VOCATECH: Vocational Education and Technology Journal 7, 1 (2025): 75-81
Website: http://ojs.aknacehbarat.ac.id/index.php/vocatech/index
ISSN 2716-5183 (online) ISSN 2686-4770 (print)

Analysis of Thermal Efficiency of the Honda GK5 Engine Fueled with Young Coconut Waste Bioethanol Using a Thermodynamic Approach

Retno wahyudi [1*]
Fauzi Ibrahim [2]
Novia Utami Putri [3]
Adam Wisnu Murti [4]
Agus Apriyanto [5]
Alexander Sembiring [6]

[1,2,3,4,5,6] Program Studi Teknologi Rekayasa Otomotif , Politeknik Negeri Lampung, Jl. Soekarno Hatta No.10, Rajabasa Raya, Kec. Rajabasa, Kota Bandar Lampung, Lampung 35141 Indonesia

Abstract

The global energy crisis and increasing awareness of the negative environmental impacts of fossil fuels have driven the development of sustainable alternative energy sources. One promising renewable fuel is bioethanol, especially when produced from agricultural waste such as young coconut waste. This study aims to evaluate the effect of using bioethanol derived from young coconut waste on the thermal efficiency of the Honda GK5 engine through thermodynamic analysis based on the Otto cycle model and verification using experimental data. The research method includes laboratory testing of the Honda GK5 engine with variations in fuel mixtures: E0, E10, E20, and E30. The test results show a significant increase in thermal efficiency up to the E20 mixture, with an experimental efficiency of 31.8% and a theoretical efficiency of 32.0%. This improvement is attributed to the high octane number of bioethanol, which supports more complete combustion. However, at the E30 mixture, a decrease in efficiency is observed due to the lower heating value of bioethanol. The Otto cycle model successfully represents the trend of thermal efficiency with an average deviation of 1–1.5% compared to experimental results. Therefore, bioethanol from young coconut waste proves not only to be environmentally friendly but also capable of enhancing engine energy performance optimally without requiring significant modifications.

Keywords:
Bioethanol, Young Coconut Waste, Thermal Efficiency, Honda GK5 Engine, Otto Cycle, Thermodynamics..

Abstrak

Krisis energi global dan meningkatnya kesadaran akan dampak lingkungan negatif dari bahan bakar fosil telah mendorong pengembangan sumber energi alternatif yang berkelanjutan. Salah satu bahan bakar terbarukan yang menjanjikan adalah bioetanol, khususnya yang diproduksi dari limbah pertanian seperti limbah kelapa muda. Penelitian ini bertujuan untuk mengevaluasi pengaruh penggunaan bioetanol yang berasal dari limbah kelapa muda terhadap efisiensi termal mesin Honda GK5 melalui analisis termodinamika berbasis model siklus Otto dan verifikasi menggunakan data eksperimen. Metode penelitian mencakup pengujian laboratorium pada mesin Honda GK5 dengan variasi campuran bahan bakar: E0, E10, E20, dan E30. Hasil pengujian menunjukkan adanya peningkatan signifikan pada efisiensi termal hingga campuran E20, dengan efisiensi eksperimental sebesar 31,8% dan efisiensi teoretis sebesar 32,0%. Peningkatan ini dikaitkan dengan angka oktan bioetanol yang tinggi, yang mendukung pembakaran lebih sempurna. Namun, pada campuran E30 terjadi penurunan efisiensi akibat nilai kalor bioetanol yang lebih rendah. Model siklus Otto berhasil merepresentasikan tren efisiensi termal dengan deviasi rata-rata sebesar 1–1,5% dibandingkan hasil eksperimen. Dengan demikian, bioetanol dari limbah kelapa muda terbukti tidak hanya ramah lingkungan, tetapi juga mampu meningkatkan kinerja energi mesin secara optimal tanpa memerlukan modifikasi signifikan.

Kata kunci:
Bioetanol, Limbah Kelapa Muda, Efisiensi Termal, Mesin Honda *GK5,* Siklus *Otto,* Termodinamika.

DOI: 10.38038/ vocatech.v7i1.214
Received: 14 Juli 2025; Accepted: 8 Agustus 2025; Published: 12 Agustus 2025

*Corresponding author:**
Email:

Citation in APA Style: Wahyudi, R., Ibrahim, F., Putri, N. U., Murti, A. W., Apriyanto, A., & Sembiring, A (2025). Analysis of Thermal Efficiency of the Honda GK5 Engine Fueled with Young Coconut Waste Bioethanol Using a Thermodynamic Approach. *VOCATECH: Vocational Education and Technology Journal, 7*(1), 75-81.

