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Evaluation of Rapeseed Oil and Methyl Ester Blends for Enhancing Environmental and Performance Characteristics of Diesel Engines

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Keywords:

Biofuel; Rapeseed oil; Diesel engine; Emissions reduction; Tractor performance; Fuel consumption; Alternative fuels; Agricultural machinery.

Highlights:

- *Using a 50% rapeseed oil blend reduced nitrogen oxide emissions by 9.3% compared to standard diesel fuel.*
- *Field tests showed only a moderate 6.5% decrease in tractor productivity despite increased biofuel content.*
- *The comprehensive performance index maintained a value exceeding 0.83, even when utilizing rapeseed methyl ester–bioethanol blends.*

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Abstract: This research presents a comparative assessment of rapeseed oil blends and Rapeseed Methyl Ester (RME) as alternative fuels, analyzing their impact on engine performance metrics, specific fuel consumption, and exhaust emission profiles in agricultural tractors. The experimental investigation employed a John Deere 6930 Premium tractor featuring a High-Pressure Common Rail (HPCR) injection system. Performance evaluations were executed under dynamic operating regimes, encompassing a broad spectrum of load and speed profiles. Results showed that blending diesel fuel with up to 50% rapeseed oil reduced nitrogen oxide emissions by approximately 9.3%, while particulate emissions increased slightly. Using rapeseed methyl ester with bioethanol further reduced NOx emissions to 4.90 g/kWh but increased unburned hydrocarbons and fuel consumption to 275 g/kWh. Field trials found that partial diesel substitution increased specific energy consumption by up to 12% and slightly reduced tractor productivity. Long-term operation of biofuel mixtures did not cause critical failures but required more frequent fuel filter maintenance. Despite a marginal decrement in the aggregate performance metric, the study validates the feasibility of rapeseed-based blends as a partial substitute for diesel. This approach sustains satisfactory engine stability while delivering significant environmental mitigation.

