EVALUATION OF THE SUITABILITY OF BIOETHANOL AND BUTANOL BLENDS FOR POWERING INTERNAL COMBUSTION ENGINES

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Abstract

This study investigates the suitability of bioethanol–butanol blends as alternative fuels for internal combustion engines, focusing on their calorific value and combustion residue mass. Fuel samples with varying ethanol-to-butanol weight ratios (100:0, 70:30, 50:50, 30:70, and 0:100) were prepared from high-purity components and tested using a KL-Mn 12 calorimeter. Results showed that blends produced higher combustion residue masses than pure components, with the 50:50 mixture yielding the highest value. Calorific value increased proportionally with butanol content, from 27.43 MJ·kg^{-1} for pure ethanol to 34.71 MJ·kg^{-1} for pure butanol. Statistical analysis confirmed significant differences between compositions. The findings suggest that ethanol–butanol blends, despite increased residue formation, have favorable energy characteristics and potential for use in spark-ignition engines, warranting further studies on engine performance, octane ratings, and exhaust emissions.

Key words: *biofuels, bioethanol–butanol blends, calorific value, ash (residue) mass, bomb calorimetry, alternative fuels, spark-ignition engines*

INTRODUCTION

Despite the increasing use of electric propulsion systems in vehicles, internal combustion engines still remain the predominant source of energy in machines and vehicles. The search for solutions that would reduce emissions generated by their operation while maintaining high functional performance prompts efforts to find various means of continuing their use. These efforts are being realized in several directions: modifications in engine design to improve efficiency and reduce fuel consumption (and consequently reduce harmful emissions), the implementation of hybrid propulsion systems, and also the exploration of alternative fuels, whose use may result in lower fossil fuel consumption or improved exhaust gas composition. Various fuels—both gaseous and liquid—are known to be used as alternatives. Among gaseous fuels with practical applications, LPG (a mixture of propane and butane) and CNG (compressed natural gas) are the most commonly used. Less popular but still applied in practice are biogas and wood gas (holzgas). This solution was especially prevalent in times of limited access to crude oil (*Zakrzewski, 2016*). It is used for powering both stationary engines and vehicles. Gaseous fuels are mainly used in spark-ignition engines, but also in compression-ignition engines, with the use of diesel injection to initiate combustion. LPG is the most widely used, while CNG is used to a lesser extent. Current European regulations require the use of bio-components in fuel blends in quantities of at least 7% for diesel fuels and at least 10% for gasoline.

The primary liquid fuel for spark-ignition engines is gasoline, composed of aliphatic, aromatic, and unsaturated hydrocarbons. Until the mid-1980s, leaded gasoline was commonly used, which released toxic lead oxide during combustion. Currently, unleaded gasoline marked as 95 and 98 is used, with the numbers referring to the octane rating of the fuel (*VMC, 2024*). Bio-components that can also serve as standalone fuels for spark-ignition engines include ethanol, methanol, and butanol. Selected properties of these alcohols compared with gasoline are presented in Table 1. Noteworthy are their high octane numbers, low calorific value—especially in the case of bioethanol—and high heat of vaporization. These properties significantly influence combustion processes in such engines, although they are not the subject of this study.

The most commonly used additive to gasoline in the European Union is bioethanol. Currently, its inclusion in fuel is mandated by Directive 2009/30/EC (*European Parliament and Council, 2009*).

Tab. 1 Selected properties of fuels for spark-ignition engines

Parameters / Fuel	Density at 15°C [kg·m^{-3}]	Research Octane Number	Motor Octane Number	Boiling point [°C]	Calorific value [MJ·kg^{-1}]	Heat of vaporization [kJ·kg^{-1}]
Methanol	795.6	107	91	64.7	19.9	1100
Bioethanol	793.2	108	92	78.3	26.8	910
Butanol	810	105.1	96 [15]	117	35.69	683
Gasoline 95	720-775	95	min. 85	215	410	380

Bioethanol is considered a renewable fuel, most commonly produced through the process of alcoholic fermentation from plant-based raw materials such as corn, sugar beets, grains, or sugarcane (*Smuga, 2011; Bedyk & Oleksiak, 2002*). This technology is well established and widely accessible. However, concerns have been raised about the use of food-grade crops for biofuel production, as it may contribute to global food shortages. Therefore, increasing attention is being given to the production of so-called second-generation bioethanol from waste materials, including wood (especially from fast-growing trees), straw, cellulose industry residues, and even municipal waste. Nevertheless, second-generation bioethanol still represents a small share of overall production (*Smuga, 2011*).

