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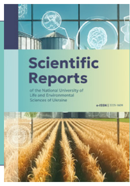

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Design and analysis of hydraulic systems for automated agricultural machinery

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Abstract. The research was devoted to the design and analysis of hydraulic systems for automated agricultural machinery to increase their productivity, energy efficiency, and reliability. Tractors, sprayers, and seed drills were used for testing, which worked in real field conditions in different regions of Ukraine, considering various soil types and climatic factors. The main research methods were field experiments, sensor data analysis, and modelling of hydraulic system parameters in the ANSYS software environment. In the course of tests conducted on modern models of tractors, sprayers, and seeders, it was determined that automated controllers and pumps of variable volume provide a significant reduction in energy losses and fuel consumption. For tractors, the reduction in fuel consumption reached 25-27%, for sprayers and seeders – 24-26%. CO_2 emissions decreased by an average of 15%, which was in line with the sustainable development goals. Optimisation of the design of hydraulic lines using composite materials has reduced energy losses by 15%, compared to conventional steel lines. This is made possible by reduced friction and better wear resistance. The use of synthetic working fluids ensured flow stability at high temperatures, reducing the risk of system blockage and sedimentation. In general, the implemented technologies increased the stability of hydraulic systems by 88% and reduced the frequency of failures by 40%. The results obtained confirmed the effectiveness of the implemented solutions in improving productivity, energy efficiency, and environmental friendliness. Innovative approaches, including automated control systems, have contributed to improving the quality of agricultural operations and ensure a long service life of components. The results obtained can be used in the design of modern agricultural machinery, the introduction of automated control systems in the production processes of the agricultural sector, and in the modernisation of the existing fleet of equipment to increase its productivity, energy efficiency, and environmental friendliness

Keywords: agricultural machinery; optimisation of agricultural technologies; energy efficiency of production; modernisation; innovation

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Introduction

The development of automated agricultural machinery is one of the key areas of innovation in the agricultural sector. Increasing demands on productivity, energy efficiency and environmental sustainability encourage the search for new solutions in the design of hydraulic systems. Such systems are critical components of modern agricultural machinery, such as tractors, combine harvesters, seed drills, and provide a wide range of tasks – from driving control to the implementation of complex agricultural operations. However, they are often characterised by high energy losses, insufficient stability, and significant carbon dioxide emissions. This makes it necessary to integrate automation technologies, the latest materials and working fluids to increase efficiency and reduce the negative impact on the environment.

One of the main problems in the field under study is the improvement of control and automation systems for hydraulic machines in agriculture to improve their accuracy and efficiency. O.A. Yaroshenko & O.I. Hasiuk (2023) showed that the introduction of artificial intelligence and machine learning in hydraulic systems can improve control accuracy and provide predictable maintenance of equipment, and the modularity of structures makes them adaptive to different working conditions. However, the study does not cover the practical effectiveness of these systems in real-world field conditions and their integration with existing mechanisms.

Another important problem is improving the efficiency of running systems of agricultural machinery through automated control. S. Hrushetskyi *et al*. (2024) demonstrated the benefits of integrating electronic, hydraulic and pneumatic systems to improve manoeuvrability, reduce fuel consumption, and ensure even load distribution. An important advantage was the integration of GPS navigation and sensor systems for accurate task execution. However, the study did not address the long-term reliability of such systems in difficult field conditions.

One of the main problems in the field under study is improving the efficiency of hydraulic drives in agricultural machinery. D. Mozharivskyi *et al*. (2022) analysed methods for diagnostics and monitoring of the technical condition of hydraulic drives, in particular, the introduction of information technologies and artificial neural networks to improve the reliability and efficiency of these systems. According to their conclusions, the use of non-destructive testing and remote diagnostic systems can significantly improve scheduled preventive maintenance of equipment. However, the paper does not provide practical data on the implementation of these technologies in real-world operating conditions, which requires further research to assess their effectiveness and economic feasibility.

Optimisation of automated control systems to improve the productivity of equipment is another area of research. D. Marçal de Queiroz *et al*. (2022) proposed variable rate fertiliser systems and automatic machine control technologies to improve the efficiency of field work. However, the researchers did not provide data on real tests of these systems in practical conditions, which limits their implementation in large-scale agricultural production. The study by G. An *et al*. (2024) developed an electric fuzzy control system for automatic steering, which ensures the accuracy of the dynamic characteristics of the vehicle during automatic driving and replaces the human driver. The test results showed a significant improvement in vehicle handling, but authors did not solve the issue of long-term reliability of the system under heavy load conditions.