1.INTRODUCTION

In the modern world, the sustainable development of agricultural production is increasingly important amid global challenges related to the limited availability of traditional energy resources and the need to reduce anthropogenic impacts on the environment. As the population grows and agricultural lands expand, the load on energy infrastructure increases, leading to higher diesel consumption and, consequently, higher emissions of carbon dioxide, particulate matter, and other pollutants. According to statistics, agriculture accounts for up to 10-12% of the world's consumption of liquid hydrocarbon fuels. At the same time, more than 60% of diesel engines used in tractors and other energy-intensive machines operate under variable load conditions, which increases fuel inefficiency and environmental damage [1,2]. Such conditions create an objective need to seek alternative solutions that meet the agricultural sector's energy needs. One promising approach to mitigating environmental impacts is the use of vegetable oil-based biofuels. Among the options, rapeseed oil and its derivatives occupy the leading position, owing to their significant energy and operational advantages. The production of biofuel from rapeseed is based on relatively well-established technological cycles, including oilseed processing, oil purification, and subsequent blending with diesel fuel [3-5]. At the same time, as studies have shown, the energy income of the rapeseed oil processing technology can reach ΔE values of up to 15–18 MJ/kg, and the ηЭэ energy efficiency is about 0.65–0.75, which is quite a high figure in comparison with other alternative types of fuel. Among the advantages of biofuels are their renewability, relative environmental friendliness, and compatibility with existing engine technology without significant engine reconstruction. However, there are significant disadvantages as well. In view of this, the cost of rapeseed oil per unit of calorific value may exceed the cost of diesel by 20-30%, and the specific fuel consumption indicators often deteriorate due to the lower calorific value of the mixture, which is about 35-38 MJ/kg versus 42-45 MJ/kg for standard diesel fuel. In addition, when using biofuel, engine operating conditions change, leading to variations in the average indicator pressure and the thermal stress on components. If the mixture parameters and operating modes are incorrectly selected, the smoke from the exhaust gases and the risk of carbon deposits in the combustion chamber may increase. These features necessitate the development of methods for a comprehensive assessment of the technical level of tractors when switching to alternative fuels [6-8]. The scientific community offers various solutions to the problem. Among these, we can highlight approaches such as the full or partial replacement of diesel fuel with biofuel, the use of combustion catalysts, and modifications to fuel system parameters. Complete replacement of diesel fuel allows achieving the maximum reduction in CO2 and particulate emissions. Still, it is accompanied by a significant drop in engine power and an increase in operating costs. The partial mixing of biofuel with diesel fuel at mass fractions of 30–50% provides a compromise between reducing environmental risks and maintaining the engine's primary traction characteristics. Modifying fuel equipment and calibrating fuel supply modes can increase the degree of engine adaptation to new conditions, but require expensive testing and design modifications. Therefore, each approach has both positive aspects and obvious limitations [9-11]. Recent comparable studies further contextualise our findings. In [22], the authors showed that, relative to ULSD, rapeseed methyl ester (RME) increases BSFC and may raise NO_x under high load while lowering CO and smoke, underscoring the efficiency–emissions trade-off inherent to first-generation biodiesel [17]. Žaglinskis and Rimkus [23] quantified how blending diesel with RME and/or HVO alters engine efficiency and pollutant indices, reporting mixed NOx responses with improved soot behaviour at moderate blend ratios [18]. For ternary blends, Theinnoi et al. (2021) and Hamdi [23] reported that adding low-carbon alcohols (ethanol/pentanol) to diesel–biodiesel reduces smoke and, in some cases, NOx, albeit at the cost of higher specific consumption due to lower LHV [19, 21]. Complementarily, Chen [24] used RME–diesel blends to show that modest biodiesel shares (≤20%) can improve combustion while keeping BSFC penalties limited. They also explicitly reported measurement accuracies and uncertainty propagation, informing our error-budget approach [20]. Taken together, these works motivate the blend windows explored here and support the mixed trends we observed for NOx, HC, smoke, and BSFC. In this regard, the direction proposed in the original document is particularly relevant. The authors substantiated the need for a comprehensive assessment of the technical performance of tractors operating on alternative fuels, relying on mathematical models and algorithms that account for the relationships among operational, energy, environmental, and economic indicators. The approach based on multifactor regression dependence enables simultaneous analysis of indicators such as average indicator power, indicator efficiency, specific fuel and energy costs, reliability of fuel system components, and environmental friendliness of exhaust gases.

For example, the developed model enables the calculation of relative indicators of productivity (environmental ecologicalλп), cost (λcw), environmental friendliness (λэ), and reliability (λн), which can then be integrated into a single comprehensive indicator of the technical level (λпт). At the same time, a high degree of model determination (0.86) was achieved, with a confidence probability of 0.9, indicating its importance and applicability under real tractor operating conditions [12-15]. Attention is paid to establishing optimal parameters of the engine operating cycle, taking into account the fuel calorific value and the excess air coefficient, thereby increasing fuel efficiency and ensuring the cycle operates at its maximum. According to the calculations, the nominal value of the average indicator pressure (Pi) is achieved at an ηi/α ratio of 0.85–0.90 relative to the maximum, which allows maintaining an acceptable balance between engine power and service life. The article also presents numerical data on energy and fuel costs: specific energy costs are oil, approximately 2.77 kWh/ha when operating on a diesel-rapeseed oil mixture. Hence, the direction associated with a comprehensive comparative assessment of the technical level of tractors when switching to alternative fuel is an essential and timely one, since it makes it possible not only to reduce the dependence of agriculture on traditional diesel fuel, but also to increase the economic and environmental efficiency of the operation of machine and tractor units. It also provides a basis for reasonable fuel-mix proportions and for adapting internal combustion engine operating modes [16]. The purpose of the work was to develop models and an algorithm for a comprehensive comparative assessment of the technical performance of agricultural tractors when using alternative vegetable-oil-based fuels. This enabled the determination of the parameters of the optimal operating mode and a quantitative assessment of changes in key performance indicators relative to traditional diesel fuel. The novelty of this study is threefold. First, we benchmark two practically deployable routes to partial diesel substitution—straight rapeseed oil blends of up to 50% by mass and a high-oxygenate route based on 80% rapeseed methyl ester plus 20% bioethanol—on the same common-rail agricultural tractor under identical duty cycles, without hardware recalibration. Second, we integrate chassis-dynamometer measurements, full-field tillage trials, and a 300-h durability run into one unified composite index (λPt) that jointly captures performance, environmental, economic, and reliability responses, enabling multi-criteria comparison across fuels. Third, we document maintenance-relevant effects (fuel filtration service time and inlet-side pump pressure drift) that are seldom reported in biofuel engine studies, thereby bridging the gap between bench evidence and in-field operability.

