu et al., 2006).

Many experimental studies have been conducted to examine specific aspects of ethanol use. Studies by Suanggana et al. (2023)and Rosady et al. (2023)specifically examined the effect of ethanol blends on motorcycle engine performance in Indonesia. At the international level, various studies have investigated the impact on emissions and engine performance with different compression ratios. However, in isolation, many of these studies focus on one domain—performance, emissions, or materials. The identified gap is the lack of a comprehensive literature review that systematically integrates these three crucial domains to present a holistic picture of the trade-offs involved. Based on this gap, this study aims to critically analyze and synthesize the multifaceted impacts of adding ethanol to gasoline, covering both positive and negative aspects on engine performance, exhaust emission profiles (Gunawan & Effendy, 2019), and material compatibility, through an in-depth literature review of high-quality primary research

A. METHODOLOGY

This research is designed as a *systematic literature study* (Sugiyono, 2019). This approach was chosen because its main objective is to synthesize, analyze, and interpret findings from various published primary experimental studies, rather than to generate new empirical data (Sulistyo-Basuki, 2010). The focus is on building a coherent and nuanced understanding of the positive and negative impacts of adding ethanol to gasoline fuel.

The primary data sources for this study were research articles published in scientific journals. Strict inclusion criteria were applied to ensure the quality and relevance of the data analyzed (Templier & Paré, 2015). These criteria include: (1) the article is a primary experimental study that presents original quantitative or qualitative data on the effects of ethanol; (2) the article is published in a scientific journal indexed by reputable international databases such as Scopus, or nationally accredited with a SINTA rating to ensure a credible peer review process; and (3) the article explicitly

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discusses the effect of adding ethanol to gasoline on at least one of three areas of focus: engine performance (torque, power, fuel consumption), exhaust emissions (CO, HC, NO_x, CO_2), or material compatibility (metals, polymers, elastomers). Sources such as review articles (literature reviews), conference proceedings, and reports from popular media were deliberately avoided when analyzing primary data.

The data analysis procedure was carried out in three main stages. First, the data extraction stage, in which specific quantitative information (e.g., percentage change in torque, emission values in ppm, corrosion rate in mpy) and qualitative findings (e.g., description of combustion mechanisms, corrosion mechanisms, visual changes in materials) were systematically extracted from each article that met the criteria. Second, the thematic synthesis stage, in which the extracted data is grouped and organized into three predetermined main themes: (a) Impact on Engine Performance, (b) Effect on Exhaust Emissions, and (c) Implications for Material Compatibility. Third is the critical analysis stage, in which the findings of each theme are compared and contrasted. Special attention was given to seemingly contradictory results, such as fuel consumption and NOx emission data. At this stage, efforts were made to identify explanatory variables—such as ethanol concentration, engine operating conditions (load, speed, compression ratio), or testing methodology—that might underlie the results' differences, thereby enabling a more in-depth and nuanced synthesis.

B. RESULTS AND DISCUSSION

Analysis of various primary experimental studies reveals a complex and multifaceted picture of the impact of adding ethanol to gasoline. These findings can be grouped into three main areas: impact on engine performance, influence on exhaust emission composition, and long-term implications for the material integrity of the fuel system. Adding ethanol to gasoline has a significant but dual effect on engine performance parameters. On the one hand, there is strong evidence of improved torque and power performance. On the other hand, there is a paradox regarding fuel efficiency or consumption.

Various studies consistently report that adding ethanol increases engine torque and power output, particularly at concentrations between 10% and 20% by volume (E10-E20). For example, a study by Al-Hasan (2003) showed a 4% increase in power when using an E30 blend compared to pure gasoline, while research by Suanggana et al. (2023) found that maximum torque and power in a 150cc motorcycle engine were achieved with an E15 blend. Similar findings were also reported by Gunawan & Effendy (2019) and Nofendri(2018), confirming the trend of improved performance across various engine types.

The interrelationship between these studies reinforces the validity of the three fundamental physicochemical mechanisms underlying them. First, ethanol has a very high research octane number (RON) (around 108), significantly improving fuel resistance to detonation or *knocking*. Theoretically, this allows engines to operate with more advanced ignition timing or higher compression ratios, directly increasing thermodynamic efficiency and torque output. Second, as an oxygenate compound, ethanol molecules (C_2H_5OH) contain oxygen atoms. As explained by Abdullah et al.(2015), this internal oxygen presence helps promote more complete and efficient combustion, ensuring that more chemical energy is released into mechanical work. Third, ethanol has a much higher latent heat of vaporization than gasoline. As analyzed by Koç et al. (2009) and Al-Hasan (2003), this vaporization process creates a cooling effect on the air-fuel mixture (*charge cooling effect)*. A cooler mixture has a higher density, which in turn increases the engine's volumetric efficiency—the ability to draw more mixture mass into the cylinder—thereby producing greater power.