Butanol can be produced by three main methods: fermentation (using grains, resulting in a mixture of ethanol, butanol, and acetone, which is then distilled), carbonyl synthesis (via gasification of coke and subsequent reaction of carbon monoxide and hydrogen), and aldol condensation followed by hydrogenation—both chemical methods require the use of catalysts (*HaoFei Chemical, 2024*). Butyl alcohol is a colorless liquid with a specific odor, a lower density compared to water, and is highly flammable and explosive. In recent years, there has been growing interest in the use of biobutanol and bioethanol as alternative fuels for internal combustion engines. Research indicates that due to its physicochemical properties, biobutanol can be a beneficial additive to diesel fuel; however, careful selection of blend proportions is necessary due to its impact on fuel parameters (*Hönig et al., 2015*). Literature reviews concerning higher alcohols, such as propanol and butanol, emphasize their superior combustion performance and lower emissions compared to methanol and ethanol, making them promising candidates for engine applications (*Sharma et al, 2019*). The application of bioethanol in spark-ignition engines has been thoroughly examined with respect to CO and HC emissions—studies have shown that ethanol-gasoline blends can significantly reduce these pollutants (*Iodice & Cardone 2021*). Other studies have focused on the influence of bioethanol on combustion parameters such as cylinder pressure, thermal efficiency, and emission of harmful compounds—these effects are generally positive, although dependent on blend ratios (*Thangavelu et al, 2016*). Alcohols from the first three families (methanol, ethanol, butanol) have been analyzed in terms of efficiency, combustion, and emissions in SI engines—with butanol showing the most favorable properties (*Abdullah et al 2023*). Reviews of higher alcohols and biodiesel usage have confirmed their potential for reducing NOx, CO, and HC emissions (*Erdiwansyah et al, 2019*). More recent research supports the viability of bioalcohols as low-emission fuels in CI engines, highlighting their positive effects on combustion and emissions (*Tanwar et al 2023*). Butanol is characterized by better miscibility with diesel fuel compared to ethanol and methanol, making it more practical for diesel blending (*Kumar et al, 2013*). The literature also indicates growing interest in RCCI and PCCI engine technologies utilizing higher alcohols, which may simultaneously improve efficiency and reduce particulate matter and NOx emissions (*Hua, 2024*). Comparative studies show that primary alcohols (methanol, ethanol, n-butanol) positively affect soot and CO emissions in dual-fuel modes (*Ning et al, 2020*). Computer simulations demonstrate that alcohol-gasoline blends reduce CO and HC emissions, although engine power may decrease (*Iliev, 2021*). Studies involving tall oil and alcohol blends (including n-butanol) have shown reductions in CO emissions and smoke opacity, accompanied by increases in HC and NOx emissions (*Özer, 2020*). Further research has revealed that the addition of n-butanol to natural gas in dual-fuel engines improves combustion dynamics and enables reductions in THC and NOx emissions (*Chen et al, 2019*). The topic of the possibility of using a mixture of traditional petrol and bioethanol in terms of selected parameters and performance of compression-ignition engines was also discussed (*Zastempowski 2025*), and in particular the need for monitoring of the growth of pollutants and the changes that occur in the case of additives (*Michalides et al, 2023*) also from the point of view of the atomic emission spectrometer (*Hujo et al, 2022*). The variety of research procedures and experimental conditions makes it difficult to directly compare the obtained results, a phenomenon also observed in other fields of engineering (*Aleksandrowicz, 2020*). Finally, n-butanol has been recognized as a competitive second-generation biofuel—its combustion characteristics, engine performance impact, and emissions profile make it a superior alternative to conventional biofuels (*Jin et al 2011*).