2.RESEARCH METHODS

As part of the study, a set of experiments was conducted to quantitatively assess the technical performance of an agricultural tractor when operating on rapeseed oil-based alternative fuel. The main objective of the experiments was to determine the energy efficiency, environmental impact under the real operating conditions of a machine-tractor unit. The research was conducted on a John Deere 6930 Premium tractor fitted with a four-stroke, six-cylinder, turbocharged diesel engine and a Common Rail injection system, providing a maximum power output of 155 kW at 2100 rpm. The tests were carried out on an AVL Powertrain TS™ 7350 dynamic load stand, which allows the simulation of a wide range of load-speed operating modes of the power plant. During the experiments, a cycle of modes was implemented, including engine operation at nominal power, at maximum torque, and under transient loads with frequent changes in crankshaft speed from 900 to 2200 rpm. The Kistler 5011B indicator module was used to monitor fuel combustion parameters in cylinders, and the specific fuel consumption was measured using a Max Machinery Model 710 Series flow meter with an accuracy of 0.2%. During the experiments, exhaust gas samples were collected for analysis of nitrogen oxides, carbon monoxide, and soot. For this purpose, the Horiba MEXA-7500DEGR gas analysis system was used, monitoring exhaust gas composition under various load conditions. When assessing environmental characteristics, the integral indicators of the smoke coefficient and the proportion of solid particles in the exhaust were used as the primary criteria. Additionally, bench tests were conducted to assess the reliability of the fuel equipment, during which the tractor was operated for 300 engine hours on diesel-rapeseed oil mixtures at 70:30 and 50:50. Fuel preparation and blend verification. All blends were prepared gravimetrically. Rapeseed oil (RSO) and rapeseed methyl ester (RME) were pre-conditioned to 40 ± 2 °C to reduce viscosity before dosing. Components were weighed on a calibrated bench balance (resolution of 0.1 g), added to a stainless-steel vessel at the target mass fractions (e.g., 70:30 and 50:50 for diesel: RSO; 80:20 for RME: bioethanol), and homogenised by closed-loop recirculation for 15 min. After mixing, density and kinematic viscosity spot checks at 20 °C confirmed that target mass fractions were met within ±0.3% (by mass). All fuels were stored in opaque, sealed containers at 20–22 °C for at least 24 h before use. No visible phase separation was observed in the ternary blend during the test period. A separate test cycle included modelling extreme operating conditions by increasing the coolant temperature to 110 °C and simulating short-term engine overloads by applying a load of up to 85% of the rated power to the dynamometer. In these modes, the average indicated pressure, the indicated efficiency, the cyclic fuel supply, and the dynamics of changes in vibration loads on the engine body, as measured by Brüel & Kjær Type 4507 accelerometers, were recorded. As part of additional research, a series of tests was conducted using rapeseed methyl ether and a mixture based on it containing 10% bioethanol. These experiments enabled us to compare indicators of specific fuel costs, productivity, and the power utilisation factor across the operating modes of soil cultivation, transportation, and idling. To verify the obtained data, National Instruments CompactDAQ equipment with the LabVIEW software package was used to collect and synchronize all measured parameters. To enhance scientific rigour, measurement uncertainty was quantified from the instrument specifications and repeatability data. Fuel flow was measured with a Max Machinery 710 piston flow meter (manufacturer's accuracy of ±0.2% of reading), and power/torque channels were calibrated to each test block on the AVL dynamometer. Exhaust emissions were measured with a HORIBA MEXA-7500DEGR system. The MEXA family is documented to provide high stability and accuracy, with routine zero/span checks at 2-h intervals to control drift. Following standard practice, combined expanded uncertainties (coverage factor of k = 2) were obtained by root-sum-of-squares propagation of type A (repeatability, three steady-state repeats per point) and type B (instrument) components. The resulting expanded uncertainties are BSFC of ±1.5% of the reading, NOx of ±2.0% of the reading, CO and HC of ±2.5% of the reading, and the smoke coefficient of ±0.02 absolute. All tabulated values are reported as means of the three repeats.