1. INTRODUCTION

The global energy crisis, combined with increasing environmental concerns related to the use of fossil fuels, has intensified efforts to identify alternative energy sources that are both sustainable and environmentally friendly. Among these alternatives, bioethanol has emerged as one of the most promising renewable fuels. Bioethanol is not only capable of reducing greenhouse gas emissions, but it also helps decrease the world's dependence on finite petroleum-based energy resources. In recent years, the utilization of lignocellulosic biomass particularly organic waste materials as feedstock for bioethanol production has gained significant attention. One such underutilized resource is young coconut waste, which includes husks, shells, and other fibrous residues commonly discarded in tropical regions. The dual benefit of converting such organic waste into energy lies in its ability to address both renewable fuel generation and waste management simultaneously. Research by (Dogan et al., 2023; Jahanbakhshi et al., 2021; Milão et al., 2021) indicates that coconut waste is rich in cellulose, making it a suitable and efficient raw material for the fermentation process required in bioethanol production. On the technological side, the performance of internal combustion engines such as the Honda GK5 engine is strongly influenced by the type and properties of the fuel used. Fuel characteristics such as calorific value, volatility, and oxygen content play a crucial role in determining combustion efficiency, power output, and thermal performance. Studies, including that by (Adeleke et al., 2020; Kul & Ciniviz, 2021; Paloboran et al., 2023), have demonstrated that ethanol-gasoline blends can enhance engine performance by improving thermal efficiency, reducing emissions, and increasing power output. Ethanol, due to its higher oxygen content, facilitates more complete combustion compared to pure gasoline, potentially resulting in better engine performance.

However, while general ethanol-gasoline blends have been studied, there remains a gap in research specifically examining the effects of bioethanol derived from young coconut waste on engine thermal efficiency particularly for the Honda GK5 engine model. To address this gap, the current study aims to evaluate the thermal efficiency of the Honda GK5 engine when fueled with bioethanol produced from young coconut waste. The study will employ a thermodynamic analysis approach to assess key performance parameters such as fuel consumption, power output, and overall thermal efficiency. By developing and applying an appropriate thermodynamic model, this research intends to understand how the unique chemical and physical properties of coconut waste-derived ethanol influence engine performance. This is especially relevant for developing countries, where the use of two-wheeled transportation is predominant, and the availability of affordable, locally-sourced renewable fuels could have transformative impacts on energy access and environmental sustainability. Ultimately, the study seeks to contribute to the development of small-scale renewable energy technologies by highlighting the feasibility and benefits of utilizing agricultural waste as a fuel source. By focusing on the thermodynamic aspects of engine performance, this research will provide a comprehensive evaluation of young coconut waste-derived bioethanol as a viable, clean-burning alternative fuel. Based on the background described, two main research problems are formulated: (1) What is the effect of using bioethanol from young coconut waste on the thermal efficiency of the Honda GK5 engine? (2) What thermodynamic model can be used to analyze the thermal efficiency of the GK5 engine?.

2. MATERIALS AND METHODS

2.1. Bioethanol as an Alternative Fuel

Bioethanol is a type of alcohol that is produced through the fermentation of biomass materials rich in carbohydrates, such as starch and lignocellulosic substances. As a renewable energy source, bioethanol has gained significant attention as a viable alternative to fossil fuels, particularly in the transportation sector. Its use is widely regarded as a strategic solution to address the dual challenges of energy security and environmental degradation. One of the primary advantages of bioethanol is its environmental friendliness. When burned in internal combustion engines, bioethanol emits significantly lower levels of greenhouse gases, such as carbon dioxide (CO_2), compared to conventional gasoline. This makes it a cleaner fuel option that can contribute to reducing the overall carbon footprint of transportation systems. Additionally, bioethanol combustion tends to produce fewer pollutants, such as sulfur oxides (SOx) and particulate matter, further supporting its role in reducing air pollution (Santos et al., 2020; Xia et al., 2025; Zhang et al., 2025). Another notable benefit is that bioethanol is derived from renewable sources. It can be produced from a wide range of biomass feedstocks, including agricultural residues, food processing waste, and lignocellulosic materials like corn stalks, sugarcane bagasse, and coconut husks. This makes bioethanol production sustainable and independent of non-renewable fossil fuel reserves, which are depleting and subject to geopolitical uncertainties. Furthermore, bioethanol possesses a high octane number, which is a measure of a fuel's ability to resist engine knocking during combustion. Fuels with higher octane ratings enable smoother engine performance and can improve combustion efficiency. When blended with gasoline, bioethanol can enhance engine power output and thermal efficiency, contributing to better fuel economy and performance. The use of bioethanol as an alternative fuel has been extensively studied and implemented in numerous countries, including Brazil, the United States, and members of the European Union. These initiatives aim to reduce reliance on petroleum-based fuels, improve energy security, and mitigate the environmental impacts of fossil fuel consumption. As a result, bioethanol continues to play a vital role in the global transition toward more sustainable and eco-friendly energy systems (Dahham et al., 2022; Michael, 2024; Mohapatra & Mishra, 2024; Weissinger et al., 2025).