Despite improved power performance, the impact of ethanol on fuel efficiency, as measured by Specific Fuel Consumption (SFC), shows paradoxical and often contradictory results between studies. Some studies, such as those conducted by Rosady et al. (2023)on E10 blends and Rifal

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(2022) on E20 blends, report a decrease in SFC (better efficiency). Conversely, more studies, including those by Al-Hasan (2003), Suanggana et al. (2023), and Koç et al. (2009), report that SFC actually increases (worse efficiency) as the percentage of ethanol increases.

This contradiction can be explained by linking empirical findings to engine thermodynamics theory. There are two competing forces. On the one hand, ethanol has an inherently lower energy density (calorific value), about 30% less than gasoline. Fundamentally, this means that a larger volume of fuel is required to produce the same amount of energy, which tends to increase SFC. On the other hand, the exact mechanisms that increase power—high octane number, oxygen content, and cooling effect—also contribute to increased engine thermal efficiency, i.e., the engine's ability to convert heat energy from combustion into mechanical work. This increase in thermal efficiency will, in theory, lower the SFC.

The connection between these findings becomes clear when engine optimization factors are considered. In standard, unmodified engines, such as those used in many studies, the disadvantages of low energy density tend to be more dominant, resulting in a higher SFC. However, in optimized engines, thermal efficiency advantages can offset these disadvantages. A key study by Al-Hasan (2003) explicitly demonstrates this: at a standard compression ratio (6:1), the SFC for E30 is 13.2% higher than for pure gasoline. However, when the compression ratio is increased to 8:1 (taking advantage of E30's high octane), its SFC is actually 5% lower than pure gasoline at a compression ratio of 6:1. This implies that the full efficiency potential of ethanol cannot be realized without appropriate engine modifications and calibrations, which explains why SFC results vary significantly under different test conditions.

Table 1 below summarizes the quantitative findings from various studies on the impact of ethanol blends on engine performance parameters, visually highlighting general trends and variability in SFC results.

Table 1. Summary of the Impact of Ethanol Blends on Engine Performance Parameters

Reference (Study)	Engine Type	Ethanol Blend	Torque Change	Power Change	SFC Change
Suanggana et al. (2023)	150 cc, 4-stroke	E15 (vs Pertamax)	Increased	Increased (highest in E15)	Increased
Rosady et al. (2023)	150 cc, 4-stroke	E10 (vs Pertalite)	Not reported	Not reported	Decreased (better)
Al-Hasan (2003)	Single cylinder, SI	E10, E20, E30	Slightly increased	Increased (1.2% - 4%)	Increased (4% - 13.2%)
Koç et al. (2009)	4-cylinder, SI	E50, E85	Increased (~2%)	Increased	Increased
Nofendri (2018)	Not specified	E10, E20	Increasing	Increasing	Decreasing
Gunawan & Effendy (2019)	Otto, 4-stroke	E5, E10, E15	Not reported	Relatively high performance	Not reported
Rifal et al. (2022)	Injection, 4-stroke	E10, E20, E30	Not reported	Not reported	E10: Increased by 8%, E20: Decreased by 14%

One of the main justifications for using ethanol is its potential to reduce harmful exhaust emissions. A literature review shows that ethanol consistently reduces some pollutants, but its impact

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on other pollutants, particularly nitrogen oxides, is much more complex and often contradictory. The most significant and consistent benefit of adding ethanol is a drastic reduction in unburned carbon monoxide (CO) and hydrocarbons (HC) emissions. The correlation between studies here is robust; research by Rifal et al.(2022) found that E20 reduced CO by up to 55% and HC by up to 16%, while Al-Hasan (2003) reported a reduction in CO of up to 35% and HC of up to 19% for E30. Similar findings were also reported by Baek et al. (2021) and Abdullah et al. (2015). This consensus directly validates the combustion chemistry theory: the presence of oxygen atoms in the ethanol molecular structure enriches the air-fuel mixture, creating locally "leaner" combustion conditions. This data facilitates more complete oxidation of CO into carbon monoxide (CO) and carbon dioxide (CO2), and helps burn residual HC, resulting in cleaner exhaust gases.