MATERIALS AND METHODS

Mixtures of ethyl and butyl alcohol in varying proportions were used in the study. These mixtures can serve as alternative fuels for internal combustion engines, based on renewable sources. The evaluation focused on mixtures with different butanol and ethanol ratios, assessing their average calorific value and the mass of residue remaining after combustion, with the goal of identifying the most favorable blend composition.

The research hypothesis assumed that mixtures of ethyl and butyl alcohol could represent a viable alternative to conventional fuels, under the assumption that each blend would have a distinct calorific value. The objective was to identify the mixture that achieved the best results in the conducted experiments.

The study utilized samples of ethyl and butyl alcohol mixtures. The proportion of individual alcohols was expressed in weight ratios. The tested alcohols had a purity grade classified as "pure," containing 99.00–99.9% of the pure component. Both the stock and prepared samples were stored in tightly sealed bottles at a temperature not exceeding 8°C. After preparing the mixtures, bulk density was measured by weighing a volume of 190–250 cm^3. Each measurement was repeated five times.

The types of mixtures (percentage composition by weight) and the results of bulk density measurements are presented in Table 2.

Tab. 2 Bulk density of the tested bioethanol–butanol mixtures

Fuel composition	Component ratio	Bulk density [kg·m^{-3}]
Bioethanol	100%	782.00
Bioethanol + Butanol	70 + 30%	791.05
Bioethanol + Butanol	50 + 50%	789.01
Bioethanol + Butanol	30 + 70%	790.53
Butanol	100%	802.00

The KLMn 12 calorimeter was used for the study. The test setup is shown in Figure 1.

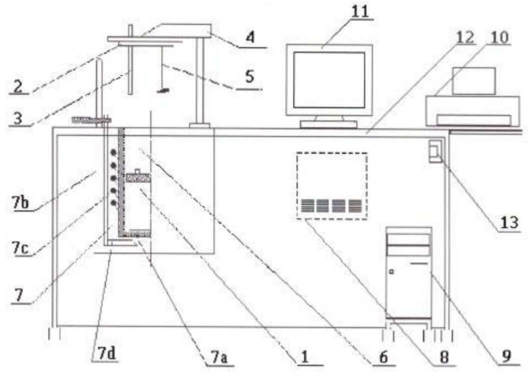

Fig. 1 Diagram of the test setup: 1 – calorimeter bomb, 2 – calorimeter lid, 3 – temperature sensor, 4 – lid holder with integrated drive for the mechanical stirrer, 5 – mechanical stirrer, 6 – calorimetric vessel, 7 – calorimeter jacket consisting of: 7a – inner wall, 7b – outer wall, 7c – coil, 7d – manual stirrer, 8 – calorimeter control unit, 9 – computer, 10 – printer, 11 – computer monitor, 12 – calorimeter table, 13 – power strip with switch [9].

The bulk density of butanol is slightly higher; the variations follow an irregular pattern.

The calorific value was tested for all fuel types with five repetitions. The tested samples were stored at a temperature of approximately 8°C.

Fuel samples (approximately 1 g) were placed in quartz crucibles, which were weighed before each measurement. To avoid contamination from residues, each crucible was used only once. The ignition wire was also weighed. The crucible containing the fuel was immediately placed in the calorimetric bomb, and a fragment of the wire was immersed in the fuel. The bomb was then tightly sealed and filled with oxygen at a pressure of 500 hPa. The bomb was placed in a water bath, and the ignition leads were connected. After the bomb was connected, the control software was launched, containing the mass of each sample, bomb number, and the sample identification with repetition number. Once the temperatures of the calorimetric bomb and the water bath stabilized, fuel ignition occurred. The temperature change over time was recorded automatically, and after the combustion process and the subsequent heat transfer had ended, the system registered the total heat released. At the end of each cycle, the bomb was opened and the crucible with the remaining ash was weighed. The tests were repeated five times for each type of fuel. The average values obtained are presented in Table 3.

