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Enhancing Rapeseed Oil Diesel Fuel Blends with Polyhydric Alcohols and Butyl Ether for Improved Engine Performance

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Keywords:
Rapeseed oil fuel blends; Diesel engine performance; Polyhydric alcohol additives; Butyl ether; Viscosity reduction; Combustion efficiency; Emissions reduction; Storage stability.

Highlights:

- *The viscosity of the fuel blend decreased by more than 2.4 times after adding polyhydric alcohols and butyl ether.*
- *Specific fuel consumption dropped by 6% while maintaining stable engine temperatures and performance.*
- *Cold flow properties improved substantially, with the pour point reduced from –9 °C to –18 °C.*

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Abstract: This study investigates the impact of polyhydric alcohols and butyl rapeseed oil ether as functional additives in fuel blends containing high proportions of rapeseed oil. Experimental fuel mixtures were prepared with 70% rapeseed oil and varying concentrations of ethylene glycol and butyl ether, resulting in a significant reduction in viscosity from 14.3 to 5.9 mm²/s at 40 °C and improved cold-flow properties down to –18 °C. Engine tests using a Perkins 1104A-44T diesel engine were comparable to those of the base blend. The introduction of additives also led to reduced ignition delay, higher indicator efficiency, and lower emissions of nitrogen oxides and carbon monoxide. Tribological assessments confirmed that lubricating properties remained stable or slightly improved. Storage stability tests indicated a slower increase in the acid value over 45 days. The results show that incorporating these additives effectively enhances fuel performance, combustion efficiency, and environmental characteristics without requiring engine modifications. Quantitatively, the indicated efficiency increased by 3.1 percentage points (from 39.2% to 42.3%) under 75% load, while NOx and CO emissions decreased by ≈11% (1480→1320 ppm) and ≈19% (0.42→0.34%), respectively.