Unlike CO and HC, the impact of ethanol on CO2 emissions shows mixed results. Some studies, such as Al-Hasan (2003) and Rifal et al. (2022), report a decrease in CO2 emissions, while other studies by Abdullah et al. (2015) and Koç et al. (2009) actually find an increase. This variability can be explained by two theoretical factors that work simultaneously. On the one hand, ethanol molecules (C2H5OH) have a lower carbon-to-hydrogen atom ratio than gasoline, which stoichiometrically should produce less CO2. However, on the other hand, because ethanol increases combustion efficiency, more CO is successfully oxidized into CO2. This process effectively converts a more toxic pollutant (CO) into a greenhouse gas (CO2), which can increase the concentration of CO2 in the exhaust. The final result depends on which factor is more dominant under specific testing conditions.

The most critical area of contradiction is the impact of ethanol on Nitrogen Oxide (NOx) emissions. Several studies, including those by Al-Hasan (2003) on low compression ratios, report that adding ethanol causes a decrease in NOx emissions. However, an equal number of studies, such as those by Koç et al. (2009), Baek et al. (2021), and Yücesu et al. (2006), report opposite results, namely an increase in NOx emissions.

This dilemma can be resolved by linking these conflicting findings to two competing theoretical mechanisms. The mechanism that supports a reduction in NOx centers on the cooling effect. Thermal NOx formation is susceptible to peak combustion temperature. As explained in one study, the high latent heat of evaporation of ethanol causes significant cooling of the air-fuel mixture, which in turn can lower peak combustion temperatures and suppress NOx formation rates. Al-Hasan's (2003) findings at a compression ratio 6:1, where NO_x decreased by up to 23% with E30, strongly support this theory.

Conversely, the mechanism supporting increased NOx is related to oxygen availability and combustion dynamics. The oxygen content in ethanol can create local zones within the combustion chamber that are "leaner" and hotter, ideal conditions for NOx formation. A study by Al-Hasan (2003) itself provides key evidence that bridges these two contradictory results. When he increased the compression ratio from 6:1 to 8:1 for E30 fuel, NOx emissions increased by about 9%. This result shows that under more extreme operating conditions (higher compression ratio, which inherently increases combustion temperature), the effect of oxygen availability takes over and becomes more dominant than the cooling effect, causing an increase in NOx emissions. This correlation explains why various studies can report conflicting results, as the outcome is highly dependent on specific engine operating parameters.

Table 2. Summary of Quantitative Impacts of Ethanol Blending on Major Exhaust Emissions

Reference (Study)	Ethanol Blend	Change in CO Emissions (%)	Change in HC Emissions (%)	Change in NOx Emissions (%)	Change in CO2 emissions (%)
Romadhon & Suhariyanto (2024)	E5 (vs Pertamax)	Increased (300%)	Not reported	Not reported	Not reported

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Reference (Study)	Ethanol Blend	Change in CO Emissions (%)	Change in HC Emissions (%)	Change in NOx Emissions (%)	Change in CO2 emissions (%)
Rifal et al. (2022)	E10, E20, E30	E10: -30, E20: -55	E10: -13, E20: -16	Not measured	E10: -6, E20: -30
Al-Hasan (2003)	E10, E20, E30	Decreasing (11% - 35%)	Decreased (7% - 19%)	Decreased (8% - 23%)	Decreased (3% - 10%)
Abdullah et al. (2015)	E20 (vs Gasoline)	Decreasing	Decreasing	Not reported	Increased
Koç et al. (2009)	E50, E85	Decreasing	Decreasing	Increasing	Not reported
Baek et al. (2021)	E15 (vs Gasoline)	Decreased (23.46%)	Decreased (44.04%)	Increased (29.93%)	Not reported

Beyond the direct impact on performance and emissions, long-term use of ethanol poses serious challenges to the durability and reliability of fuel system components. The chemical properties of ethanol, which are fundamentally different from those of gasoline hydrocarbons, make it aggressive toward metallic and non-metallic materials.

Evidence from various studies consistently shows that ethanol-gasoline blends are significantly more corrosive to metal components than pure gasoline. Quantitative studies show that the corrosion rate of aluminum in E25 is 0.096 mpy (mils per year), and increases more than twofold to 0.216 mpy in E50. These findings directly support the theory of electrochemical corrosion. The mechanism behind this increase in corrosivity is multifactorial. First, the hygroscopic nature of ethanol allows it to absorb water vapor from the atmosphere. The presence of water, as described in several studies, can cause phase separation and the formation of corrosive acetic acid. Second, ethanol is significantly more electrically conductive than gasoline. This increase in conductivity, per electrochemical principles, facilitates galvanic corrosion mechanisms. Third, contaminants such as chloride ions can dramatically accelerate the corrosion rate, a point emphasized in several analyses.