Tab. 3 Average calorific values and residue mass

Fuel		Average calorific value [$kJ \cdot kg^{-1}$]	Average residue mass [$g \cdot kg^{-1}$]
Bioethanol	100%	27425.3	0.089
Bioethanol + Butanol	70 + 30%	29866.3	0.271
Bioethanol + Butanol	50 + 50%	32009.7	0.489
Bioethanol + Butanol	30 + 70%	33301.3	0.454
Butanol	100%	34712.3	0.154

The obtained results were subjected to statistical analysis using the STATISTICA software.

RESULTS AND DISCUSSION

As a result of the conducted research, it was found that the mass of residue remaining after the combustion of fuel samples in an oxygen atmosphere varies. The highest residue mass was recorded for the fuel containing 50% bioethanol and 50% butanol. The lowest residue mass was obtained from the combustion of 100% bioethanol. In the case of 100% butanol, the residue mass was also very low, although higher than that of bioethanol. The results indicate that mixing alcohols leads to an increase in residue mass. This may be caused by disturbances in the combustion process of the mixture. The differences in residue mass values were statistically significant (p = 0.05).

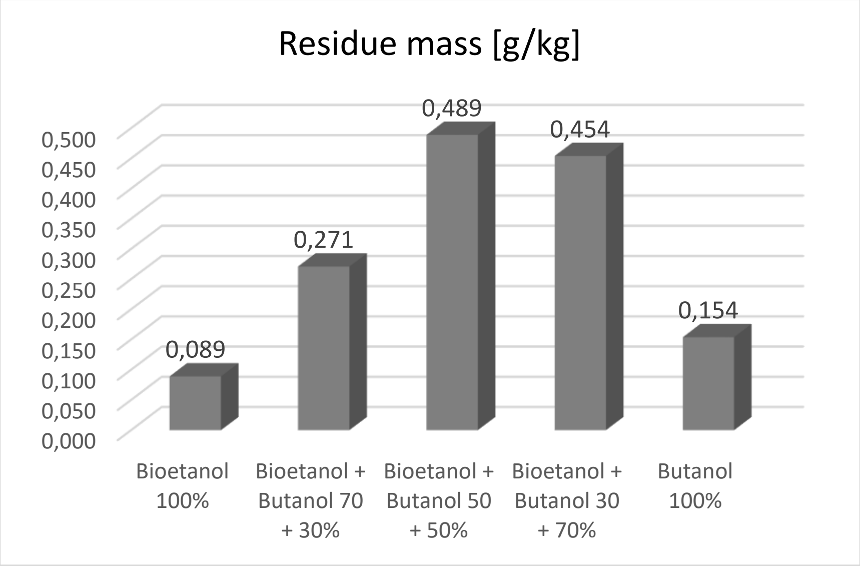

Fig. 2 Residue mass depending on fuel composition

The calorific value of the fuels changed linearly, increasing with the rising proportion of butanol in the fuel.