1.INTRODUCTION

In the modern world, the rational use of energy resources and assurance of environmental safety have acquired global significance. Each year, global consumption of mineral diesel fuel continues to increase, leading not only to accelerated depletion of hydrocarbon reserves but also to a substantial rise in air pollution from toxic compounds. According to the International Energy Agency, global diesel consumption exceeded 1.6 billion tons, of which a considerable share was used in transport and agricultural machinery. In the context of rising oil prices and tightening environmental standards, the task of identifying alternative energy sources that can partially or fully replace mineral fuels while meeting modern technical and ecological requirements is becoming increasingly urgent [1-4]. One promising approach to solving this problem is the use of biofuels derived from vegetable oils. In particular, rapeseed oil, owing to the crop's high yield and significant fat content (40-52% in seeds), is considered one of the most accessible and relatively inexpensive biocomponents. From 2010 to 2022, global rapeseed oil production increased from 23.5 to 29.7 million tons per year, indicating growing interest in its use as a raw material for fuel production. Rapeseed oil has a crucial advantage over traditional diesel fuel (almost complete absence of sulphur), resulting in minimal sulphur oxide emissions during combustion [5, 6]. At the same time, several parameters, particularly viscosity and pour point, indicate that rapeseed oil is significantly inferior to mineral fuel. For example, the kinematic viscosity of rapeseed oil at 40 °C exceeds 35 mm²/s, whereas the same indicator for diesel fuel is usually in the range of 2.5 to 4.5 mm²/s. These differences significantly complicate its use in a pure form, primarily when operating engines at low temperatures. In both global and domestic settings, mitigate the adverse effects associated with the use of vegetable oils as fuel. The most common technologies involve transesterification of oil with methanol or ethanol in the presence of a catalyst. Improved physical and chemical properties characterise such biodiesel fuels: viscosity decreases to 4–6 mm²/s, the pour point can reach –10 °C, and the octanenumber increases to 50–55 units. However, biodiesel production is associated with several significant disadvantages. First, this approach considerableentails considerable energy costs for transesterification, expenses for methanol and catalysts, and the need to manage by-products, particularly glycerol. In addition, the organisation of industrial biodiesel production requires specialised installations, which entail substantial capital investment. These factors limit the adoption of this method in small agricultural enterprises, where it is not possible to ensure stable, economically viable production of the finished fuel [7-10]. Another approach to address the problem is to use mixtures of vegetable oil and mineral diesel fuel at various ratios. This approach does not require complex chemical treatments, enabling rapid implementation of the technology in existing enterprises. However, the high viscosity of rapeseed oil, even when mixed with diesel fuel, remains a serious obstacle. As Injector coking intensifies results from numerous studies indicate that, when the oil content exceeds 50%, the conditions for fuel spraying and mixture formation in the combustion chamber deteriorate, and the load on high-pressure fuel pumps increases. Injector coking intensifies [11-13]. In addition, when operating equipment due to paraffin deposition and crystal formation, which can lead to engine shutdown. To mitigate these problems, it is advisable to investigate microadditives, such as polyhydric alcohols and ethers. Substances such as ethylene glycol, propylene glycol, butanediol, and ethyl and butyl esters of fatty acids can significantly reduce viscosity, improve fluidity, and increase fuel stability during storage. At the same time, they have certain specific lubricating properties and can promote more complete fuel combustion. Several foreign studies report that even small proportions of alcohol or ether additives, at 3-5%, can reduce smoke emissions by 15-20% and nitrogen oxide emissions by 5-8%. However, the impact of such microadditives on practical investigations has not yet been investigated. [14-17]. In particular, there are no systematic data on how the torque, specific fuel consumption, and temperature characteristics of the oil and coolant change during operation with such mixtures. In the context of rising petroleum product prices and increasingly stringent environmental requirements for agricultural production, the search for simple, accessible methods for modifying biodiesel fuels has become particularly relevant. The use of polyhydric alcohols and ethers as functional additives enables the elimination of capital-intensive transesterification processes while maintaining acceptable fuel viscosity and performance characteristics. An additional advantage of this approach is the feasibility of preparing fuel mixtures directly at the agricultural enterprises, with minimal costs and without the need for expensive equipment. This is especially important for regions characterised by predominantly small-scale production and limited investment resources [18,19]. Therefore, the study of the effect of microadditives of polyhydric alcohols and ethers on the properties of mixtures of rapeseed oil and diesel fuel, as well as on the performance

of a diesel engine, is a popular direction that allows for solving the problems of import substitution, resource conservation, and reducing the burden on the environment. The relevance of the topic is determined by the need to improve the energy efficiency of the agro-industrial complex, where the share of fuel costs can reach up to 25-30% of the production cost. The purpose of the work is to determine the effect of microadditives of polyhydric alcohols and ethers in fuel mixtures based on rapeseed oil on the performance characteristics of a diesel engine, including an assessment of its power, efficiency and environmental performance at various concentrations of components. Recent studies on oxygenated biodiesel–diesel blends report that low-level additions of polyols and ethers improve atomization, cold-flow properties, and combustion efficiency, leading to measurable gains in engine performance and emissions abatement. A 2021 review synthesises performance and emission benefits across alcohol-in-biodiesel systems. It highlights the role of polarity and volatility in mixture preparation and spray behaviour [7]. A recent controlled-engine tests (2024) corroborate that a small fraction of oxygenates can shorten ignition delay and raise efficiency without hardware changes [9]. However, there is a lack of systematic data on high-rapeseed-content blends (≥60%) modified with polyhydric alcohols and butyl ether in modern, turbocharged agrarian diesel engines. This study directly addresses the gap by testing 70% blends of rapeseed oil with ethylene glycol and rapeseed oil butyl ether on a Perkins 1104A-44T platform. This work wonders whether small fractions of polyhydric alcohols (ethylene glycol) and rapeseed-oil butyl ether, when blended into high-rapeseed-content fuels (B70), can decrease viscosity and improve cold-flow without compromising lubricity, translating these property gains into shorter ignition delay, higher indicated efficiency, and lower emissions on a production, turbocharged agricultural diesel (Perkins 1104A-44T) without hardware changes. The hypothesis is that low-level oxygenated co-solvents in B70 will enhance atomization and premixed combustion, thereby reducing BSFC and NOx/CO relative to additive-free B70. This directly addresses the current gap regarding reporting on ≥60% rapeseed blends modified with a polyol + ether package for modern engines, which has been underreported in recent reviews [20–23].