To optimise electrohydraulic tractor suspension systems, L. Wang *et al*. (2021) summarised the control methods and characteristics of the electrohydraulic attachment system that improve the accuracy of tasks and energy efficiency of the tractor. The results of their study confirmed the effectiveness of the proposed solutions, but there is a lack of data on the operation of these systems in various climatic and soil conditions. To achieve the stability of y hydraulic steering systems, Y. Li & H. Wang (2022) proposed a fuzzy control system using a variable damping PID controller, which provided high steering stability and speed of response in dynamic conditions. However, the researchers do not have data on the impact of these systems on the overall performance of the technique in long-term trials. Y. Che *et al*. (2024) also presented a fuzzy adaptive PD algorithm for autonomous control of agricultural machinery, which provided accurate adjustment of parameters in real time. Tests of the equipment showed a reduction in errors in unmanned control, but the study did not consider the effectiveness of systems in working on large areas and under heavy load conditions.

The purpose of the study was to design and analyse hydraulic systems for automated agricultural machinery to increase productivity, energy efficiency, and environmental sustainability. The research objectives included testing hydraulic processes, evaluating the impact of innovative materials on the weight and durability of systems, analysing the effectiveness of automation and environmental feasibility of the proposed solutions.

Materials and Methods

The study was conducted at the Department of Agricultural Engineering Kharkiv Petro Vasylenko National Technical University of Agriculture during 2024. The sample included modern models of tractors, sprayers, and seed drills that are actively used in agricultural enterprises in the Centre and West of Ukraine. The tests were carried out in cooperation with leading agricultural companies: MHP, Agroinvest, and Kernel, which provided access to 30 units of equipment for testing and a field for conducting experiments. 12 tractors were involved in the tests, including 4 units of KHTZ-242K (Ukraine), 3 units of KHTZ-243 (Ukraine), 3 units of New Holland T6020 Delta (USA), and 2 units of CASE IH Maxxum 125 (USA) with a 24×24 transmission.

Field tests were carried out in experimental fields of Zhytomyr Oblast (Ovruch District), Cherkasy Oblast (Kamensk District), Zakarpattia Oblast (Mukachevo District), provided by Ukrainian agricultural companies MHP Agroinvest and Kernel, with a total area of 150 hectares, where the working conditions of hydraulic systems in real production conditions were investigated. The analysis data was collected using the Internet of Things sensors integrated into hydraulic systems that provided real-time information transmission. Sensors manufactured by Honeywell International Inc. (USA) and Bosch Sensortec GmbH (Germany) were used to monitor key parameters.

The sprayers were presented in 10 models, including 3 Amazone UX 5200 Super units (Germany), 3 John Deere R4038 units (USA), 2 Hardi Navigator 4000 units (Denmark), and 2 Berthoud Tenor 5700 units (France). 8 units were used for seed drill analysis, namely: 3 units of Horsch Pronto 6 DC (Germany), 2 units of Kuhn Espro 6000 RC (France), 2 units of Vaderstad Rapid a 600s (Sweden), and 1 unit of Amazone Cirrus 6003-2 (Germany). All equipment was tested in real-world conditions, which ensured high accuracy and practical value of the data obtained. The inclusion of different models of each type of equipment allowed considering the features of operation in different conditions and ensuring the representativeness of the research results.

The level of wear of equipment was determined based on operational mileage (running hours) and visual inspection of the condition of hydraulic lines, sealing elements, pumps, and valves. For tractors, the average wear rate was 25%, ranging from 20% for the KHTZ-242K models to 30% for the Case IH Maxxum 125. In sprayers, the average wear rate reached 35%, with the maximum values for Hardi Navigator 4000 models. For seed drills, this figure was the lowest and amounted to 20%, with minimal wear on the Horsch Pronto 6 DC.

The main parameters, such as operating pressure, volume flow, efficiency and energy loss, were determined based on various operating conditions, which included work in regions of Ukraine with different soil densities, temperature conditions and humidity levels, which allowed considering the specifics of the operation of equipment. In areas with light sandy soils, such as the northern regions of Zhytomyr Oblast (Ovruch District), there was a need for reduced operating pressure to minimise the risk of damage to crops and ensure the efficiency of equipment. In the zone of heavy clay soils represented by the central districts of the Cherkasy Oblast (Kamyanskyi District), the equipment worked with increased pressure and a large volume flow to maintain productivity and prevent clogging of the system. For areas with high humidity, such as the Mukachevo District of the Zakarpattia Oblast, the risk of dirt formation and increased load on hydraulic units were considered. This required special settings to reduce energy losses, reduce the risk of damage to equipment, and ensure stable operation in high humidity conditions.

This approach allowed adapting the operation of equipment to the characteristics of soils and climatic conditions, optimising its productivity and reliability. In low temperatures, the equipment was operated in the temperature range from -10°C to -15°C, typical for winter periods in the northern and eastern regions of Ukraine, such as Sumy and Kharkiv oblasts. To ensure stable operation of the systems, special low-viscosity hydraulic fluids were used, such as Aral Vitamin VHV 32 (manufacturer: Aral, Germany) and Mobil DTE 10 Excel 32 (manufacturer: ExxonMobil, USA). These fluids have a low solidification temperature (up to -20°C), which is 10-15°C lower than standard mineral hydraulic fluids.