2.2. Young Coconut Waste as a Source of Bioethanol

Young coconut waste, especially in the form of coconut husks and coconut water, represents a promising and underutilized source of lignocellulosic biomass for bioethanol production. Typically discarded as agricultural waste, these components of young coconuts contain valuable organic materials that can be transformed into renewable energy. Coconut husks are rich in cellulose, hemicellulose, and lignin three key structural polymers that are essential for the production of bioethanol through biochemical conversion processes. Among these components, cellulose and hemicellulose are the primary sources of fermentable sugars. Through hydrolysis, these complex carbohydrates can be broken down into simpler sugars such as glucose and xylose. These sugars are then fermented by specific microorganisms to produce ethanol. Lignin, while not fermentable, plays a structural role and is typically removed or altered during pretreatment to improve the accessibility of the other two components (Paparao et al., 2025; Yang et al., 2023).

The process of converting young coconut waste into bioethanol involves several key stages:

a. Pretreatment: This initial stage involves breaking down the rigid structure of the lignocellulosic material to remove or disrupt lignin and increase the accessibility of cellulose and hemicellulose. Pretreatment can be physical, chemical, or biological in nature and is crucial for enhancing the efficiency of subsequent steps.
b. Hydrolysis: Enzymatic or acid hydrolysis is used to convert cellulose and hemicellulose into simple fermentable sugars. Enzymes such as cellulase and hemicellulase are typically employed to catalyze this process.
c. Fermentation: The simple sugars resulting from hydrolysis are fermented using microorganisms such as Saccharomyces cerevisiae or Zymomonas mobilis, which convert the sugars into ethanol under controlled conditions.
d. Distillation: The final step involves separating and purifying the ethanol from the fermentation broth to achieve fuel-grade bioethanol.

Utilizing young coconut waste for bioethanol production adds economic and environmental value to agricultural byproducts. It helps reduce organic waste accumulation, lowers pollution levels, and provides a sustainable energy source, especially in tropical regions where coconuts are abundant. This approach contributes to circular economy practices by transforming waste into a clean, renewable fuel (Chen et al., 2023; Jagtap et al., 2020; Yang et al., 2023).

2.3. Thermal Efficiency of Internal Combustion Engines

Thermal efficiency is a key performance metric for internal combustion engines, representing the ratio of useful mechanical work output to the total chemical energy input from the fuel. In essence, it measures how effectively an engine converts the energy stored in fuel into motion. Achieving high thermal efficiency is critical not only for optimizing fuel consumption but also for reducing emissions and improving overall engine performance. Several factors influence the thermal efficiency of internal combustion engines, including engine design, combustion chamber geometry, ignition timing, operating conditions, and, importantly, the type and quality of fuel used. Among alternative fuels, bioethanol has gained attention due to its potential to positively impact engine performance and efficiency. One of the primary advantages of bioethanol is its high octane number, which allows for higher compression ratios without causing engine knocking. This enables more complete and efficient combustion, which can enhance the thermal efficiency of the engine. Blending bioethanol with gasoline—commonly referred to as ethanol-gasoline blends can offer improved combustion characteristics. Studies have shown that these blends can increase the thermal efficiency of engines, improve power output, and reduce certain types of harmful emissions. However, bioethanol also has a lower heating value (LHV) compared to gasoline, meaning it contains less energy per unit volume. As a result, engines running on higher concentrations of ethanol may require more fuel to produce the same amount of energy, potentially affecting fuel economy. Given these competing effects, it is crucial to conduct a thermodynamic analysis to accurately evaluate how the use of bioethanol particularly that derived from biomass such as young coconut waste affects engine performance. In the case of the Honda GK5 engine, understanding the interaction between fuel properties and engine operation through thermodynamic modeling can help determine the optimal fuel blend and combustion strategy. Such analysis typically involves evaluating parameters like heat input, work output, combustion temperature, and exhaust losses to calculate the actual thermal efficiency under various fuel conditions. This approach is essential for making informed decisions about integrating bioethanol into conventional engines while maintaining or improving energy efficiency and sustainability (Janković et al., 2023; Paparao et al., 2025; Xia et al., 2025).