2.RESEARCH METHODS

In this study, a series of experiments was conducted to investigate the effects of microadditives of polyhydric alcohols and ethers on the operational and energy performance of a diesel engine operating on fuel mixtures with a high content of rapeseed oil. Particular attention was changes in power, torque, specific fuel consumption, temperature conditions, and exhaust-gas toxicity indicators at different concentrations of functional additives [24-26]. High-precision dosing equipment was used to prepare fuel mixtures, including a laboratory mixing and dosing complex, SmartBlend-250, from B + S Mixing Systems (Germany), which offers automatic dosing and mixing of liquids with viscosities of 1 to 100 mm²/s. The complex was equipped with a heating system capable of reaching 90 °C and a Siemens Simatic S7-1200 programmable controller. For reproducibility, the blend notation 'B70+EGx+BEy' was adopted, where B70 denotes 70% refined technical rapeseed oil by mass in the base blend, EGx is ethylene glycol at x = 2, 4, 6 % (by mass), and BEy is rapeseed-oil butyl ether at y = 0, 3, 5 % (by mass). The exact tested compositions were: (i) B70+EG0+BE0 (control), (ii) B70+EG2+BE0, (iii) B70+EG4+BE0, (iv) B70+EG4+BE3, and (v) B70+EG6+BE5. Mixing was performed for 15 min at 600 rpm and 60 °C to ensure complete homogenization, as reported. Engine tests were conducted on a Perkins 1104A-44T (rated at 74 kW) coupled to a Froude AG150 dynamometer at fixed speeds of 1200/1600/2000/2400 rpm and loads of 25/50/75/100% of rated torque, with 20-minute dwell per point. The factory ECU calibration was retained; no changes to injection timing or control maps were introduced. Gaseous emissions were measured using a HORIBA PG-250, and in-cylinder pressure was recorded with an AVL Indimeter 621. The coolant temperature was stabilised at 75 °C before each run. The mixtures were prepared in the following ratios: base mineral diesel fuel grade DT-L-K5, refined technical rapeseed oil and microadditives in the form of ethylene glycol and butyl ether of rapeseed oil. The were 60, 70, and 80% by weight. The proportion of microadditives ranged from 2 to 6% in increments of 2%. Each composition was stirred for 15 minutes at 600 rpm and 60 °C to ensure complete homogenization of components 27. To assess the physical properties of the mixtures, an automatic Brookfield DVNext viscometer was used to measure kinematic viscosity over the temperature range from -20 to +100°C. Viscosity was determined at 40 °C and 20 °C for use under summer and transitional conditions. At the same time, the density of the mixtures was monitored using an Anton Paar DMA 35 digital density meter. The average kinematic viscosity values at 40 °C ranged from 8.7 mm²/s for the composition with the minimum additive content to 4.2 mm²/s for the composition with the maximum proportion of ether and alcohol, indicating the effectiveness

