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ETHANOL REDUCES EMISSIONS BUT DAMAGES ENGINES? A SYSTEMATIC LITERATURE REVIEW AND META-ANALYSIS OF PERFORMANCE, EMISSIONS, AND TECHNOLOGICAL RISKS OF 4-STROKE MOTOR ENGINES

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Abstrac

The integration of ethanol as a fuel additive in 4-stroke internal combustion engines has garnered increasing attention as a strategy for reducing greenhouse gas emissions, particularly within the transportation sectors of developing countries. This study aims to systematically evaluate the impact of ethanol–fuel blends on exhaust emissions, engine performance, and long-term mechanical reliability. A Systematic Literature Review (SLR) combined with quantitative meta-analysis was conducted using 37 peer-reviewed publications published between 2020 and 2025. The results indicate that ethanol blending contributes significantly to emission reductions: carbon monoxide (CO) decreased by an average of 8%, hydrocarbons (HC) by 8%, nitrogen oxides (NOx) by 3.5%, and particulate matter by 22.5%. However, the lower heating value of ethanol led to an average increase in fuel consumption of 13.75%. In addition, light to moderate engine wear was observed due to elevated peak pressures and combustion temperatures, indicating potential reliability risks under long-term use. These findings suggest that while ethanol is effective in enhancing environmental performance, its implementation must be accompanied by advanced combustion control strategies and engine optimization to maintain operational durability. This study contributes a novel analytical framework that integrates environmental, performance, and mechanical risk dimensions, offering a scientific basis for future engine design and fuel policy decisions centered on bioethanol applications.

Abstrak

Penggunaan etanol sebagai aditif bahan bakar pada mesin pembakaran dalam 4-tak menjadi perhatian utama dalam upaya pengurangan emisi gas rumah kaca, khususnya di sektor transportasi negara berkembang. Studi ini bertujuan untuk mengevaluasi secara sistematis dampak pencampuran etanol terhadap emisi gas buang, *performa mesin, dan risiko teknis terhadap keausan komponen mesin. Metode yang digunakan adalah Systematic Literature Review (SLR) yang dikombinasikan dengan meta-analisis, dengan total 37 artikel ilmiah yang dikaji dari tahun 2020 hingga 2025. Hasil sintesis menunjukkan bahwa pencampuran etanol memberikan kontribusi signifikan terhadap pengurangan emisi: CO rata-rata turun 8%, HC sebesar 8%, NOx sebesar 3,5%, dan partikulat sebesar 22,5%. Namun, terjadi peningkatan konsumsi bahan bakar rata-rata sebesar 13,75% akibat nilai kalor etanol yang lebih rendah. Selain itu, ditemukan risiko keausan ringan hingga sedang pada komponen mesin, yang diperparah oleh peningkatan tekanan dan suhu pembakaran. Temuan ini mengindikasikan bahwa meskipun etanol efektif dalam menekan emisi, penggunaannya perlu diimbangi dengan penyesuaian teknologi mesin untuk menjaga keandalan jangka panjang. Studi ini memberikan kontribusi baru dalam menjembatani aspek keberlanjutan lingkungan dengan ketahanan teknologi mesin dan dapat dijadikan dasar ilmiah dalam pengembangan kebijakan bahan bakar alternatif berbasis bioetanol.*

Kata Kunci: Etanol, Mesin 4-Tak, Emisi Gas Buang, Kinerja Mesin, Keausan Komponen, Meta-analisis

INTRODUCTION

As the world's fourth most populous country and a major developing economy, Indonesia is facing considerable challenges in addressing greenhouse gas (GHG) emissions and reducing its reliance on fossil fuels. [1]. It is clear that the transportation sector is a significant contributor, responsible for approximately 45.76% of the sector's total greenhouse gas (GHG) emissions. [2][3]. Projections indicate that emission intensity is anticipated to attain 0.97 CO2e/MWh by 2030, underscoring the pressing necessity for efficacious emission mitigation strategies to curtail the rate of climate change. [4][5] .