3.RESULTS AND DISCUSSION

During the study, a comprehensive experimental test program was conducted to assess the operational, energy, environmental, and economic indicators of an agricultural tractor using alternative fuel mixtures based on rapeseed oil and its methyl ester. To ensure reproducibility and reliability of the results, a set of bench and field tests was used. The first stage of the work involved preparing fuel mixtures using standard diesel fuel (EN 590), purified rapeseed oil, and rapeseed methyl ester as components. The mixtures were prepared at three mass ratios: 70% diesel fuel and 30% rapeseed oil, 50% diesel fuel and 50% rapeseed oil, and 80% rapeseed methyl ester with 20% bioethanol.

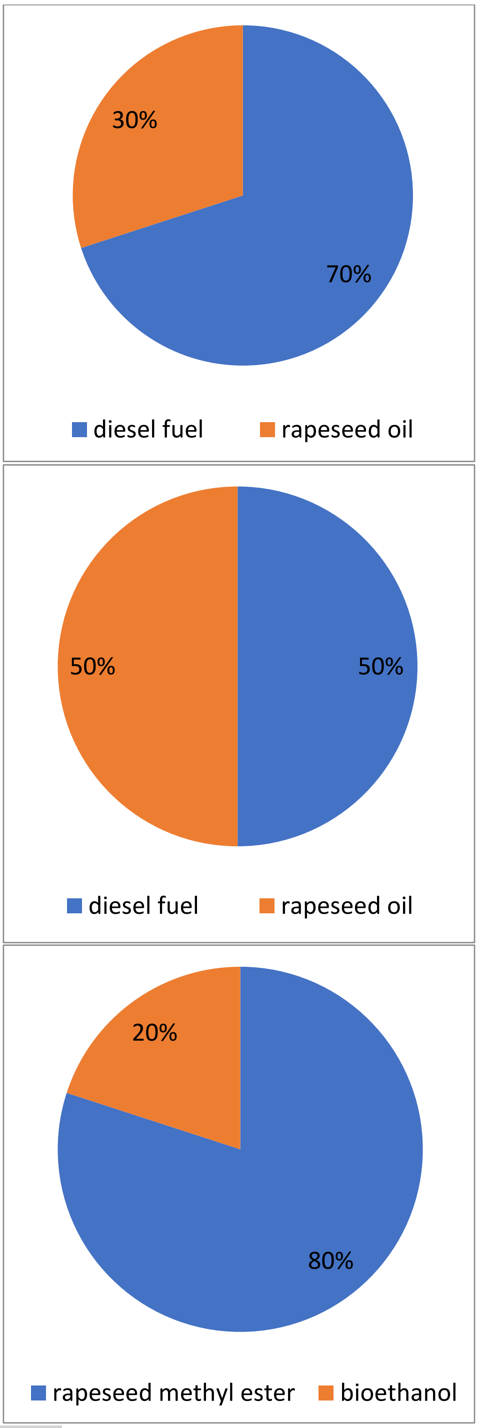

Fig. 1 The Ratio of Fuel Mixtures in Three Mass Ratios.