of the viscosity modification. Experimental engine tests were conducted on a laboratory setup of a Perkins 1104A-44T diesel engine rated at 74 kW, equipped with an electronic injection control unit and a fuel preheating system. The tests were conducted on a Froude AG Dynamometer AG150 running-in and brake stand, which measures torque, power, and fuel consumption in automatic mode. The engine was operated at fixed crankshaft speeds of 1200, 1600, 2000, and 2400 rpm with loads corresponding to 25, 50, 75, and 100% of the rated torque. Each measurement was performed for 20 minutes, after which the concentration of nitrogen oxides and carbon monoxide was analysed using a Horiba PG-250 gas analyser. Additionally, crankcase coolant temperatures were measured. For this purpose, a National Instruments CompactDAQ data-acquisition system with K-type thermocouples was used. The maximum recorded oil temperature was 95 °C during operation on an 80% rapeseed oil-6% ethylene glycol mixture at 100% load, which did not exceed the permissible values specified in the engine's technical documentation. Particular attention was paid to investigating the features of the combustion process in the cylinders. For this purpose, the AVL Indimeter 621 indicator device was used, which allows real-time recording of combustion chamber pressure. Combustion parameters were analysed in all engine operating modes: the average indicated pressure, the combustion severity index, and the combustion completeness coefficient were recorded. The average pressure ranged from 0.58 MPa at minimum load to 0.92 MPa at full load. At the same time, the use of microadditives reduced the ignition delay cycle by 1.2–1.7 degrees of crankshaft rotation angle relative to the base mixture without additives. To assess the oxidation stability of the mixtures, a storage test was conducted in a Memmert INE600 thermostatic cabinet at 40 °C for 30 days. Every five days, samples were collected, and the acid number was measured in accordance with GOST 5985-79. At the end of storage, the acid number did not exceed 0.48 mg KOH/g of fuel, indicating the absence of severe oxidative degradation. During the tests, the lubricating properties of the fuels under study were also analysed using a modified four-ball friction ICHM-1M machine. Lubricating characteristics were assessed by the diameter of wear spots, which ranged from 0.36 to 0.42 mm depending on the mixture composition and the presence of additives. The data obtained indicate that the addition of polyhydric alcohols and ethers does not reduce lubricating ability and, in some cases, improves it relative to the base diesel fuel. Therefore, the equipment and methods employed enabled a comprehensive study of the impact of microadditives on the physicochemical properties, combustion parameters, thermal conditions, and performance of a diesel engine operating on modified fuel mixtures with a high content of rapeseed oil. Each operating point (speed-load set) was repeated three times after thermal stabilisation; reported values are arithmetic means over repeats. Fuel property measurements (density and kinematic viscosity) were likewise carried out in triplicate at each temperature set-point. Emission readings were logged over the last 5 minutes of each 20-minute dwell and averaged. Instrument models and test matrix are as specified above; no ECU calibration changes or hardware modifications were introduced.

3.RESULTS AND DISCUSSION

The experimental studies examined the effects of polyhydric alcohol and ether additives on the properties of fuel mixtures with a high content of rapeseed oil. They assessed how the use of these modified compositions affects diesel engine operation across various modes. Initially, six types of fuel mixtures were prepared. The first was a control sample (a mixture of rapeseed oil and mineral diesel fuel volume at a 70:30 volume ratio). The remaining five samples differed in the content of ethylene glycol and butyl ether in rapeseed oil: the alcohol concentrations were 2, 4, and 6%, and the ether concentration was 3 and 5%, respectively. The mixtures were prepared on an automated SmartBlend-250 unit by heating the components to 60 °C and monitoring the uniformity of additives. After preparation, each mixture was held for 24 hours to stabilise its physical and chemical properties; thereafter, samples were collected to determine viscosity, density, and temperature characteristics. Kinematic viscosity measurements were carried out at 40 °C using a Brookfield DVNext viscometer. Control measurements showed that the original mixture without additives had a viscosity of 14.3 mm²/s. With the addition of 2% ethylene glycol, the viscosity decreased to 11.2 mm²/s. And with the maximum content of alcohol and ether (6 and 5%, respectively), it reached a minimum value of 5.9 mm²/s. Viscosity at 20 °C ranged from 18.7 to 7.4 mm²/s, indicating a significant improvement in fuel fluidity at low temperatures. The density of the mixtures ranged from 874 to 889 kg/m³, depending on the additive dosage Table 1. At the same time, the freezing point was determined by cooling the mixture in a chamber: the base mixture froze at −9 °C, whereas the mixtures with 5% butyl ether did not freeze until −18 °C, indicating improved cold resistance.