In addition to metals, non-metallic components such as hoses, seals, and gaskets are also susceptible to degradation. Experimental studies have consistently observed phenomena such *as swelling* due to fuel absorption and *leaching*, in which ethanol acts as a solvent and "washes" out important components such as *plasticizers* from the material. The correlation between these findings suggests that degradation is a physical (swelling) problem and a chemical (solubilization of components) one. As a result, there are significant changes in the material's mechanical properties, including a decrease in tensile strength and changes in hardness, which can lead to premature failure and fuel leakage. This compatibility issue is a significant technical barrier to adopting high-concentration ethanol blends, especially for older vehicles not designed with ethanol-resistant materials.

Table 3 summarizes key findings from material compatibility studies, which consolidate evidence regarding the long-term durability risks of ethanol use.

Table 3. Key Findings Regarding Material Compatibility with Ethanol Fuel

Material Category	Specific Material	Ethanol Blend	Observed Effects	Reference
Metals	Aluminum	E20, E25, E50, E100	Increased corrosion rate; susceptible to pitting corrosion; corrosion accelerated by high temperatures and inhibited by water. Corrosion rate: 0.096 mpy (E25), 0.216 mpy (E50).	(Brito-Franco et al., 2020) (Pawel et al., 2012)
	Lightweight Steel	E25, E50	Increased corrosion rate. Corrosion rate: 0.297 mpy (E25), 0.487 mpy (E50).	(Kass et al., 2014) (Thangavelu et al., 2016)

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Material Category	Specific Material	Ethanol Blend	Observed Effects	Reference
	Copper	E25, E50	Increased corrosion rate. Corrosion rate: 0.285 mpy (E25), 0.441 mpy (E50).	(Thangavelu et al., 2016)
	Steel (Tank)	E10 - E30, E100	Increased corrosion risk, especially in the presence of contaminants such as chloride.	(Setiyo et al., 2018)(Matějovský et al., 2021)
Elastomer & Polymer	Neoprene, NBR, HNBR	E5, E10	Volume change (swelling), weight change, reduction in tensile strength, and hardness change.	(Dhaliwal et al., 2014) (Bawase et al., 2013)

C. CONCLUSION

Based on a comprehensive analysis of this literature study, it can be concluded that adding ethanol to gasoline fuel is a "double-edged sword" with equally significant advantages and disadvantages. On the positive side, ethanol effectively functions as an octane booster, which has been consistently proven to increase engine torque and power. The most indisputable benefit is its ability to promote cleaner combustion, substantially reducing carbon monoxide (CO) and hydrocarbon (HC) emissions. However, these advantages must be balanced against a series of technical challenges. Ethanol's lower energy density often causes increased fuel consumption in standard engines, while its impact on nitrogen oxide (NOx) emissions is ambiguous and depends on operating conditions. The most concerning challenge lies in its long-term impact: ethanol's aggressive chemical properties have been shown to increase the rate of corrosion in metal components and cause degradation in elastomeric materials, threatening the reliability and safety of fuel systems. Ethanol is not a simple "plug and play" solution; its full potential can only be realized through an integrated systems approach, encompassing engine design and appropriate material selection.

For future research, several priority areas need to be explored further. Long-term durability studies are needed on engines optimized for ethanol, such as those using high compression ratios, to validate performance, efficiency, and component wear rates under real-world conditions. Additionally, research to develop and test the effectiveness of corrosion inhibitor additives designed explicitly for ethanol-gasoline fuel environments is crucial to mitigate the risk of material degradation. Investigation of new generation elastomer and polymer materials that are inherently resistant to ethanol exposure's swelling and dissolution effects should also be a priority. Finally, more in-depth studies are needed to precisely map the engine operating conditions that cause the transition from a decrease to an increase in NOx emissions to develop more adaptive engine control strategies.

From a practical standpoint, automotive manufacturers are advised to accelerate the adoption of materials proven to be corrosion- and ethanol-resistant, such as stainless steel and fluoroelastomers, throughout fuel system components, especially if a mandate for high-concentration ethanol use is to be implemented. Policymakers should consider the hidden costs associated with infrastructure upgrades and the potential negative impact on older vehicles before mandating above E10. In addition, stricter fuel quality standards regarding maximum contaminant limits in bioethanol, such as water and chloride ion content, must be established and enforced to minimize the risk of accelerated corrosion and ensure the continued use of ethanol as an alternative fuel.

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