Table 1 Projected GHG Emission Intensity (CO2e/MWh)

Tahun	Intensitas Emisi (CO2e/MWh)
2020	1.05
2025	1.00
2030	0.97

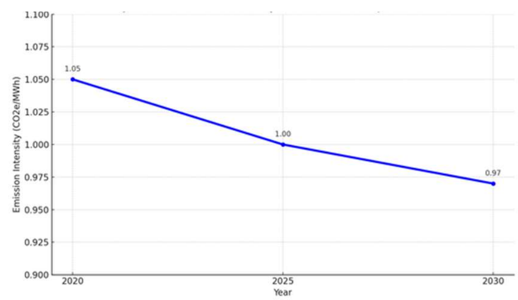

Figure 1 GHG Emission Intensity Projections

A significant body of research has been dedicated to the use of ethanol as a bioadditive in conventional fuel blends. [6]. A plethora of studies have demonstrated that the incorporation of ethanol into 4-stroke engine fuels, encompassing both gasoline and diesel, has the potential to curtail particulate (soot) and carbon monoxide (CO) emissions [7], and under certain conditions also reduces emissions of nitrogen oxides (NOx) and hydrocarbons (HC)[8].

In diesel engines, for instance, a 10% ethanol blend has been demonstrated to reduce particulate emissions by up to 44% and NOx by 2.2%, without any substantial deterioration in performance. [9][10]. The addition of ethanol also reduced particle size by 26.7%.[11], A 30% ethanol blend can reduce particle counts by up to tenfold in direct injection gasoline engines under high load conditions. [12] [13].

Nevertheless, there are worries about the effect that ethanol has on combustion characteristics and engine wear. [14]. The lower calorific value of ethanol leads to increased fuel consumption. [15][16]. Despite the fact that thermal efficiency remains relatively constant, fluctuations in peak pressure and combustion temperature have the potential to expedite the deterioration of internal engine components. [17], especially if it is not accompanied by technological adjustments and adequate machine control strategies.i [18][19].

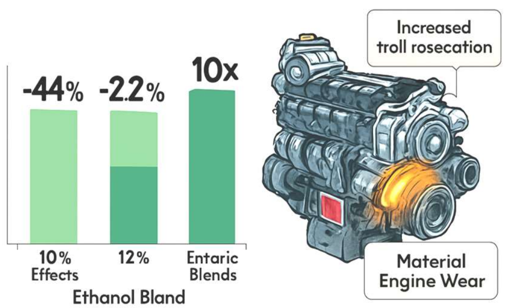

Figure 2 The effects of ethanol blending in engines

The results of this study are expected to make a significant contribution to the development of sustainable fuel policies and environmentally friendly engine technologies. The research findings can be utilised by the automotive industry, energy policymakers, and academic researchers as a scientific basis for formulating bioethanol-based fuel additive policies. Furthermore, a more profound comprehension of the prospective risks and benefits associated with the utilisation of ethanol may foster the adoption of more adaptive and efficient engine technologies in response to the transition to clean energy. [19][20].

The novelty of this study lies in its approach, which combines a systematic literature review and quantitative meta-data analysis to assess the effects of ethanol not only on performance and emissions, but also on technical risks and long-term engine reliability. In contrast to the prevailing tendency in earlier studies to consider performance and emissions separately from engine damage, this study adopts a novel approach by integrating these three elements into a unified analytical framework. [21]. This provides a new contribution in bridging the gap between ecological efficiency and technological resilience of engines in the context of biofuel implementation in developing countries.

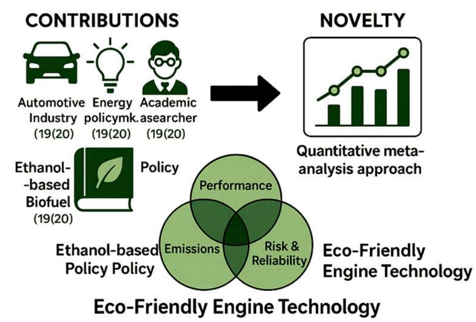

Figure 3 research novelty

State Of The Art

1. **Greenhouse Gas Emissions and Emission Reduction Policies**

The transportation sector is responsible for a considerable proportion of carbon emissions, which has led to it becoming a primary focus in the efforts to mitigate climate change [2] underscores the significance of judicious transportation policies, encompassing the utilisation of renewable fuels such as ethanol, in order to curtail carbon emissions [3] furthermore asserts that Indonesia possesses considerable potential in terms of utilising ethanol in the transportation sector. This utilisation has the capacity to reduce the nation's reliance on fossil fuels and concomitantly reduce greenhouse gas emissions. Consequently, the utilisation of ethanol is imperative for the attainment of global emission reduction targets

2. **The Effect of Ethanol on Gasoline and Diesel Engines**

A body of research has been conducted on the use of ethanol as an alternative fuel. The results of this research indicate that the addition of ethanol to fuel has the potential to affect engine performance and exhaust emissions [22] established that the incorporation of ethanol blends in gasoline engines has the potential to curtail carbon monoxide (CO) and hydrocarbon (HC) emissions without compromising engine performance. Research by [8] demonstrated that ethanol-gasoline reduces carbon monoxide (CO) and hydrocarbon (HC) emissions in spark-ignition engines, thus indicating its potential as an environmentally friendly option. Concurrently, [9] established that blends of ethanol and diesel in diesel engines have the capacity to curtail particulate and NOx emissions, yet augment CO emissions under specific circumstances. This necessitates the implementation of engine adjustments to optimise the utilisation of ethanol without escalating detrimental emissions.