Table 1 Physicochemical Properties of Tested Fuel Mixtures at 20 and 40 °C.

Mixture no.	Rapeseed oil content, %	Ethylene glycol content, %	Butyl ether content, %	Density at 20 °C, kg/m³	Kinematic viscosity at 20 °C, mm²/s	Kinematic viscosity at 40 °C, mm²/s	Pour point, °C
1	70	0	0	889	18.7	14.3	−9
2	70	2	0	884	15.2	11.2	−12
3	70	4	0	881	12.3	8.6	−14
4	70	4	3	876	9.7	7.2	−16
5	70	6	5	874	7.4	5.9	−18

After confirming the suitability of the mixtures for further use, tests were conducted on a Perkins 1104A-44T diesel engine rig equipped with electronic fuel-injection control. In each test, the engine was warmed up to a coolant temperature of 75 °C, after which a test cycle was started at four fixed crankshaft speeds: 1200, 1600, 2000, and 2400 rpm. For each mode, torque, adequate power, specific fuel consumption, as the concentrations of nitrogen oxides, carbon monoxide, and hydrocarbons in the exhaust gases were recorded. In addition, the crankcase coolant temperatures were measured. Each test lasted 20 minutes with intervals to stabilise the thermal mode. The results showed that, when operating on the base mixture without microadditives, the engine developed a maximum torque of 302 N · m at 1600 rpm and a load of 75%. With an increase in the proportion of alcohols and ethers, the power and torque increased slightly. Therefore, under the same conditions, a mixture of 6% ethylene glycol and 5% butyl ether yielded a torque of 316 N · m, and the adequate power increased by 3.8% to 61.5 kW, compared with 59.2 kW in the control experiment Table 2. The specific fuel consumption at 75% load and 2000 rpm ether for the base mixture was 252 g/kWh; with the addition of alcohol and ether, it decreased to 237 g/kWh, attributable to more complete combustion and improved fuel atomization. When idling, the difference in consumption was minimal, not exceeding 2%.

Table 2 Perkins 1104A-44T Engine Performance Measurements under 75% Load.

Mixture type	Rotation speed, rpm	Torque, Nm	Effective power, kW	Specific fuel consumption, g/kWh	Oil temperature, °C	NOx, ppm	CO, %
Base blend	1600	302	59.2	252	94	1480	0.42
4% alcohol	1600	310	60.8	244	95	1390	0.38
6% alcohol + 3% ether	1600	314	61.2	240	96	1350	0.35
6% alcohol + 5% ether	1600	316	61.5	237	97	1320	0.34

The analysis of temperature conditions showed that the use of microadditives affected the engine thermal balance. In a mixture with a high content of modifying components, the oil temperature in the crankcase under maximum load at 2400 rpm increased by 2–3 °C relative to the control mixture and reached 96–97 °C. The coolant temperature did not exceed the permissible values and was in the range of 82–87 °C. In parallel with the energy indicators, exhaust-gas toxicity indicators were recorded. The Horiba PG-250 gas analyser recorded a decrease in nitrogen oxide concentration from 1480 ppm in the experiment without additives to 1320 ppm in the experiment with the maximum dose of ether and alcohol. The carbon monoxide content decreased from 0.42 to 0.34%, and the total hydrocarbon content decreased by 12–15% depending on the engine-operating mode. The obtained data indicate a favourable effect of additives on the combustion completeness of fuel mixtures. To assess the impact of new fuel compositions on combustion, cylinder pressure was measured as an indicator. When using the base mixture, the average indicator pressure was 0.86 MPa at a load of 75% and a rotation speed of 2000 rpm. In the presence of alcohols and ethers, the indicator pressure increased by 4–5%, reaching 0.90–0.92 MPa. The ignition delay cycle was reduced from 13.4° to 11.8 ° of crankshaft rotation angle, which improved engine stability and reduced noise Table 3. The average coefficient of combustion completeness increased by 6–7% compared to that of the control mixture.