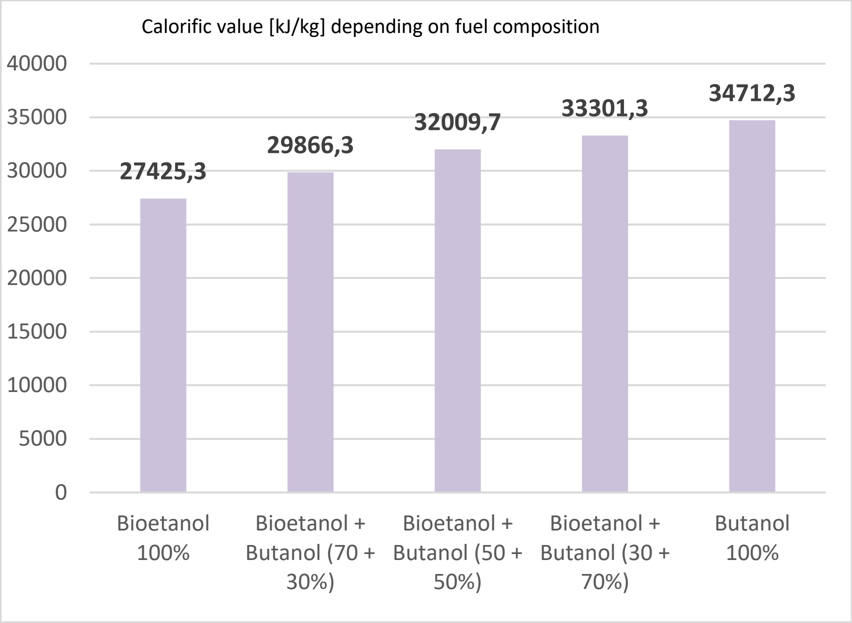

Fig. 3 Calorific value depending on fuel composition

CONCLUSIONS

Based on the conducted research on the suitability of ethyl and butyl alcohol blends, it can be concluded that the search for alternatives to conventional fuels is progressing in the right direction. Alcohol-based fuels can be produced in a significantly more environmentally friendly manner, and the exhaust emissions from such fuels are much less harmful to the environment compared to, for example, gasoline. Alcohol blends could potentially be used in spark-ignition engines.

1. Alcohols possess characteristics that allow their use as fuels for spark-ignition engines. Their calorific values are comparable to those of fossil fuels.
2. Based on the analysis of combustion residues, it can be observed that the use of fuels with varying alcohol ratios is more advantageous, as these mixtures produce lower ash content.
3. To obtain a complete picture of the suitability of alcohols for engine fueling, further research is necessary—particularly in determining octane numbers and conducting engine tests to assess combustion behavior.
4. It is also recommended to carry out exhaust gas composition analysis in engines powered by alcohol blends.

The research conducted by the authors confirms that bioethanol–biobutanol blends can represent a promising alternative to conventional fuels used in spark-ignition internal combustion engines. It was demonstrated that increasing the proportion of butanol in the blend leads to a linear increase in calorific value—from 27.43 MJ·kg^{-1} for pure bioethanol to 34.71 MJ·kg^{-1} for pure biobutanol-while simultaneously increasing the combustion residue mass, particularly for the 50:50 blend. These results are consistent with trends reported in the literature, indicating the favorable energy characteristics of higher alcohols (*Sharma et al., 2019; Abdullah et al., 2013; Tanwar et al., 2023*), although they do not always fully align with the values reported by other researchers.

For pure ethanol, the obtained calorific value (27.42 MJ·kg^{-1}) was close to the value reported by Haynes (~27.00 MJ·kg^{-1}) (*Haynes, 2015*), but notably lower than the 29.7 MJ·kg^{-1} reported by Martinka et al. (2019). Similar discrepancies were observed for butanol-the result of 34.71 MJ·kg^{-1} differed slightly from the values of 35.6 MJ·kg^{-1} and 34.92 MJ·kg^{-1} obtained by Antoni et al. (2007). It should be emphasized, however, that direct comparison of results from different studies is subject to significant uncertainty due to variations in experimental procedures, types of equipment, purity of the tested samples, as well as differing environmental conditions during measurements.