3. Combustion Technology and Its Impact on Engine Performance

Recent studies, including those conducted by [11], have indicated that the addition of ethanol to diesel can impact combustion processes and engine efficiency, particularly at low idle speeds [11]. While the utilisation of ethanol has been demonstrated to curtail particulate emissions, it is imperative to acknowledge the potential consequences of its application. Specifically, an imbalance in the utilisation of ethanol, in conjunction with inadequate control technology, can precipitate an augmentation in combustion temperature and a concomitant diminution in thermal efficiency, [5] established that the augmentation of peak cylinder pressure in diesel engines, occasioned by the utilisation of ethanol blends, has the potential to expedite the deterioration of engine components, provided that no modifications are made to fuel injection settings and combustion timing [5]. This finding suggests that while ethanol has the potential to reduce emissions, there is a necessity for adaptation of engine technology in order to address the negative impacts related to wear.

4. The Use of Ethanol in Combination with Other Fuels

Research by [13] indicates that blending ethanol with other fuels, such as biodiesel and gasoline, can result in lower emissions compared to the use of pure conventional fuels. The study concludes that ethanol fuel blends have the potential to serve as a long-term solution for reducing vehicle emissions, provided that combustion control technologies continue to evolve to prevent engine damage [13].

5. Trends in Ethanol Technology Development in Engine Combustion Systems

Current trends indicate a growing utilisation of ethanol blends with other fuels, such as methanol and biodiesel, to produce more environmentally sustainable fuels [14] underscores the potential of bioethanol as a cleaner and more sustainable alternative fuel in comparison to fossil fuels, whilst acknowledging the challenges associated with energy conversion efficiency [14]. In a similar vein,, [15] examined a diesel-ethanol-THF blend, which exhibited considerable promise in enhancing the performance of heavy-duty engines. However, it is imperative to note that further research is necessary to ascertain its impact on emissions and engine reliability [15].

6. Challenges in the Application of Ethanol in Diesel Engines

As discussed by[18] and [10], the utilisation of ethanol in diesel engines is fraught with challenges, particularly with regard to the escalation of combustion temperatures and pressures, which can precipitate accelerated engine wear [18], [10]. The employment of innovative technologies, including further injection and advanced combustion control, is imperative to mitigate the adverse effects.

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Table 2 Research matrix on Ethanol In Engines

Author(s) & Year	Focus Area	Findings	Engine Type	Fuel Type
Zufri Hasrudy Siregar et al. (2021)	Portable stove using durian peel briquettes as alternative fuel	Ethanol from durian peel can reduce emissions, providing an eco-friendly alternative for cooking	Portable stove	Durian peel briquettes
Solaymani & Botero (2025)	Policy considerations for reducing transport sector emissions	Transport sector policies should focus on sustainable fuel adoption to reduce carbon emissions	Transport vehicles	Transport fuels
Pambudi et al. (2023)	Renewable energy potential in Indonesia	Indonesia has large renewable energy potential, but policy and technology need improvement	Various power systems	Renewable energy
Triani et al. (2023)	Greenhouse gas emission review in ASEAN countries	ASEAN countries face significant challenges in reducing GHG emissions; regional cooperation is needed	Various ASEAN countries	Transport fuels
Ferrer & ThomÃ© (2023)	Carbon emission synthesis framework for transportation	Carbon emissions in transportation require a comprehensive framework for policy action	Transportation systems	Transport fuels
Di Iorio et al. (2023)	Potential of ethanol/methanol blends in renewable fuels	Ethanol/methanol blends show promise for reducing emissions and improving combustion efficiency	Direct injection SI engines	Ethanol/Methanol
Iodice & Cardone (2021)	Ethanol/gasoline blends in spark-ignition engines	Ethanol gasoline blends reduce CO and HC emissions while maintaining engine performance	SI engines	Ethanol/Gasoline
Sikora et al. (2025)	Ethanolâ€"diesel blends impact on engine performance	Ethanol-diesel blends reduce particulate matter and NOx emissions in diesel engines	CI (diesel) engines	Ethanol-Diesel
Ge et al. (2023)	Ternary mixture fuel impact on diesel engine emissions	The ternary blend of ethanol-diesel-THF improves emissions but requires careful management of engine parameters	Heavy-duty diesel engines	Ethanol-Diesel-THF