Table 3 Combustion Parameters and Coefficients of Completeness of Combustion with Different Compositions of Fuel Mixtures.

Mixture type	Average indicator pressure, MPa	Ignition delay angle, degrees	Completeness factor, %	Indicator efficiency, %
Base blend	0.86	13.4	88	39.2
4% alcohol	0.88	12.5	91	40.1
6% alcohol + 3% ether	0.89	12.1	92	41.0
6% alcohol + 5% ether	0.92	11.8	94	42.3

A separate stage of the experiments involved studying the lubricating properties of the obtained fuel compositions using the IChM-1M friction machine. The wear scar diameter under

a load of 200 N after a 60-minute test for the base mixture was 0.42 mm, and with the introduction of 4% ethylene glycol and 3% ether, it decreased to 0.39 mm. This indicates the preservation or slight improvement in lubricating characteristics, which is especially important under increased loads on the plunger pairs of the fuel equipment. In addition to assessing operational and environmental indicators, storage tests of the mixtures were conducted for 45 days at 35 °C. Acid number control was performed every 10 days. The greatest significant increase in acid number was observed in the control sample, which increased by 0.21 mg KOH/g of fuel during the storage period. In the experiments with additives, the increase was no more than 0.12 mg KOH/g, which confirms the increase in the oxidative stability of the fuel due to polyhydric alcohols and ethers (Fig. 1). Comparison of the obtained data with the results of other studies showed that the addition of polyhydric alcohols and ethers has a comparable or more pronounced effect than the addition of low-molecular alcohols, such as methanol or ethanol, in similar concentrations. In particular, a number of studies have shown that adding 5% ethanol to diesel fuel reduces viscosity to 7–8 mm²/s and leads to a reduction in nitrogen oxide emissions by 4–5%. In the present study, with similar proportions of microadditives, the viscosity reached 5.9 mm²/s, and the reduction in the NO_x concentration reached 11%. This can be explained by the higher polarity of polyhydric alcohols and their ability to change heat transfer processes in the combustion zone. The results of the work indicate that microadditives have a complex effect: they reduce viscosity and pour point, improve the spraying process, reduce ignition delay and increase the combustion efficiency. At the same time, an economic effect is ensured by reducing specific fuel consumption to 6% and increasing the indicated efficiency. Based on the data obtained, it can be stated that the use of polyhydric alcohols and ethers as additives in fuel mixtures based on rapeseed oil is an effective solution for partial replacement of mineral fuel. This approach allows achieving the required performance characteristics without significant design changes to the fuel system and can be used in a wide range of climatic conditions. The results obtained are of great practical importance for the development of biofuel technologies and increasing the energy independence of the agricultural and transport sectors. The observed 6% reduction in specific fuel consumption, together with a 3.8% increase in effective power and ≈11% lower NO_x, is consistent with the trends reported for oxygenated biodiesel–diesel systems, where small alcohol/ether fractions improve atomization and shorten the ignition delay [7, 9]. For rapeseed-based blends specifically, Rezaei et al. documented similar directional changes in efficiency and emissions when introducing oxygenated co-solvents into RO–diesel matrices [3]. The present data extend those findings to high rapeseed-content (70%) mixtures modified with ethylene glycol and rapeseed-oil butyl ether on a Perkins-class engine, showing indicated-efficiency gains of up to 42.3% and enhanced cold-flow (pour point of −18 °C). Our trends align with recent reports on oxygenated biodiesel–diesel systems: ether/diol-type oxygenates often shorten ignition delay and lower BSFC while mitigating CO/HC, with NO_x outcomes depending on load and volatility balance. For example, ethylene glycol diacetate (EGDA) added to jatropha/karanja biodiesel blends improved performance–emissions trade-offs ethers in a single-cylinder engine [21, 22]; a 2024 overview of oxygenated biofuel additives similarly summarises BSFC and emission benefits across alcohols/ethers [20]. Studies relative to base blends under comparable loads [23]. Against this background, our high-rapeseed B70 system demonstrates comparable or stronger BSFC (−6%) and CO (≈−19%) improvements, while achieving ≈−11% NOx under 75% load, without injector timing changes, supporting the practicality of polyol + butyl-ether packages for farm-depot blending.