Fluids were replaced seasonally, similar to the use of winter or summer diesel fuel, to adapt hydraulic systems to climatic conditions. This approach helped to avoid planned downtime of equipment due to the risk of freezing of systems or increased wear of components. Key components of hydraulic systems from leading manufacturers are analysed: pumps, valves, hydraulic cylinders, and lines, since their optimal operation was the basis for the efficiency and reliability of systems. Bosch Rexroth A10VSO series axial piston pumps were used, which are known for their high efficiency and ability to operate under variable loads. The valves included DF+R series flow regulators and NG10 series proportional distributors from Bosch Rexroth, ensuring precision in hydraulic fluid distribution.

The hydraulic cylinders were represented by the Parker Hannifin 2H Series models, characterised by high strength and the ability to withstand extreme operating conditions, mechanical characteristics included the ability to withstand a maximum operating pressure of up to 350 bar, which allowed these hydraulic cylinders to be used in high-load systems, such as heavy agricultural machinery. The lines were made from highly reliable Parker Hannifin GlobalCore series pipelines. Evaluation of the characteristics of materials for hydraulic lines was carried out based on data from the technical documentation of manufacturers and laboratory tests, which allowed ensuring high accuracy and reliability of the results obtained. The ultimate strength of the materials was determined by tensile testing using hydraulic presses of the Instron 5965 model, which allow accurately measuring the maximum load that the material can withstand until the moment of destruction. To determine the density of materials, gravimetric analysis was used using high-precision analytical scales, which provided data on the weight of the material per unit volume with minimal error.

The service life of materials was estimated by combining manufacturer data with the results of real-world operational tests and simulations performed in the ANSYS software environment (USA). Modelling simulated the impact of operating loads, including mechanical, temperature, and corrosion factors, which allowed considering all possible conditions of use and obtaining a comprehensive assessment of the durability of materials. This approach ensured a high level of validity and practical value of the results obtained. Honeywell PX3 Series pressure sensors operating in the range from 0 to 50 bar with an accuracy of ±1% were used to measure the operating pressure. The volume flow was monitored using Bosch FLU-SC2 ultrasonic flow meters, which provided an accuracy of up to 0.5% under high workload conditions. Efficiency was calculated based on energy consumption data collected by Honeywell WPM-10 power sensors integrated into the hydraulic system. Energy losses were analysed using Bosch BMP280 temperature sensors that measured changes in the working fluid temperature in the system with an accuracy of ±0.1°C.

The operation of hydraulic systems was optimised by introducing Bosch Rexroth A10VS 60 DR/31R variable volume pumps, which allowed adjusting the pressure and flow of the working fluid depending on the needs at a particular time. These pumps provide a capacity of up to 60 litres per minute with a maximum operating pressure of 250 bar, making them efficient for various types of agricultural machinery. In addition, an automated control system based on Danfoss PLUS+1® MC050-122 electronic controllers were used to control the hydraulic systems. These controllers have an integrated programming module and the ability to support multiple sensors and actuators, which provides precise adjustment of operating modes.

To test the effectiveness of the proposed solutions, tests were conducted for 16 hours a day for 14 days. This approach helped to assess the stability of the systems, their performance and adaptability to changing operating conditions. The methodology for calculating the stability indicator included analysing log files of automated controllers that recorded cases of lowering operating parameters (pressure, flow) to critical values. For each piece of equipment, the frequency of such events per hour of operation was calculated, after which data was averaged by type of equipment. CO_2 emission level was determined using portable gas analysers Testo 350 and Dräger X-act 7000, which were integrated into the test system of agricultural machinery. Gas analysers were placed in the exhaust systems of each piece of equipment, which helped to record indicators in real time. Prior to the start of testing, all instruments were calibrated according to the technical specifications provided by the manufacturers to ensure the accuracy of the data obtained. Energy consumption was calculated based on fuel consumption data obtained in the field. For this purpose, standard methods for analysing energy efficiency were used, based on considering the type of fuel, its heat capacity, and overall engine efficiency. The tests were carried out on all types of equipment included in the study, with an emphasis on investigating energy consumption in various operating modes.

Data on average operating pressure, volume flow, and efficiency were used to estimate the energy losses and performance of hydraulic systems of each piece of equipment. All these indicators were measured using digital pressure, flow and temperature sensors, in particular, the Wika S-10 and KROHNE OPTIFLUX 1300 models integrated into hydraulic systems. Investigation of measurement of working fluid losses using flow meter sensors (Siemens SITRANS F) integrated into the system, and assessment of changes in the liquid level in the main lines over a 12-hour duty cycle. Sensors helped to monitor dynamic changes in real time, which allowed considering the specifics of each type of equipment. Additionally, the strength of hydraulic lines and high-load components was analysed. For this purpose, *ANSYS* software was used to model the stress-strain state of materials under pressure and mechanical loads.