2.4. Thermodynamic Models in Engine Analysis

Thermodynamic models play a crucial role in the analysis of internal combustion engine performance, particularly in evaluating combustion efficiency and overall thermal behavior. These models help engineers and researchers understand the conversion of chemical energy from fuel into mechanical work and assess how changes in engine design or fuel properties impact performance. Among the various thermodynamic models, the Otto cycle is one of the most widely used for analyzing spark-ignition engines, such as those found in conventional gasoline-powered vehicles. The Otto cycle is an idealized model that represents the sequence of thermodynamic processes occurring within a four-stroke internal combustion engine. It consists of two adiabatic (isentropic) processes and two isochoric (constant volume) processes, forming a complete theoretical cycle (Adeleke et al., 2020; Chen et al., 2023; Jahanbakhshi et al., 2021; Mohapatra & Mishra, 2024; Xia et al., 2025). This model is particularly useful for examining how key engine parameters, such as compression ratio, air-fuel mixture, and ignition timing, influence thermal efficiency. One of the most significant insights provided by the Otto cycle is the direct relationship between compression ratio and thermal efficiency: as the compression ratio increases, the thermal efficiency of the cycle also increases, assuming ideal conditions. In this study, the Otto cycle is applied as a theoretical framework to analyze the thermal efficiency of the Honda GK5 engine when fueled with bioethanol derived from young coconut waste. The study combines this theoretical model with a quantitative experimental method conducted in a laboratory setting. Through this dual approach, real engine performance data can be collected and compared against the predictions made by the thermodynamic model, allowing for validation and refinement of theoretical assumptions. Thermodynamic simulations using the Otto cycle also offer the advantage of enabling the prediction of combustion behavior, fuel efficiency, and exhaust emissions. This is particularly relevant when evaluating alternative fuels, such as bioethanol, which may possess different thermochemical properties than conventional gasoline. By applying the Otto cycle model to coconut-waste-derived bioethanol, the study aims to quantify its effects on engine efficiency and emissions, contributing valuable insights into the feasibility of using agricultural waste as a clean, renewable energy source for automotive applications (Dahham et al., 2022; Santos et al., 2020; Yang et al., 2023).

3. RESULTS AND DISCUSSION

3.1. Experimental Data and Theoretical Calculations

This study investigates the thermal efficiency of the Honda GK5 engine when fueled with bioethanol derived from young coconut waste. To achieve this objective, both experimental testing and theoretical modeling using the Otto cycle were employed. The experimental method involved operating the Honda GK5 engine under controlled laboratory conditions, using different ethanol-gasoline blends: E0 (100% gasoline), E10 (10% ethanol), E20 (20% ethanol), and E30 (30% ethanol). Each mixture was analyzed for its impact on fuel consumption, exhaust gas temperature, power output, and overall thermal efficiency. The theoretical aspect of this analysis was based on the ideal Otto cycle model, which provides a useful approximation of spark-ignition engine behavior under varying compression ratios and fuel properties. This model was used to estimate the theoretical thermal efficiency of the engine using the same fuel blends as tested experimentally. The Otto cycle's ideal nature assumes adiabatic and isochoric processes without accounting for real-world losses such as friction, incomplete combustion, or heat transfer to the surroundings.

Table 1. Experimental Results and Theoretical Calculations of Thermal Efficiency of the Honda GK5 Engine.

Fuel Composition	Heating Value (MJ/kg)	Exhaust Temperature (°C)	Power Output (kW)	Experimental Thermal Efficiency (%)	Theoretical Thermal Efficiency (%)
E0 (100% Bensin)	44.0	450	9.2	28.7	30.1
E10	42.5	435	9.5	30.2	31.3
E20	41.2	425	9.7	31.8	32.0
E30	39.8	418	9.6	31.1	31.5

Based on Table 1, it can be observed that thermal efficiency increases with the rising concentration of bioethanol in the fuel mixture, reaching an optimal point at E20. This improvement is attributed to the high octane rating of bioethanol, which supports more complete combustion within the combustion chamber. However, at the E30 mixture, a slight decrease in efficiency is noted due to the lower heating value of bioethanol, resulting in less energy produced per unit mass of fuel.