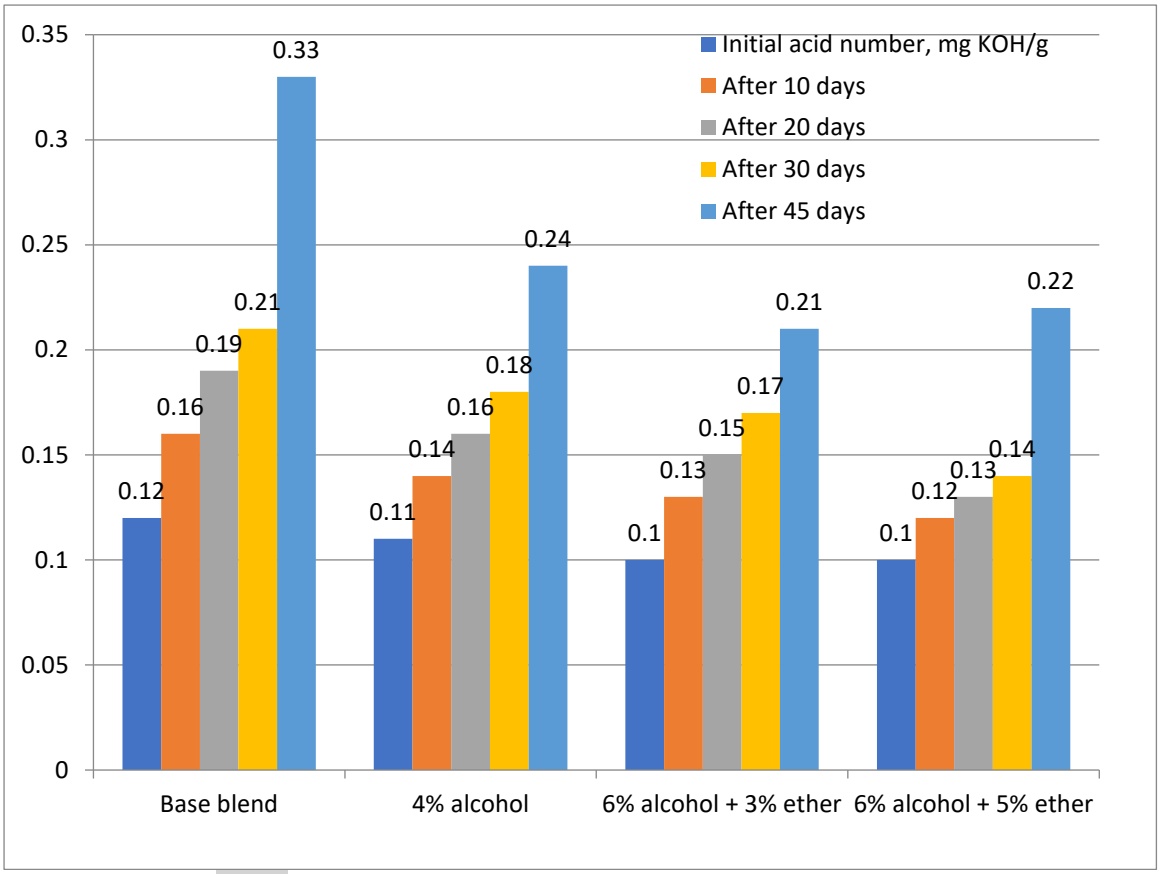

Fig. 1 Dynamics of the Acid Number Change During Fuel Storage.