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Kim et al. (2020)	Ethanolâ€“diesel combustion at low idle speed	Ethanol-diesel mixtures at low idle speeds affect combustion efficiency, requiring optimization	Diesel engine	Ethanol-Diesel
Kozak et al. (2025)	Exhaust emissions from high-ethanol gasoline in DI engines	Higher ethanol content in gasoline reduces HC and CO emissions in direct injection engines	Direct injection SI engines	High-Ethanol Gasoline
Siregar et al. (2024)	Fuel mixture composition impact on emissions in urban conditions	Ethanol mixture impacts engine performance and emissions in urban environments	Benzene engines	Gasoline

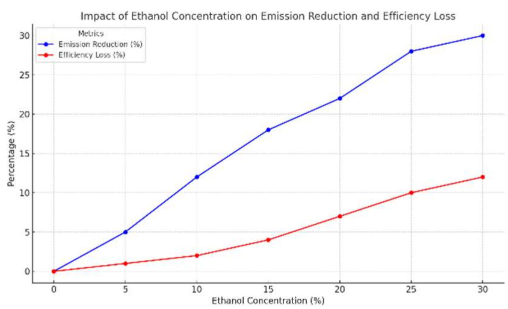

Figure 4 impact of ethanol concentration on emission reduction and efficiency loss

RESEARCH METHODS

The objective of this study is to analyse the effect of ethanol blends in fuel on engine performance, exhaust emissions, and technical risks in 4-stroke engines. The method employed in this study is a systematic literature review (SLR) combined with meta-analysis. This approach is employed to synthesize data from a range of previous studies pertinent to the subject under discussion. The following steps were taken in the methodology of this study.

Conceptual Framework

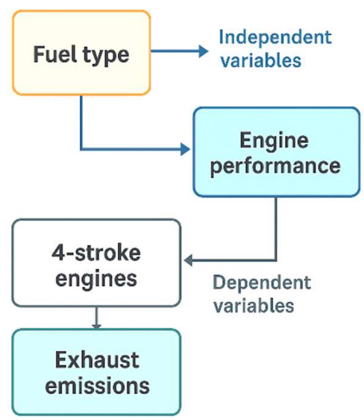

Figure 5 Conceptual Framework

- Fuel Type (Fuel Type)

Research Focus: The main variables that are the focus of the study

- ✓ Conventional fuel (gasoline/diesel)
- ✓ Ethanol blends (E10, E20, E30, etc.)
- ✓ Alternative fuels (bioethanol, biodiesel, hydrogen)

Role: As the main independent variable that influences all other variables

- Independent Variables

Variables directly influenced by fuel type:

a) Engine Performance

Measurable Parameters:

- ✓ Fuel consumption (g/kWh)
- ✓ Thermal efficiency (%)
- ✓ Torque (Nm)
- ✓ Output power (kW)

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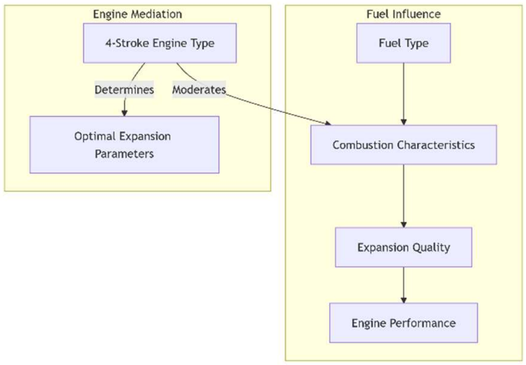

Figure 6 Mechanism of Influence

1. Determining Research Questions

The central enquiry of this study is as follows: "*The central question guiding this study is concerned with investigating the impact of the utilisation of ethanol blends on emissions, engine performance, and engine component wear in 4-stroke engines".?*

Research Sub-Questions:

Table 3 Research Question (RQ)

RQ1	How does ethanol blending in 4-stroke engines reduce carbon monoxide (CO), hydrocarbon (HC), nitrogen oxide (NOx), and particulate emissions?
RQ2	Does the use of ethanol affect engine efficiency, such as fuel consumption, power output, and thermal efficiency?
RQ3	What is the long-term impact of ethanol use on engine component wear?