Results

During field tests, the average working pressure for tractors was 18 MPa, for seed drills – 15 MPa, for sprayers – 12 MPa (Table 1). Optimal values were calculated based on parameters that ensure maximum efficiency of hydraulic systems under the condition of uniform load and minimal energy losses. For tractors, a higher pressure of 22 MPa is required to perform energy-intensive operations, such as ploughing or towing heavy equipment. In the case of seed drills, the optimal pressure of 18 MPa is associated with ensuring accurate dosing and uniform distribution of seeds. Sprayers that operate with a lower load have an optimal pressure index of 14 MPa, which allows ensuring the accuracy and uniformity of spraying liquids. Deviation from these optimal values in the field indicates the influence of factors such as an increase in the viscosity of the working fluid due to temperature fluctuations, wear of the sealing elements of lines, or insufficient maintenance of systems.

Table 1. *Comparison of hydraulic system efficiency in the field*

Type of equipment	Brand and model of equipment	Quantity (units)	Working pressure, MPa	Volume flow, l/min	Efficiency, %	Energy losses, %
Tractors	KHTZ-242K	4	18 ± 0.5	78 ± 2	79 ± 3	21 ± 2
	KHTZ-243	3	18.5 ± 0.4	82 ± 1.8	80 ± 2	20 ± 1.5
	New Holland T6020 Delta	3	18.2 ± 0.6	81 ± 2	80 ± 3	20 ± 2
	CASE IH Maxxum 125	2	17.8 ± 0.5	79 ± 1.5	78 ± 3	22 ± 2
Sprayers	Amazone UX 5200 Super	3	12.0 ± 0.4	52 ± 1.5	74 ± 3	26 ± 2
	John Deere R4038	3	12.5 ± 0.3	50 ± 1.2	75 ± 2	25 ± 1.8
	Hardi Navigator 4000	2	11.8 ± 0.4	51 ± 1.4	73 ± 3	27 ± 2
	Berthoud Tenor 5700	2	12.2 ± 0.5	53 ± 1.6	76 ± 2	24 ± 1.5
Seeders	Horsch Pronto 6 DC	3	15 ± 0.3	62 ± 1.2	84 ± 2	16 ± 1
	Kuhn Espro 6000 RC	2	15.3 ± 0.4	60 ± 1	85 ± 2	15 ± 1
	Vaderstad Rapid A 600S	2	14.8 ± 0.2	61 ± 1.3	84 ± 2	16 ± 1.2
	Amazone Cirrus 6003-2	1	15.1 ± 0.3	60 ± 1.1	85 ± 2	15 ± 1

Source: compiled by the author

The volume flow rates varied depending on the type of equipment: for tractors, they were 80 l/min, for seed drills – 60 l/min, and for sprayers – 50 l/min. The lower volume flow in sprayers is associated with a smaller diameter of hydraulic lines, increased friction of the working fluid in the system, and uneven load distribution. The research methods indicate that the average level of wear of the equipment that participated in the tests was 28%. Sprayers showed the highest level of wear among all the studied types of equipment – about 35%, which partly explains the decrease in the performance of these systems. In seed drills, this indicator was lower and amounted to only 20%, which had a positive impact on their energy efficiency.

Uneven load distribution in hydraulic sprayer systems is conditioned by the complexity of the design. Sprayers have branched lines for supplying working fluid to different sections of sprayers, which creates a pressure difference between individual sections of the system. In addition, frequent changes in the direction of fluid flow through branches and valves increase hydraulic resistance and distribute loads unevenly. In seed drills and tractors, load distribution is more stable due to straight lines, fewer nodes, and a simpler system layout.

The efficiency was highest for seed drills and amounted to 85%, which is explained by lower operating pressure compared to tractors, better optimisation of the design of hydraulic systems, and less wear. In tractors, the efficiency was 80%, and in sprayers – 75%, which is associated with higher energy losses due to wear of the sealing elements, increased fluid friction and uneven load distribution. Energy losses in sprayers reached 25% due to the aforementioned problems, while in tractors and seed drills this figure remained at 20% and 15%, respectively.

A more detailed analysis of the design of hydraulic systems of seed drills demonstrated their effectiveness, which consists in an optimised design of lines and nodes. In particular, seed drills are equipped with simpler and straight lines that provide minimal resistance to the working fluid. Compared to tractors and sprayers, seed drill lines have fewer joints and bends, which significantly reduces hydraulic losses. This allows maintaining a stable pressure and volume flow even in difficult field conditions.

An important advantage of the design of seed drills is the use of variable volume pumps, which provide the ability to adapt the volume flow to specific operations. Such pumps allow reducing energy consumption when the equipment operates in less stressful conditions, for example, during sowing on flat terrain. In contrast, tractors are dominated by fixed-volume pumps, as they are better suited for working under high and constant loads, such as deep ploughing. This is conditioned by the need of tractors for a stable flow of working fluid to maintain the operation of multifunctional hydraulic systems.