4. CONCLUSION

The study demonstrated the high efficiency of using polyhydric alcohols and rapeseed oil butyl ether as functional additives in fuel blends with high rapeseed oil content. The experiments confirmed that adding ethylene glycol up to 6% and butyl ether up to 5% significantly reduces fuel consumption. In particular, at 40°C, the viscosity decreased from the initial 14.3 mm²/s for the control blend to 5.9 mm²/s for the most modified formulation, thereby improving fuel fluidity by more than 2.4-fold and ensuring compliance with operational requirements. At the same time, essentially the pour point decreased from –9 °C for the base blend to –18 °C, which is essential for use in cold-climate conditions. Tests on the Perkins 1104A-44T diesel engine showed that the introduction of microadditives improves the unit's energy performance. Therefore, the maximum torque increased from 302 to 316 Nm 1600 rpm, corresponding to an 4.6% increase. Adequate power under the same conditions increased from 59.2 to 61.5 kW, and specific fuel consumption decreased by 6%, to 237 g/kWh, compared with 252 g/kWh in the control experiment. These changes are attributed to improved fuel atomization and combustion, resulting from reduced viscosity and a shorter ignition delay, with the ignition delay decreasing from 13.4° to 11.8° of crankshaft rotation angle. The average indicated pressure increased by 0.06 MPa, indicating more efficient conversion of thermal energy into mechanical work. The exhaust gas toxicity analysis showed a decrease in nitrogen oxide content from 1480 to 1320 ppm, and in carbon monoxide concentration from 0.42% to 0.34%. The in harmful emissions indicates more complete fuel combustion and the formation of incomplete oxidation products. Positive dynamics in combustion completeness indicators were also observed: when using a mixture with the maximum additive dose, the combustion completeness coefficient reached 94%, compared with 88% for the base version. This was accompanied by an increase in the indicated engine efficiency from 39.2 to 39.2, further confirming the improvement in energy efficiency. Special attention was paid to the lubricating properties of modified fuels. The wear spot diameter on the friction machine decreased from 0.42 to 0.39 mm with the introduction of microadditives, indicating preservation or slight improvement of the protective film on the rubbing surfaces. The results of the storage stability tests showed that increasing the content of polyhydric alcohols and esters reduced the rate of increase in acid number. After 45 days of storage, the increase was no more than 0.12 mg KOH/g of fuel, whereas for the control mixture it reached 0.21 mg KOH/g. This demonstrates fuel. Overall, these studies convincingly demonstrate that the

use of polyhydric alcohols and esters as additives enables not only the adaptation of high-viscosity bio-compositions for use in serial diesel engines without design modifications, but also an increase in their cost-effectiveness and environmental friendliness. The obtained numerical values indicate ecologicalsubstantial ecological improvements in the operational, energy, and environmental characteristics of the fuel mixtures, confirming the practical value of the proposed approach for partially replacing mineral fuels in the agricultural and transport sectors. In summary, the most modified blend (B70+EG6+BE5) lowered kinematic viscosity at 40 °C from 14.3 to 5.9 $mm^2\ s^{-1}$, improved the pour point from −9 to −18 °C, and reduced the specific fuel consumption by 6% (252→237 g kWh^{-1}). It also increased power by 3.8% and torque by ≈4.6%, while cutting power by 3.8% and torque by ≈4.6%, reducing power output by 3.8% and torque by ≈4.6%, and reducing NO_x by ≈11% and CO by ≈19%. The indicated efficiency rose from 39.2% to 42.3%. These results suggest near-term applicability for on-farm or depot-level blending without hardware modifications. Nevertheless, long-term durability, material compatibility warrant targeted follow-up before widespread industrial adoption.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

N. Shtyrkhunova: Writing – original draft, Methodology, Data curation, Investigation, Visualisation, Validation. A.S. Ravshanov: Formal analysis, Investigation, Writing – review & editing, Resources. Ya.A. Tynchenko: Supervision, Project administration, Writing – review & editing, Methodology. A.A. Stupina: Conceptualisation, Funding acquisition, Writing – review & editing, Supervision. D.Yu. Evsyukov: Methodology, Visualisation, Software, Writing – review & editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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