REFERENCES

1. Abdullah, M., Yusop, A., Mamat, R., Hamidi, M., Sudhakar, K., & Yusaf, T. (2023). Sustainable biofuels from first three alcohol families: A critical review.
2. Aleksandrowicz, P. (2020). Modeling head-on collisions: The problem of identifying collision parameters. *Applied Sciences, 10*(18), 6212. https://doi.org/10.3390/app10186212
3. Antoni, D., Zverlov, V., & Schwarz, W. H. (2007). Biofuels from microbes. *Applied Microbiology and Biotechnology, 77*(1), 23–35. https://doi.org/10.1007/s00253-007-1163-x
4. Bedyk, I., & Oleksiak, S. (2002). Biofuels in the European Union – promotion and conditions. *Paliwa, Oleje i Smary w Eksploatacji*, (101).
5. Chen, Z., Wang, L., & Zeng, K. (2019). A comparative study on the combustion and emissions of dual-fuel engine fueled with natural gas/methanol, natural gas/ethanol, and natural gas/n-butanol.
6. European Parliament and Council. (2009). *Directive 2009/30/EC of the European Parliament and of the Council*. Retrieved January 5, 2024.
7. Erdiwansyah, M., Mamat, R., Sani, M., Sudhakar, K., Kadarohman, A., & Sardjono, R. (2019). An overview of higher alcohol and biodiesel as alternative fuels in engines.
8. HaoFei Chemical. (2024). Butanol production process. Retrieved January 6, 2024.
9. Haynes, W. M. (2015). *Handbook of chemistry and physics* (96th ed., p. 2677). CRC Press.
10. Hönig, V., Smrčka, L., Ilves, R., & Küüt, A. (2015). Adding biobutanol to diesel fuel and impact on fuel blend parameters.
11. Hujo, Ľ., Janoušková, R., Simikić, M., Zastempowski, M., Michalides, M., & Hajdáková, M. (2022). Characteristics of ecological energy carriers used in agricultural technology. *Processes, 10*(9), 1895. https://doi.org/10.3390/pr10091895
12. Hua, Y. (2024). Research progress of higher alcohols as alternative fuels for compression ignition engines.
13. Iliev, S. (2021). A comparison of ethanol, methanol, and butanol blending with gasoline and its effect on engine performance and emissions using engine simulation.
14. Iodice, P., & Cardone, M. (2021). Ethanol/gasoline blends as alternative fuel in last generation spark-ignition engines: A review on CO and HC engine-out emissions.
15. Jin, C., Yao, M., Liu, H., Lee, C., & Ji, J. (2011). Progress in the production and application of n-butanol as a biofuel.
16. Martinka, J., Rantuch, P., & Wachter, I. (2019). Impact of water content on energy potential and combustion characteristics of methanol and ethanol fuels. *Energies, 12*(18), 3491. https://doi.org/10.3390/en12183491
17. Michalides, M., Čorňák, Š., Jelínek, J., Janoušková, R., Hujo, Ľ., & Nosian, J. (2023). Degradation of ecological energy carriers under cyclic pressure loading. *Applied Thermal Engineering, 26*, 173–179. https://doi.org/10.2478/ata-2023-0023
18. Nafta-Gaz. (2020). Potencjał użytkowo-eksploatacyjny butanolu jako paliwa alternatywnego do zasilania silników ZI [Utility-exploitation potential of butanol as an alternative fuel designed for car SI engines] (Z. Stępień). *Nafta-Gaz, 76*(2), 126–135. https://doi.org/10.18668/NG.2020.02.07
19. Ning, L., Duan, Q., Chen, Z., Kou, H., Liu, B., Yang, B., & Zeng, K. (2020). A comparative study on the combustion and emissions of a non-road common rail diesel engine fueled with primary alcohol fuels (methanol, ethanol, and n-butanol)/diesel dual fuel.
20. Özer, S. (2020). The effect of diesel fuel–tall oil/ethanol/methanol/isopropyl/n-butanol/fusel oil mixtures on engine performance and exhaust emissions.
21. Precyzja – BIT. (n.d.). *KL-12Mn calorimeter user manual.*
22. Sharma, R., Kumar, D., Chhabra, M., & Dwivedi, G. (2019). Analysis of higher alcohol fuel blends for IC engine—A review.
23. Smuga, M. (2011). Innovative methods of obtaining second-generation bioethanol as fuel. *Autobusy*, (5).
24. Tanwar, M., Torres, F., Alqahtani, A., Tanwar, P., Bhand, Y., & Doustdar, O. (2023). Promising bioalcohols for low-emission vehicles.
25. Thangavelu, S., Ahmed, A., & Ani, F. (2016). Review on bioethanol as alternative fuel for spark ignition engines.
26. VMC. (2024). Composition of gasoline and diesel oils – production methods. Retrieved January 8, 2024.

27. Zakrzewski, B. (2016). Application of wood gas for powering car engines on the example of the Dodge Command WC 56 vehicle. *Autobusy*, (4).
28. Zastempowski, M., Kaszkowiak, J., Jablonicky, J., Hujo, L., & Gromnicki, M. (2025). Effect of using gasoline with bioethanol on power, torque and selected exhaust gas components: Case study of a small spark-ignition outboard engine. *Polish Maritime Research, 32*(1/125), 95–102. https://doi.org/10.2478/pomr-2025-0009.

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