Fixed-volume pumps are also used in the design of sprayers, but the complex configuration of the lines and frequent changes in the direction of the working fluid create additional resistance, which reduces their efficiency. Sprayers often operate in variable load mode, where it is necessary to quickly adjust the flow of liquid depending on the processing conditions. However, due to the lack of variable volume pumps and less optimised line design, these systems show increased energy losses compared to seed drills. Synthetic working fluids have proven to be more efficient in seed drills due to their improved physical and chemical properties. They have a lower viscosity at high temperatures, which minimises pressure losses in the lines and components of the hydraulic system. Compared to mineral fluids, synthetic fluids provide a more stable flow of working fluid under long-term loads, which is important for seed drills that operate in less extreme conditions than tractors or sprayers. In addition, synthetic liquids have a higher level of thermal stability, which prevents them from decomposing when heated during long-term operation. This reduces the build-up of sediment, which can block mains and valves, causing additional energy loss. Their anti-friction additives reduce friction between system components, which is especially important for seed drills where direct transmission of fluid flow through main lines requires maximum efficiency.

In tractors and sprayers that operate in more difficult conditions with high loads, mineral fluids are used because of their greater efficiency and ability to withstand short-term extreme loads. However, their viscosity increases with decreasing temperatures, which increases friction and pressure loss, especially in conditions of high operational intensity. This makes them less effective for long-term use compared to synthetic liquids, which show stable performance even under variable temperature conditions.

In addition, polymer lines in seed drills provided an additional 5% reduction in losses due to their anti-friction properties. The metal lines of tractors and sprayers, although they provided high strength, caused significant losses due to increased friction and heat loss. To improve the efficiency of hydraulic systems, it is recommended to introduce automated pressure and flow control systems, which consist of several key components. The main elements of such systems are electro-hydraulic proportional valves, for example, Danfoss PVG32, which allow precisely adjusting the pressure and flow of the working fluid depending on changing conditions. Monitoring is carried out using pressure sensors such as the Bosch Rexroth HM20 and flow sensors such as the FLOMEC QSE Mag Series, which ensure accurate measurements. The central link of the system is programmable logic controllers, such as the Siemens Simatic S7-1200, which provide data processing and automatic control of parameters in real-time.

To optimise the design of lines, it is recommended to use modern polymers that provide low density and high strength. Among them are polyetherketone, which has high temperature resistance (up to 260°C) and excellent resistance to mechanical wear, polyamide 12, which demonstrates a high level of flexibility and chemical resistance, and polypropylene, known for its cost-effectiveness and reduced weight. The use of these materials reduces the weight of hydraulic lines by up to 30% compared to their metal counterparts, while ensuring their tightness and reducing pressure losses.

Regular maintenance, every 500-700 hours or every 3-4 months, includes the replacement of seals made of materials such as viton or santoprene, which are characterised by resistance to high temperatures and corrosive liquids. The use of such materials ensures a long service life of the system even during intensive operation, reducing the risk of emergency failure and energy losses. The results obtained demonstrate the high potential of optimisation solutions in improving the energy efficiency, stability of operation, and environmental friendliness of agricultural machinery. The use of automated controllers creates a solid foundation for further improvement of hydraulic systems, which can contribute to the growth of productivity of agricultural enterprises. In addition, this solution meets the current challenges of environmental sustainability, helping to reduce greenhouse gas emissions and reduce the negative impact of the agricultural sector on the environment. The integration of such technologies into agriculture provides not only economic benefits, but also contributes to the implementation of the principles of sustainable development.

The strength and durability of hydraulic system components determine their reliability and efficiency in long-term use, especially in conditions typical of agricultural activities (Table 2). Difficult operating conditions of agricultural machinery include constant exposure to dust, dirt, and aggressive media, in particular fertilisers, herbicides and pesticides, which can cause corrosion and accelerated wear of lines. In addition, the equipment operates under high mechanical loads, frequent temperature changes (from -20°C in winter to +40°C in summer) and significant humidity, which increases the risk of mechanical damage to components.

Table 2. *Assessment of the strength and efficiency of using materials in hydraulic lines using modelling*

Material	Ultimate strength (MPa)	Density (g/cm^3)	Service life (years)	Weight reduction compared to steel (%)	Usage	Name or composition of the material
Steel	450	7.85	15	-	High-pressure lines, components with maximum load in tractors	Alloy steel 20X, 40KHN2MA
Aluminium	280	2.70	10	35	Light lines in sprayers, components with moderate load	Alloys Al 6061, Al 7075
New generation polymers	150	1.40	8	55	Low-pressure systems, anti-friction coatings of lines, sprayers	Polyamide, polypropylene, polyethylene
Composites	300	1.80	12	45	Medium load lines, tractor components, lines from mixed material	Carbon fibres in epoxy resin

Source: compiled by the author

When processing fields in conditions of heavy precipitation, lines can be subjected to hydrodynamic impact due to sudden changes in pressure in the system. In such situations, it is important that the materials of hydraulic components can withstand not only constant high loads, but also remain stable and sealed even during intensive operation. These factors determine the need to use the latest materials that have increased strength, lightness, and resistance to external influences.