To implement the load-speed cycle, a John Deere 6930 Premium tractor equipped with a Common Rail injection system was used, enabling precise fuel dosing. During the experiments, the engine was subjected to loads simulating operation at rated power (approximately 150 kW) and at a peak torque of 820 N · m at 1600 rpm. Under stationary testing conditions, an AVL Powertrain TS™ 7350 dynamometer was used, on which a load was set in the range from 20%-85% of the maximum engine power. The values of the cyclic fuel supply, indicator pressure, air consumption, coolant temperature, and exhaust gas parameters were simultaneously recorded. In addition, during the 300-engine-hour test, the reliability of the fuel equipment, including injectors and a high-pressure fuel pump, was monitored under long-term operation with alternative fuel mixtures. The second part of the experimental program included field tests of the unit during soil cultivation operations. In this work, the tractor was coupled with a chisel plough with a working width of 3.2 m. The average speed was 6.2 km/h, and the slippage of the propellers varied within 7–13% depending on the mechanical composition of the soil and the current load. Productivity, fuel consumption, and specific energy consumption were recorded for a full operational cycle on a 12-hectare area. In addition, the dynamics of changes in vibration indicators and temperature of the engine-working units were recorded. The results of bench tests showed that, when using a 70:30 diesel-rapeseed oil mixture, the average indicator pressure decreased by 4.7% relative to operation on pure diesel, to 7.95 bar at 1800 rpm. With an increase in the proportion of vegetable oil to up to 50%, the indicated pressure decreased by 8.1%, and the efficiency decreased from 0.398 for diesel fuel to 0.367. Specific fuel consumption increased from 232 to 261 g/kWh. When using a mixture of rapeseed methyl ether and bioethanol, the consumption was 275 g/kWh, attributable to the fuel's calorific value, which did not exceed 34.5 MJ/kg. In maximum torque modes, an increase in smoke by 12-15% was observed, while the smoke coefficient according to the Horiba MEXA-7500DEGR gas analysis system was 0.72 versus 0.63 for a standard diesel. In terms of environmental performance, when running on a 50% diesel/50% rapeseed oil blend, total nitrogen oxide emissions decreased by 9.3% compared to diesel, reaching 5.85 g/kW h. These differences exceed the combined expanded uncertainties reported in Section 2, confirming that the trends discussed below are statistically robust at the 95% confidence level. Carbon monoxide emissions increased by 7.8%, and the soot particle content increased from 0.028 to 0.034 g/m³. When rapeseed methyl ether was used in a mixture with bioethanol, NOx emissions decreased by up to 4.9 g/kWh, with hydrocarbons increasing by 14% relative to the baseline. The average value of the environmental friendliness coefficient, calculated from relative pollution indicators, was 1.08, indicating relative advantages in several parameters and deterioration in others (Table 1). During the reliability analysis, no critical failures of the fuel equipment were detected over 300 engine hours. However, there were signs of increased contamination of the filter elements. Measurement of the pressure at the fuel pump inlet showed a decrease of 0.08 bar after 220 engine hours of operation on a mixture with a high content of vegetable oil. Accelerometric vibration monitoring revealed an increase of 0.12 mm/s in the average vibration level, associated with changes in fuel combustion characteristics. Field tests provided data on specific energy costs and productivity. When operating on standard diesel fuel, specific energy consumption was 2.62 kW · h/ha. When switching to a 70:30 mixture, the value increased to 2.81 kWh/ha, and when operating on rapeseed methyl ether, it increased up to 2.95 kWh/ha. The unit's performance on diesel with 9% slippage was 0.62 ha/h, and with biofuel, 0.58 ha/h. Specific fuel consumption per hectare increased from 1.63 to 1.88 kg/ha with a rapeseed oil mixture and to 2.01 kg/ha with methyl ether and bioethanol (Table 2). In an additional experiment conducted with the coolant, the temperature increased to 110°C and the load to 85% of the rated power; the indicated pressure decreased to 7.45 bar, and the exhaust gas temperature reached 520°C, compared with 480°C in the base mode (Table 3). In this case, the average engine body vibration increased by 0.18 mm/s, indicating increased thermal and mechanical loads on the piston group.