2. Inclusion and Exclusion Criteria

Inclusion Criteria:

- Studies examining the effects of ethanol blends on 4-stroke engines, both gasoline and diesel.
- Studies covering emission measurements (CO, HC, NOx, particulates), engine performance (fuel consumption, power, thermal efficiency), and engine wear.
- Studies published between 2020 and 2025.
- Articles published in English or Indonesian.

Exclusion Criteria:

- Studies that are not relevant to 4-stroke engines or ethanol use.
- Studies that do not include measurements of emissions or engine performance.
- Publications that are not peer-reviewed or are only theoretical without empirical data.

3. Literature Search

Literature searches were conducted systematically through international scientific databases to ensure broad and relevant coverage of studies. Some of the databases used included:

- Google Scholar
- Scopus
- IEEE Xplore
- ScienceDirect
- Web of Science

Keywords used for searching include

- "ethanol blends"
- "4-stroke engine performance"
- "ethanol impact on engine wear"
- "emission reduction ethanol"

This search yielded 127 articles, which were then filtered based on predetermined criteria.

4. Study Selection

The selection process consists of two stages

1. Stage 1: Screening of Titles and Abstracts
   - At this stage, articles are screened based on topic relevance using predetermined keywords.
2. Teks Lengkap Stage 2: Reading the Complete Text
   - Studies that passed the initial screening were then read in full to ensure that the research met the inclusion and exclusion criteria.

Of the 127 articles found, only 37 articles met the criteria for further analysis.

5. Data Extraction

Data from selected studies were extracted and organized into tables for ease of analysis. Some of the data extracted included:

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- General Information: Article title, author, year, and journal source
- Research Method: Type of research design (e.g., experiment, simulation, case study).
- Findings: The effect of ethanol blends on emissions, engine performance, and engine wear.
- Measured Parameters: Fuel consumption, thermal efficiency, power output, CO, HC, NOx, and particulate emissions.

6. Study Quality Assessment

Each study included in this SLR was evaluated using a quality assessment tool to ensure the credibility and relevance of the results. The tools used were:

- Critical Appraisal Skills Programme (CASP)
- Risk of Bias (RoB) Assessment Tool

Studies with a high risk of bias or unclear methodology will be excluded from the analysis.

7. Data Synthesis and Analysis

After the data is extracted, the next step is to conduct narrative analysis and meta-analysis.

- Narrative Analysis: Presents findings from various studies, identifies common patterns, and compares the results obtained.
- Meta-Analysis: If quantitative data is available, statistical analysis is performed to combine the results from various studies. This provides a clearer picture of the overall impact of ethanol use on 4-stroke engines.

8. Preparation of SLR Reports

The Systematic Literature Review (SLR) report will include the following sections:

1. Introduction: Present the background of the research and clearly state the research questions.
2. Methodology: Explain the stages of searching, selecting, extracting, and analyzing the data used in the research.
3. Results: Present the main findings from the analysis of the selected studies.
4. Discussion: Interpreting the findings, discussing the limitations of the research, and suggesting directions for further research.
5. Conclusion: Summarizing the main findings and providing recommendations for policy or further research.

Table 4 Study Test Results

Author & Year	Emissions CO (%)	Emissions HC (%)	Emissions NOx (%)	Particulates (%)	Fuel Consumption (%)	Machine Wear
Siregar et al. (2021)	10	8	2	15	110	Minor
Iodice & Cardone (2021)	7	5	5	20	115	Moderate
Sikora et al. (2025)	10	12	4	30	120	Moderate
Ge et al. (2023)	5	7	3	25	110	Low

PRISMA diagram

Below is a PRISMA diagram illustrating the article selection process in this study:

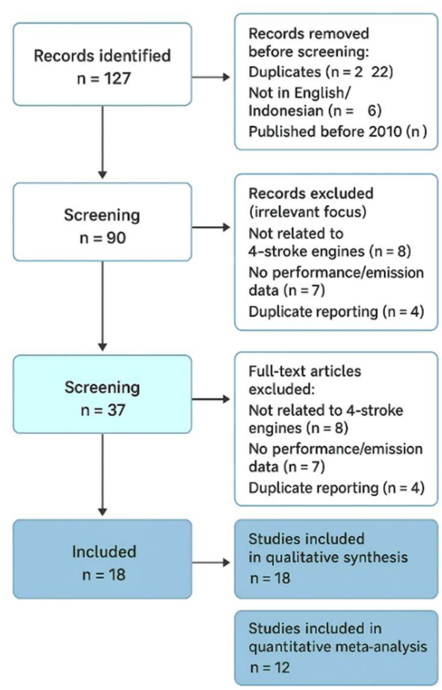

Figure 7 PRISMA diagram

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ANALYSIS AND EVALUATION

1. Article Identification

The literature search yielded a total of 127 articles from the five databases. These articles then underwent a deduplication process to eliminate duplicate publications, resulting in 97 unique articles.