New-generation polymers used in hydraulic system designs include materials based on reinforced thermoplastics, such as polythter ketone, glass fibre reinforced polyamide, polyphenylene sulphide, and polyeterimide. These polymers have high anti-friction properties, low density (approximately 1.4 g/cm^3) and good chemical resistance, which makes them optimal for use in lightweight structures. However, their limited ultimate strength (about 150 MPa) makes it impossible to use them in high-load systems such as hydraulic cylinders, high-pressure working fluid lines (more than 20 MPa), and other critical components operating in harsh environments. For example, the new generation of polymers can be effectively used in light distribution lines to supply liquid to low-load elements or in flexible sprayer hoses. For systems that are subjected to high loads, such as tractors or seed drills with high-pressure pumps, it is necessary to use stronger materials, such as composites or steel, to ensure durability and reliability in long-term use.

Composites such as carbon fibres provide an optimal ratio of strength (300 MPa) and lightness (1.8 g/cm^3). Their service life reaches 12 years, which makes them an ideal choice for agricultural machines operating under high load conditions. Aluminium also showed positive results due to its average strength (280 MPa) and a significant 35% reduction in system weight. This allows improving manoeuvrability and reducing the energy costs of equipment. However, aluminium shows limited feasibility in environments with high humidity, high concentrations of aggressive chemicals, and in regions with frequent temperature changes that cause condensation. For example, aluminium components of hydraulic lines lose their effectiveness in sprayer systems that work with agrochemical solutions, since aluminium can be subject to rapid corrosion under the influence of chemical compounds. In conditions of high humidity, such as the use of machinery in rice fields or in regions with frequent precipitation, aluminium parts are prone to the development of an oxide film, which over time weakens their mechanical strength. In addition, in environments with a high salt content in the air or soil, such as coastal regions, aluminium is subject to galvanic corrosion upon contact with other metals, which reduces the durability of systems.

Modelling of the stress-strain state of nodes using ANSYS software has shown that new-generation polymers, such as polyetheretherketone and polycarbonate, demonstrate high flexibility and resistance to wear in systems with medium loads. Average loads in the context of hydraulic systems refer to the operating pressure in the range of 10-15 MPa, which is typical for fluid distribution units, valve blocks, and connecting lines. In high-pressure units such as hydraulic cylinders, pump chambers, and pressure amplifiers, the operating pressure can exceed 20 MPa, which creates an increased risk of breaking polymer components. In such cases, polymers require additional reinforcement in the form of carbon fibre-based composite materials or glass fibre reinforcement. For example, for hydraulic cylinders, polyetheretherketone polymers reinforced with carbon fibres are successfully used, which increase their tear resistance and endurance.

Composite materials such as reinforced epoxy polymer have also found application in high-pressure assemblies, ensuring reliability and long service life. These materials combine high mechanical strength with lightness, making them ideal for applications in challenging environments such as hydraulic systems of tractors, sprayers, and seed drills that operate under heavy loads. During field testing, composite materials were installed in the hydraulic lines of 6 units of equipment, in particular, in tractors KHTZ-242k, KHTZ-243 and sprayers Amazone UX 5200 Super and John Deere R4038. Steel lines were used in 24 units of equipment, including tractors New Holland T6020 Delta, CASE IH Maxxum 125, sprayers Hardi Navigator 4000, Berthoud Tenor 5700, and all models of seed drills (Horsch Pronto 6 DC, Kuhn Espro 6000 RC, Vaderstad Rapid a 600s, Amazone Cirrus 6003-2.

The results showed that the loss of working fluid in composite lines was reduced by 15% compared to conventional steel lines. This is made possible by less friction of the liquid against the smooth inner walls of composite materials, and their greater resistance to temperature changes and mechanical wear. The high efficiency of composite lines was particularly noticeable in machinery that operated under high loads, such as tractors that performed deep ploughing and sprayers that operated on large farms.

In addition, the use of composite materials significantly increased corrosion resistance, which is an important factor in environments with high humidity or harsh chemicals. The integration of such materials into the design of the equipment allows ensuring its durability, reducing the load on engines due to lower weight, and increasing reliability in the long term. Assessment of the impact of the introduction of variable volume pumps and automated controllers on the energy efficiency of agricultural machinery shows significant positive changes, which are confirmed by the results of a comprehensive analysis (Table 3). The installation of variable volume pumps provided a significant reduction in energy losses that were previously observed due to a fixed flow rate, regardless of operating conditions. For tractors that performed heavy tasks, such as deep ploughing, energy losses were reduced by 30%. In sprayers that operated under less stressful conditions, the reduction reached 35%. For seed drills, this figure was 25%, which also indicates the effectiveness of new technologies for less energy-intensive operations.