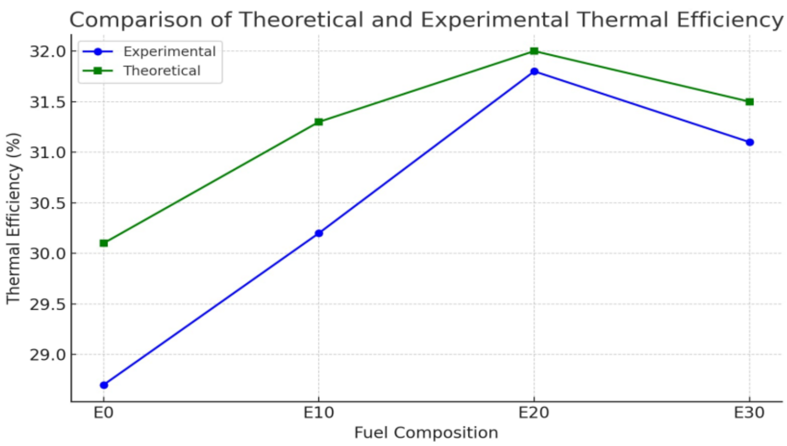

Figure 1. Thermal Efficiency Comparison Chart

From the data presented, it is evident that thermal efficiency improves with increasing bioethanol content up to the E20 blend. This improvement is largely attributed to the higher octane number of bioethanol, which allows for more efficient combustion by enabling higher compression ratios without causing engine knock. Moreover, ethanol contains oxygen within its molecular structure, promoting more complete combustion and reducing unburned hydrocarbon emissions. The peak thermal efficiency of 31.8% (experimental) and 32.0% (theoretical) was observed with the E20 blend. Beyond this point, however, a slight decline in efficiency is noted with the E30 blend. This can be attributed to the lower heating value (LHV) of ethanol compared to gasoline. As ethanol concentration increases, the total energy content per unit mass of the fuel mixture decreases, requiring greater volumes of fuel to produce the same energy output. Consequently, although combustion remains efficient, the net energy conversion efficiency begins to decline. Figure 1 illustrates the comparison between experimental and theoretical thermal efficiencies across the different blends. The trends in both curves are closely aligned, indicating a strong correlation between real engine behavior and the Otto cycle model. The deviations between theoretical and experimental results range from 1 to 1.5%, which is acceptable considering the idealized assumptions of the thermodynamic model. These discrepancies are primarily due to engine heat losses, mechanical friction, and non-ideal combustion phenomena, which are not accounted for in the simplified Otto cycle. The experimental setup demonstrates that using bioethanol derived from young coconut waste in ethanol-gasoline blends has a measurable impact on engine performance. The results validate the applicability of theoretical thermodynamic modeling in predicting real-world engine behavior, especially when evaluating alternative fuels. This combined methodology of experimental validation and theoretical prediction is essential in energy research, allowing for better fuel blend optimization and performance forecasting.

3.2. Comparative Analysis of Results

From the results obtained, it can be concluded that the use of bioethanol derived from young coconut waste has the potential to improve the thermal efficiency of the Honda GK5 engine, reaching its optimal point with the E20 mixture. This improvement is associated with more efficient combustion and lower exhaust temperatures. Overall, the experimental results show good correlation with the theoretical model's predictions, confirming that a thermodynamic approach can be effectively used to evaluate engine performance under varying alternative fuel compositions.

4. CONCLUSION

This study affirms that bioethanol derived from young coconut waste can enhance the thermal efficiency of the Honda GK5 engine, particularly when used in a 20% ethanol (E20) fuel blend. The findings not only align with the expectations stated in the introduction regarding improved engine performance and sustainability, but also reflect the theoretical assumptions developed through the thermodynamic model. The close agreement between experimental and theoretical results suggests that the Otto cycle model is an effective framework for evaluating ethanol-gasoline mixtures. This reinforces the relevance of thermodynamic analysis in optimizing renewable fuel applications. Beyond confirming the viability of bioethanol as a cleaner-burning fuel, this research highlights its potential as a practical solution for energy diversification, especially in developing regions rich in agricultural waste. Future investigations may expand upon these results by exploring engine calibration techniques or hybrid fuel strategies to further improve energy efficiency and broaden the applicability of bioethanol across engine types and operational conditions.