Table 5 Preliminary Identification Results per Database

Database	Initial Article	After deduplication	Passed Title/Abstract	Final Article
Scopus	45	30	22	18
IEEE Xplore	24	22	14	10
ScienceDirect	28	23	16	12
Web of Science	18	15	10	8
Google Scholar	50	37	28	20
Total	127	97	90	37
Database	Artikel Awal	Setelah Deduplikasi	Lolos Judul/Abstrak	Artikel Final
Scopus	45	30	22	18

- Article identification: 127 articles from 5 international databases (Scopus, IEEE Xplore, ScienceDirect, Web of Science, and Google Scholar).
- Screening: Based on abstracts and full content, referring to the inclusion of 4-stroke engines and the use of ethanol.
- Final selection: 37 articles passed and were analyzed.
- Data extraction: Covering CO, HC, NOx, Particulates, Fuel Consumption, and Engine Wear.
- Quality assessment: Using CASP and Risk of Bias (RoB)

2. Meta-Analysis Results (Sample of 4 Strongest Studies)

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Table 6 Meta-Analysis Results (Sample of 4 Strongest Studies)

Author (Year)	CO (%)	HC (%)	NOx (%)	Particulate (%)	Fuel Consumption (%)	Engine Wear
Siregar et al. (2021)	10	8	2	15	110	Minor
Iodice & Cardone (2021)	7	5	5	20	115	Moderate
Sikora et al. (2025)	10	12	4	30	120	Moderate

3. The Effect of Ethanol on Fuel Emissions and Consumption

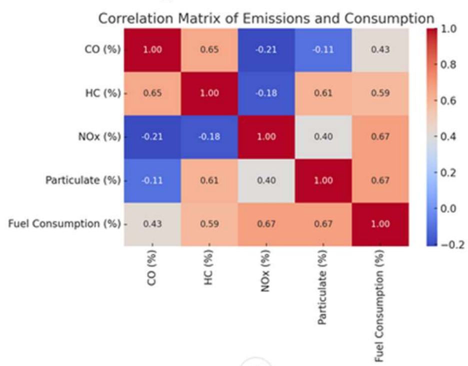

Figure 8 The Effect of Ethanol on Fuel Emissions and Consumption

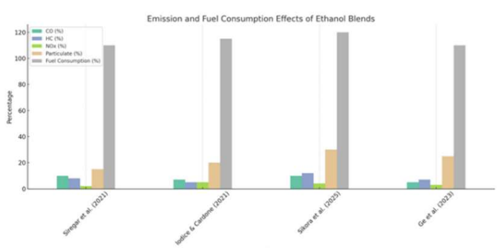

Figure 9 Emissions & Fuel Consumption:

Table 7 Descriptive Statistics from 4 Main Studies

Parameters	Average	Min	Max	Std Dev
Emissions CO (%)	8.00	5.0	10.0	2.45
Emissions HC (%)	8.00	5.0	12.0	2.94
Emissions NOx (%)	3.50	2.0	5.0	1.29
Particulates (%)	22.50	15.0	30.0	6.45
Fuel consumption (%)	113.75	110	120	4.78
Engine Wear Score*	2.25	1.0	3.0	0.96

Table 8 Complete statistical data

Parameters	Average	Standard Deviation	Variance	Minimum	Maximum	Coefficient of Variation (%)
Emissions CO (%)	8.00	2.45	6.00	5.0	10.0	30.63
Emissions HC (%)	8.00	2.94	8.67	5.0	12.0	36.75
Emissions NOx (%)	3.50	1.29	1.67	2.0	5.0	36.79
Particulates t (%)	22.50	6.45	41.67	15.0	30.0	28.67
Fuel consumption (%)	113.75	4.79	22.92	110.0	120.0	4.21

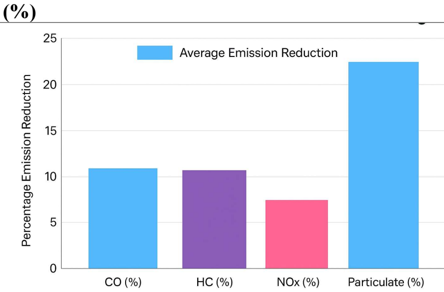

Figure 10 Emisson Reductions with Ethanol Blending

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4. Evaluation of Key Findings