Table 3. *Changes in key indicators in the field, after installation of the variable volume pump*

Type of equipment	**Tractors**		**Sprayers**			**Seeders**	
Model	KHTZ-242K	KHTZ-243	Amazone UX 5200 Super	Hardi Navigator 4000	Berthoud Tenor 5700	Horsch Pronto 6 DC	Kuhn Espro 6000 RC
Fuel consumption before (l/h)	16.5	16.2	10.4	10.2	10.5	7.3	7.5
Fuel consumption after (l/h)	12.3	12	7.6	7.4	7.7	5.5	5.7
Reduced fuel consumption (%)	25	26	27	27	26	25	24
CO_2 emissions before (kg/h)	32	31.5	27	26.8	27.2	21.5	21.8
CO_2 emissions after (kg/h)	24.2	23.8	19	18.8	19.2	16.2	16.5
Energy consumption before (kWh)	46	45	29	28.5	29	20.5	20.8
Energy consumption after (kWh)	34	33	22	21.5	22	15.3	15.5
Reduction of energy costs (%)	26	27	24	25	24	25	26

Source: compiled by the author

The automated controllers used in the study included the Bosch Rexroth BODAS RC12-10, Parker IQAN-MC43, and Danfoss PLUS+1 MC050-010 models. Each of the models performed specific functions in regulating the parameters of hydraulic systems in accordance with the type of equipment and the specifics of its operation. In tractors, Bosch Rexroth BODAS RC12-10 controllers were installed on the central control unit for variable volume hydraulic pumps. They were responsible for maintaining a stable operating pressure (18-20 MPa), regulating the volume flow depending on the operating mode, and monitoring pump efficiency. This reduced fuel consumption by 4 litres per hour by reducing the excessive load on the system.

Parker IQAN-MC43 controllers were used for sprayers, which were integrated into the hydraulic lines of the spray system. Their main task was to ensure a uniform distribution of liquid pressure (12 MPa) throughout the system, regardless of the speed of the sprayer. The controllers also controlled valves that regulated fluid flow, which reduced fuel consumption by 2.5 litres per hour. The seed drills used Danfoss PLUS+1 MC050-010 controllers, which were installed in the control units of seed metering devices. They provided the optimal pressure and flow adjustment (15 MPa) required to maintain accurate seeding depending on the type of soil. The controllers also controlled the flow distributors, which reduced the load on the pump, reducing fuel consumption by 1.8 litres per hour.

This reduction in fuel consumption was accompanied by a significant reduction in greenhouse gas emissions. For example, carbon dioxide emissions (CO_2) for tractors decreased by 18 kg/h, while for sprayers and seed drills – by 15 and 12 kg/h, respectively. These results are an important contribution to reducing the negative impact of agriculture on the environment, contributing to the sustainable development of the agricultural sector. In addition, the introduction of automated systems reduced the load on the engines, which had a positive impact on their service life and reduced maintenance costs on the path towards energy efficiency and environmental friendliness of agricultural processes, these results demonstrate the promise of automated technologies to improve productivity and reduce environmental impact.

The stability of the systems is significantly improved by evenly distributing the load between key components, such as variable volume pumps (Bosch Rexroth A10VSO, Parker Hannifin PVplus), distribution valves (Danfoss PVG 32), and hydraulic cylinders (Eaton Vickers C5). Automated controllers (Siemens S7-1200, Schneider Modicon M241) provided precise adjustment of pressure and fluid flow in real time, adapting the operation of systems to loads. The indicator of reducing the failure rate by 40% and achieving stability by 88% is the average value for all types of equipment involved in testing. For tractors, the stability indicator was 85%, for seed drills – 92%, and for sprayers – 87%.

Automated control systems have shown high efficiency in maintaining optimal operating pressure and fluid flow in real time. This helped to reduce friction and wear of components, extending the service life of hydraulic systems to 8-10 years compared to 5-7 years in systems without automated control. In conventional hydraulic systems, where control is carried out manually or through mechanical regulators, problems with excessive wear of seals, hydraulic cylinders and pumps were much more common, which reduced their service life.

Automated control systems are characterised by a reduction in overloads and an even distribution of the workload between components, which additionally helps to extend the service life. The reduction in maintenance and repair costs achieved through the use of automated systems was up to 15-20% compared to conventional systems. This is a significant economic factor for agricultural enterprises, especially in conditions of intensive use of equipment during sowing and harvesting operations.

The introduction of new technologies, in particular, automated control systems, variable volume pumps and high-precision controllers, has significantly improved the productivity of agricultural operations. For tractors equipped with automatic pressure and flow control systems, deep ploughing time has been reduced by 15%.

This was made possible by faster lifting and lowering of the plough, which reduced downtime, and due to greater manoeuvrability on turns. Such improvements have made it possible to reduce fuel consumption and increase overall operational efficiency.

Sprayers equipped with automated controllers provided stable pressure in the system, which provided uniform spraying of liquids and increase the efficiency of crop protection by 12%. In conventional systems without controllers, uneven spraying was often caused by pressure fluctuations that occurred due to changes in the speed of movement or uneven valve actuation. Based on automation, these problems were eliminated, which positively affected the quality of field processing and reduced the loss of working fluids.

Seed drills equipped with variable volume pumps and automatic dispensers demonstrated a significant improvement in the quality of crops. This was obtained by precise seed dosing and uniform distribution over the area, which was achieved through automated fluid flow control and constant monitoring of sowing parameters. As a result, this helped to reduce seed costs, increase the uniformity of germination, and reduce the time spent on repeated sowing in problem areas.