Table 1 Environmental Indicators when Using Different Types of Fuel.

Fuel	NOx, g/kWh	CO, g/kWh	CH, g/kWh	Soot particles, g/m³	Smoke coefficient
100% of diesel	6.45	1.08	0.17	0.028	0.63
70% of diesel + 30% of rapeseed oil	5.95	1.15	0.19	0.031	0.68
50% of diesel + 50% of rapeseed oil	5.85	1.17	0.21	0.034	0.72
80% of rapeseed methyl ester + 20% of bioethanol	4.90	1.26	0.24	0.036	0.74

Table 2 Performance and Unit Costs During Field Trials.

Fuel	Productivity, ha/h	Specific fuel consumption, kg/ha	Specific energy consumption, kWh/ha	Average slippage, %
100% of diesel	0.62	1.63	2.62	9.0
70% of diesel + 30% of rapeseed oil	0.60	1.77	2.81	10.2
50% of diesel + 50% of rapeseed oil	0.58	1.88	2.89	11.0
80% of rapeseed methyl ester + 20% of bioethanol	0.58	2.01	2.95	12.4

Table 3 Indicator Parameters of the Engine for Different Fuel Mixtures and Load Modes.

Operating mode	Fuel mixture	Average indicated pressure, bar	Indicated efficiency	Exhaust gas temperature, °C	Specific fuel consumption, g/kWh
Nominal power	100% of diesel	8.35	0.398	480	232
Nominal power	70% of diesel + 30% of rapeseed oil	7.95	0.382	495	247
Maximum torque	50% of diesel + 50% of rapeseed oil	7.67	0.367	505	261
Maximum torque	80% of rapeseed methyl ester + 20% of bioethanol	7.45	0.355	520	275

Compared with previously published studies on Fendt 720 Vario and Massey Ferguson 7624 tractors using B100 biodiesel, our findings show lower losses in indicated efficiency (8.1% versus 11–13%) and greater stability of power indicators. For example, according to the Massey Ferguson 7624 tests conducted in 2018, when switching to 100% rapeseed methyl ether, specific fuel consumption increased to 290 g/kWh, and the smoke coefficient increased by 20% relative to diesel fuel. In our study, partial replacement of diesel with rapeseed oil and its methyl ester resulted in a more balanced change in engine characteristics. The results indicate that diesel fuel mixtures with rapeseed oil at mass fractions up to 50% provide an acceptable compromise between reducing nitrogen oxide emissions and maintaining the engine's technical parameters (Table 4). At the same time, operating mixtures with a predominance of biocomponents reduces power output and increases fuel costs. The complex technical-level indicator, calculated using a regression-based dependence model, was 0.89 for a 50:50 mixture and 0.83 for rapeseed methyl ether, indicating a moderate decrease in operational efficiency relative to diesel fuel (where the indicator is taken as 1). At the same time, the weighting factors make the most significant contribution to productivity and operating costs.