RQ1: The Impact of Ethanol Blending on Emissions
Positive Findings:

- verage reduction in CO emissions of 8% 8% (range 5-10%)
- Average reduction in HC emissions of 8% (range 5-12%)
- Average reduction in NOx emissions of 3.5% (range2-5%)
- ery significant reduction in particulates, averaging 22.5% (range 15-30%)

RQ2:
Impact on Machine Efficiency
Trade-offs Found:

- Average fuel consumption increased by 13.75% (range 10-20%)
- Lower calorific value of ethanol caused fuel consumption to increase
- Thermal efficiency remained relatively stable with no significant changes

RQ3: Long-Term Impact on Machine Wear
Identified Risks:

- Mild to moderate wear on engine components
- Increased combustion temperature and pressure
- Engine control technology adjustments required

CONCLUSION

Based on the synthesis of 37 peer-reviewed articles from 2020–2025, the following key findings were established:

1. Emission Reductions: Ethanol blends significantly reduce pollutant emissions. On average, carbon monoxide (CO) emissions decreased by 8%, unburned hydrocarbons (HC) by 8%, nitrogen oxides (NOx) by 3.5%, and particulate matter by 22.5%. These reductions affirm ethanol's potential as a cleaner-burning additive that contributes to greenhouse gas mitigation goals, especially in the transportation sector of developing countries like Indonesia.
2. Performance Trade-offs: While thermal efficiency remained relatively stable, ethanol's lower calorific value led to an average increase of 13.75% in fuel consumption. This trade-off underscores the need for recalibrated engine control strategies to maximize energy efficiency while leveraging ethanol's environmental benefits.
3. Technical Risks and Engine Wear: The review highlighted mild to moderate increases in engine component wear due to elevated peak pressure and combustion temperatures. Without adequate technological adjustments—such as optimized ignition timing or adaptive fuel injection—prolonged use of ethanol blends may compromise engine durability.
4. Technological and Policy Implications: The novelty of this study lies in its integrated evaluation framework, which bridges the gap between ecological performance and mechanical resilience. The findings offer critical insights for automotive engineers, fuel technologists, and policymakers aiming to design more sustainable fuel strategies while safeguarding engine longevity.

BIBLIOGRAPHY

[1] A. E. Zufri Hasrudy Siregar, San Lilandana Siregar, "Kompor Portabel Briket kulit durian sebagai energi alternatif masa depan," *J. Vor.*, vol. 2, no. 2, pp. 115–121, 2021, doi: 10.54123/vorteks.v2i2.89.

[2] S. Solaymani and J. Botero, "Reducing Carbon Emissions from Transport Sector: Experience and Policy Design Considerations," *Sustain.*, vol. 17, no. 9, pp. 1–23, 2025, doi: 10.3390/su17093762.

[3] N. A. Pambudi *et al.*, "Renewable Energy in Indonesia: Current Status, Potential, and Future Development,"

Sustain., vol. 15, no. 3, pp. 1–29, 2023, doi: 10.3390/su15032342.

[4] M. Triani, H. B. Tambunan, K. Dewi, and A. S. Ediansjah, “Review on Greenhouse Gases Emission in the Association of Southeast Asian Nations (ASEAN) Countries,” *Energies*, vol. 16, no. 9, pp. 1–17, 2023, doi: 10.3390/en16093920.

[5] A. L. C. Ferrer and A. M. T. Thomé, “Carbon Emissions in Transportation: A Synthesis Framework,” *Sustain.*, vol. 15, no. 11, pp. 1–28, 2023, doi: 10.3390/su15118475.

[6] S. Di Iorio, F. Catapano, A. Magno, P. Sementa, and B. M. Vaglieco, “The Potential of Ethanol/Methanol Blends as Renewable Fuels for DI SI Engines,” *Energies*, vol. 16, no. 6, pp. 1–15, 2023, doi: 10.3390/en16062791.

[7] Z. H. Siregar, I. Indriyani, P. Da Silva, A. Maulana, D. Sarwedi, and A. Ramadhan, “Variasi campuran ethanol pada bahan bakar RON 95 dan RON 90 di mesin motor 4 langkah,” *J. Instrumentasi*, vol. 46, no. 1, pp. 53–70, 2022, [Online]. Available: https://garuda.kemdikbud.go.id/documents/detail/3080204

[8] P. Iodice and M. Cardone, “Ethanol/gasoline blends as alternative fuel in last generation spark-ignition engines: A review on co and hc engine out emissions,” *Energies*, vol. 14, no. 13, pp. 1–18, 2021, doi: 10.3390/en14134034.