REFERENCES

Adeleke, A. E., Oni, K., & Ogundana, T. (2020). Thermodynamic Considerations On The Design Of A Bioethanol Processing Plant Condenser. *Fuoye Journal Of Agriculture And Human Ecology*, *3*(2).

Chen, H., Cai, D., Wen, J., Su, C., & Wang, J. (2023). Distillation separation of bioethanol: The current advances. In *Bioethanol Fuel Production Processes. II* (pp. 393–408). CRC Press.

Dahham, R. Y., Wei, H., & Pan, J. (2022). Improving thermal efficiency of internal combustion engines: recent progress and remaining challenges. *Energies*, *15*(17), 6222.

Dogan, B., Yilbasi, Z., Yaman, H., & Yesilyurt, M. K. (2023). Thermodynamic and economic analyses of a spark-ignition engine operating with bioethanol-gasoline blends. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *45*(4), 10697–10719.

Jagtap, S. P., Pawar, A. N., & Lahane, S. (2020). Improving the usability of biodiesel blend in low heat rejection diesel engine through combustion, performance and emission analysis. *Renewable Energy*, *155*, 628–644.

Jahanbakhshi, A., Karami-Boozhani, S., Yousefi, M., & Ooi, J. B. (2021). Performance of bioethanol and diesel fuel by thermodynamic simulation of the miller cycle in the diesel engine. *Results in Engineering*, *12*, 100279.

Janković, T., Straathof, A. J. J., & Kiss, A. A. (2023). Advanced downstream processing of bioethanol from syngas fermentation. *Separation and Purification Technology*, *322*, 124320.

Kul, B. S., & Ciniviz, M. (2021). An evaluation based on energy and exergy analyses in SI engine fueled with waste bread bioethanol-gasoline blends. *Fuel*, *286*, 119375.

Michael, I. (2024). Application of thermodynamic methods to the study of plant biomass and its components—a review. *Applied Biosciences*, *3*(4), 577–616.

Milão, R. de F. D., Araújo, O. de Q. F., & de Medeiros, J. L. (2021). Sugarcane-based ethanol biorefineries with bioenergy production from bagasse: Thermodynamic, economic, and emissions assessments. In *Waste Biorefinery* (pp. 125–158). Elsevier.

Mohapatra, T., & Mishra, S. S. (2024). Parametric optimization of a VCR diesel engine run on diesel-bioethanol-Al2O3 nanoparticles blend using Taguchi-Grey and RSM method: a comparative study. *World Journal of Engineering*, *21*(4), 767–780.

Paloboran, M., Syam, H., & Yahya, M. (2023). ENERGY AND EXERGY ANALYSIS ON SPARK IGNITION ENGINES UNDER VARYING IGNITION TIMING WITH PURE BIOETHANOL FUEL. *Вестник Московского Государственного Технического Университета Им. НЭ Баумана. Серия «Естественные Науки»*, *2 (107)*, 140–159.

Paparao, J., Singh, P., Patil, V., Khandelwal, B., & Kumar, S. (2025). Applicability of furan-gasoline blends with energy, exergy, sustainability, and entropy generation analysis for SI engines. *Energy*, 136345.

Santos, M. C., Albuquerque, A. A., Meneghetti, S. M. P., & Soletti, J. I. (2020). Property modeling, energy balance and process simulation applied to bioethanol purification. *Sugar Tech*, *22*(5), 870–884.

Weissinger, F., Lacava, P., Peñaranda, A., Martelli, A., Rufino, C. H., Curto-Risso, P., & Martinez-Boggio, S. (2025). Enhancing Efficiency of Ethanol-Powered Range Extenders in the BMW i3: A Simulation-Based Optimization Approach. *Renewable Energy*, 123394.

Xia, W., Zhang, Y., Ma, C., Jiang, Z., Wang, X., Chen, K., Liu, D., & Wang, Y. (2025). Comprehensive analysis of zirconium dioxide catalyzed bioethanol conversion to light olefins: From thermodynamics to kinetics. *Energy*, *319*, 135024.

Yang, W., Wang, Y., Bai, Y., Hao, L., & Liu, X. (2023). Experimental study of the bioethanol substitution rate and the diesel injection strategies on combustion and emission characteristics of dual-fuel-direct-injection (DFDI) engine. *Journal of the Energy Institute*, *106*, 101153.

Zhang, Z., Wang, J., Zhu, K., Li, S., Li, M., Fan, X., & Gao, J. (2025). An efficient heat-pump extractive distillation process for recovering lower alcohols from bioethanol fusel oil. *Chemical Engineering and Processing-Process Intensification*, *213*, 110291.