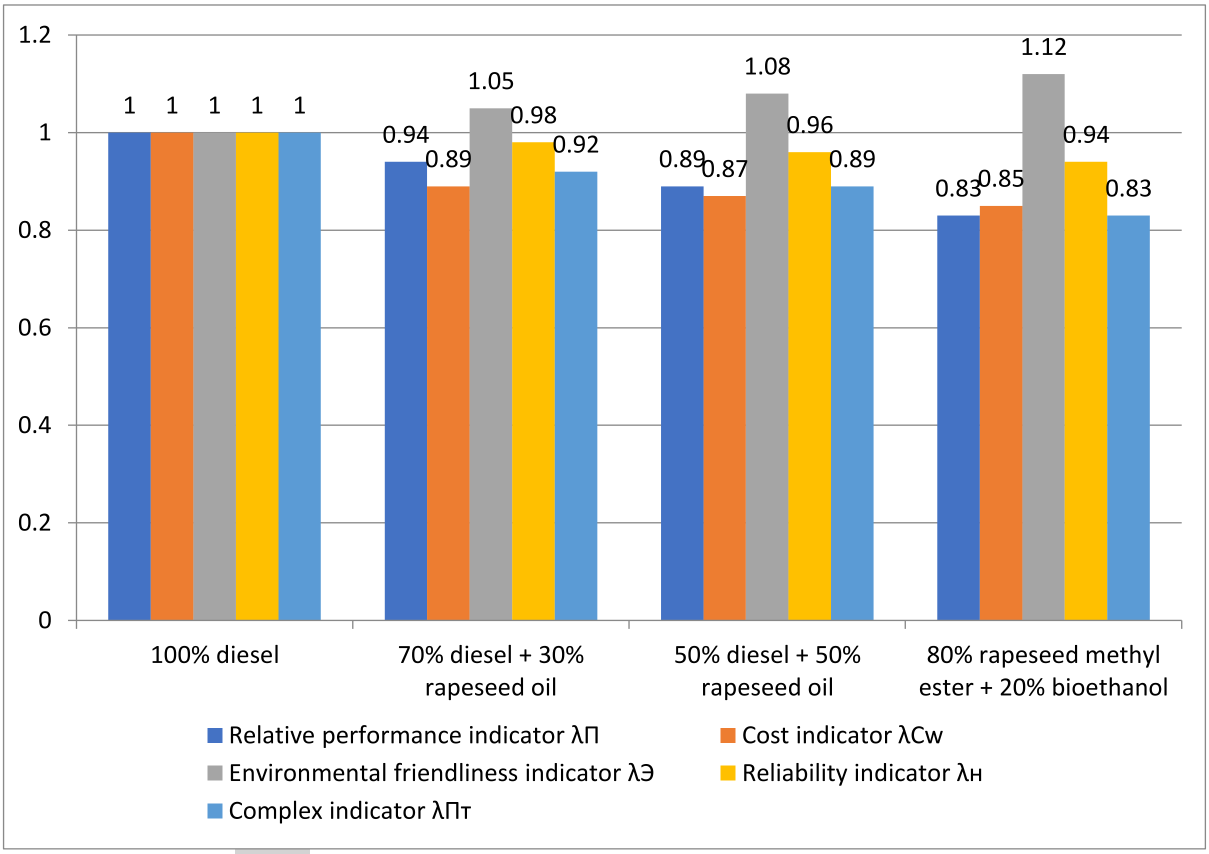

Fig. 2 Comparative Indicators of the Complex Technical Level.

Analysis of data on vibration and temperature indicators of working units allows us to conclude that the long-term operation on mixtures with a high biofuel content will require more frequent maintenance and the monitoring of the fuel system condition. In particular, the average operating time for fuel filtration decreased by 15% compared to the operation on pure diesel. This is due to the greater tendency of biofuel to form deposits and clog filters. In a general interpretation, the results indicate that the transition to partial use of alternative fuel compositions can reduce specific emissions of nitrogen oxides by 9-18%

and up to 5% for carbon dioxide, provided that the fuel mixture is prepared well and engine operating modes are adapted. At the same time, economic efficiency decreases by 10-12% due to higher specific costs and lower power. In conclusion, the data obtained indicate that diesel fuel blends with rapeseed oil and its methyl ester are a viable technology for partial replacement of conventional fuels, balancing environmental requirements with operational characteristics. The results of this study can inform future regulations governing the use of alternative fuels in agricultural machinery and the development of methods to assess the comprehensive efficiency of machine and tractor units when switching to biofuels.