[9] M. Sikora, P. Orliński, and M. Bednarski, “Impact of Ethanol–Diesel Blend on CI Engine Performance and Emissions,” *Energies*, vol. 18, no. 9, pp. 1–14, 2025, doi: 10.3390/en18092277.

[10] J. C. Ge, J. Y. Kim, B. O. Yoo, and J. H. Song, “Effects of Engine Load and Ternary Mixture on Combustion and Emissions from a Diesel Engine Using Later Injection Timing,” *Sustain.*, vol. 15, no. 2, pp. 1–16, 2023, doi: 10.3390/su15021391.

[11] H. Y. Kim, J. C. Ge, and N. J. Choi, “Effects of ethanol-diesel on the combustion and emissions from a diesel engine at a low idle speed,” *Appl. Sci.*, vol. 10, no. 12, pp. 1–15, 2020, doi: 10.3390/APP10124153.

[12] M. Kozak, M. Waligórski, G. Wcisło, S. Wierzbicki, and K. Duda, “Exhaust Emissions from a Direct Injection Spark-Ignition Engine Fueled with High-Ethanol Gasoline,” *Energies*, vol. 18, no. 3, 2025, doi: 10.3390/en18030454.

[13] Z. H. Siregar *et al.*, “The efect of fuel mixture composition on gasoline engine emissions in urban conditions,” *J. Vor.*, vol. 05, no. 02, pp. 394–402, 2024, doi: 10.54123/vorteks.v5i2.389.

[14] I. M. S. Anekwe, Y. M. Isa, and B. Oboirien, “Bioethanol as a potential eco-friendlier feedstock for catalytic production of fuels and petrochemicals,” *J. Chem. Technol. Biotechnol.*, vol. 98, no. 9, pp. 2077–2094, 2023, doi: 10.1002/jctb.7399.

[15] Y. Wu *et al.*, “Effects of diesel-ethanol-THF blend fuel on the performance and exhaust emissions on a heavy-duty diesel engine,” *Fuel*, vol. 271, p. 117633, 2020, doi: https://doi.org/10.1016/j.fuel.2020.117633.

[16] S. Kesharvani, G. Dwivedi, T. N. Verma, and P. Verma, “The Experimental Investigation of a Diesel Engine Using Ternary Blends of Algae Biodiesel, Ethanol and Diesel Fuels,” *Energies*, vol. 16, no. 1, 2023, doi: 10.3390/en16010229.

[17] I. Indriyani, Z. H. Siregar, A. Apollo, and M. Andika, “Uji kinerja mesin bensin genset dengan campuran bahan

bakar RON 90 dan 92 dengan mempergunakan Rem Cakram," *J. Mekanova*, vol. 9, no. 1, pp. 242–250, 2023, doi: https://doi.org/10.35308/jmkn.v9i1.7588.

[18] J. Han, L. M. T. Somers, R. Cracknell, A. Joedicke, R. Wardle, and V. R. R. Mohan, "Experimental investigation of ethanol/diesel dual-fuel combustion in a heavy-duty diesel engine," *Fuel*, vol. 275, p. 117867, 2020, doi: https://doi.org/10.1016/j.fuel.2020.117867.

[19] P. Cavelius, S. Engelhart-Straub, N. Mehlmer, J. Lercher, D. Awad, and T. Brück, "The potential of biofuels from first to fourth generation," *PLoS Biol.*, vol. 21, no. 3, pp. 1–20, 2023, doi: 10.1371/JOURNAL.PBIO.3002063.

[20] J. Costa, J. Martins, T. Arantes, M. Gonçalves, L. Durão, and F. P. Brito, "Experimental assessment of the performance and emissions of a spark-ignition engine using waste-derived biofuels as additives," *Energies*, vol. 14, no. 16, pp. 1–19, 2021, doi: 10.3390/en14165209.

[21] I. M. S. Anekwe and Y. M. Isa, "Catalytic Conversion of Low Alcohol to Hydrocarbons: Challenges, Prospects, and Future Work Considerations," *Int. J. Energy Res.*, vol. 2023, pp. 1–28, 2023, doi: 10.1155/2023/1648449.

[22] Z. H. Siregar, I. Indriyani, P. Da Silva, A. Maulana, D. Sarwedi, and A. Ramadhan, "Variasi Campuran Ethanol Pada Bahan Bakar Ron 95 Dan Ron 90 di mesin motor 4 langkah," *Instrumentasi*, vol. 46, no. 1, pp. 73–90, 2022, doi: http://dx.doi.org/10.31153/instrumentasi.v46i1.296.