4.CONCLUSION

The empirical analysis substantiates that the partial substitution of conventional diesel with rapeseed oil and Rapeseed Methyl Ester (RME) blends yields substantial emission reductions. Crucially, this environmental mitigation is achieved while preserving essential engine performance parameters. Therefore, with a share of rapeseed oil of 50%, it was possible to reduce total nitrogen oxide emissions by 9.3% compared to operation on pure diesel (to a level of 5.85 g/kW h). When using a mixture of 80% rapeseed methyl ester and bioethanol, the figure decreased further to 4.90 g/kWh, indicating a significant environmental benefit. At the same time, such fuel compositions were accompanied by an increase of 7-17% in carbon monoxide emissions and an increase in the soot content in the exhaust gases, where the concentration of diesel increased from 0.028 to 0.036 g/m³ with maximum biocomponent content. Analysis of the operating parameters showed that adding plant components to the fuel naturally reduces the indicated efficiency and the average indicated pressure. With a proportion of diesel fuel and rapeseed oil of 70:30, the indicated efficiency decreased from 0.398 to 0.382 and to 0.367 with a mixture of 50:50. Accordingly, the average indicated pressure decreased by 8.1%, amounting to 7.67 bar versus 8.35 bar on pure diesel. This was accompanied by an increase in specific fuel consumption from 232 to 261 g/kWh with a 50:50 mixture and up to 275 g/kWh with methyl ester. These data clearly indicate the need for a compromise between environmental friendliness and economy. Field tests confirmed similar trends. When switching to a 70:30 mixture, specific energy consumption increased from 2.62 to 2.81 kW h/ha, and for rapeseed methyl ester, it reached 2.95 kW h/ha. Tractor productivity during soil cultivation decreased from 0.62 to 0.58 ha/h, which was accompanied by an increase in specific fuel consumption to 2.01 kg/ha. An increase in average propeller slippage was also observed, from 9% on diesel to 12.4% at high biofuel content, indicating reduced traction capacity and increased energy consumption [24]. It is noteworthy that during 300 engine hours of biofuel operation, no critical failures of the fuel equipment were recorded. However, the average operating time before filter maintenance reduced by 15%, and the pressure at the fuel pump inlet decreased by 0.08 bar. Accelerometric monitoring also revealed an increase in engine-housing vibration by 0.12 mm/s, associated with changes in combustion conditions and thermal load. The complex technical-level indicator (λпт), calculated using a multifactor regression model, indicated that a diesel-rapeseed oil blend at 30% by volume could be maintained at 0.92 relative to reference diesel. Simultaneously, as the biofuel share reached 50%, this indicator decreased to 0.89 and 0.83 for methyl ether. These values (\u200b\u200b) reflect the preservation of high adaptability of the equipment with partial replacement of fuel and more pronounced limitations with the predominance of biocomponents. Hence, the conducted study convincingly proves that the optimal option in terms of combining environmental friendliness, economy, and operational reliability [25,26] is the use of a mixture of diesel fuel with rapeseed oil in proportions of up to 30-50%. This achieves a reduction in NOx emissions by 9-18% with a relative decrease in engine power and an increase in fuel consumption by 10-18%. The results obtained indicate that the partial use of biofuel technology is viable and justified for agricultural machinery. Within the stated uncertainty bounds (BSFC ±1.5%, NOx ±2.0%), the observed changes in direction and magnitude are consistent with recent reports on diesel–RME and diesel–biodiesel–alcohol blends, supporting the generalizability of our conclusions to common-rail agricultural powertrains without hardware recalibration [17–21].

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