Discussion

The results of the study revealed the effectiveness of upgraded hydraulic systems for agricultural machinery. It is established that pumps with variable volume provide a reduction in energy losses by up to 35%, which confirms their feasibility for widespread implementation. Among the advantages, there is a reduction in fuel consumption by up to 25% and a reduction in CO_2 emissions up to 30%, which is a significant indicator for the environmental sustainability of the agricultural sector. These results are consistent with the findings of R. Jin *et al.* (2019), who confirmed the significant potential of upgraded pumps for energy efficiency.

Composite materials introduced into hydraulic systems have demonstrated the ability to reduce the weight of systems by up to 45%, increasing the efficiency of equipment. These data are consistent with conclusions of M. Lubecki *et al.* (2022), who argued that composites are capable of reducing the values of bending moments acting on the booms of working machines, reducing the power consumption of drive systems and improving the reliability of cylinders in aggressive environments and places with strong electromagnetic fields. The results of the study also confirm that composite materials have a sufficient level of wear resistance, which contributes to their successful use even in high-load units.

Automated controllers have proven to be a key element in improving the stability of hydraulic systems. Reducing the failure rate by 40% and increasing stability to 88% confirm the effectiveness of the technology. Automated systems simplify operation and reduce maintenance costs. However, G.R. Aby & S.F. Issa (2023) noted that self-propelled automated agricultural machinery, on the contrary, poses risks to people and the environment due to the complexity of developing reliable service safety systems. In addition, the researchers note the need to involve all specialists in the development of safer machines without exception: ergonomists, engineers, doctors, manufacturers, developers of the Internet of Things, officials, and international organisations.

Environmental indicators also improved significantly: fuel consumption was reduced by 25%, and CO_2 emissions were reduced by 22-30%, depending on the type of equipment. Results of a study published by Z. Zhu *et al.* (2022), showed that the introduction of a mechanical-electronic-hydraulic power system in tractors can reduce fuel consumption during various operations, such as ploughing, harvesting, and transportation. This confirms the feasibility of using such technologies to improve energy efficiency in the agricultural sector. The seed drills demonstrated the highest level of efficiency – up to 85%, which is explained by the adaptation of variable volume pumps to specific tasks. These results do not coincide with the conclusions of F. Breidi *et al.* (2017), who experimentally found that most variable displacement pumps (axial piston pumps) have low efficiency at low volume levels due to constant losses that do not scale with the power produced, and only digital variable volume pumps can minimise this inefficiency. But the results of the study confirmed the versatility of variable volume pumps and the ability to provide high efficiency even in less loaded operating modes.

The use of polymer pipelines in hydraulic systems can reduce pressure losses due to the smooth inner surface, which contributes to improved energy efficiency. Antifriction properties of polymers ensure tightness and reduce wear of components. This is not consistent with the results of D. Kraiem & A. Triki (2023), who noted that polyethylene pipes can be subject to hydraulic cavitation, which can negatively affect their durability and efficiency. Therefore, the researchers proposed to improve the capacity of the steel line by using polyethylene pipes only in the gate and in the built-in short section at the outlet.

The study proves that the introduction of variable volume pumps helps to increase the productivity of agricultural machinery. This is consistent with the findings of J. Kärnell & A. Ericson (2022), and Y. Zhao *et al*. (2023). J. Kärnell & A. Ericson investigated the performance of a digital pump with a discrete number of displacement settings and suggested using a shunt to improve its dynamics during switching. Y. Zhao *et al*. emphasised the importance of using variable volume pumps to increase the productivity of tractors. The study supplemented their research, proving that such pumps are universal for different types of equipment. Several other solutions for optimising the operation of variable volume hydraulic pumps were offered by P. Casoli *et al*. (2020). The researchers noted the feasibility of using alternative architectures to reduce energy costs, in particular, a separate electric steering pump and a Load Sensing Signal Combiner.

Upgraded pumps and automated controllers proved effective not only for tractors, but also for sprayers. Reducing energy losses by 35% allows the equipment to work more stably even in difficult conditions. X. Tian *et al*. (2024) also upgraded the hydraulic control system for agricultural machinery and its tools. Their proposed methods of reducing fuel consumption in different ways eliminated conflicts that exist between the control valves of the tractor and the tool, which cause an excessive increase in the pressure of the supply pumps and, consequently, high throttling losses.

Y. Li *et al*. (2022) highlighted the benefits of using composites to reduce the weight of hydraulic lines, which is confirmed by the results of this study. Composite materials not only reduce weight, but also provide the high strength required for field conditions. X. Sun *et al*. (2022) also upgraded tractor hydraulics to automatically adjust the depth of cultivation depending on soil conditions. The integration of automated controllers proposed by them made it possible to reduce fuel consumption and noise levels, and therefore, ensure comfortable operation of operators.

The uniqueness of the study lies in the combination of environmental, economic and technical aspects of improving the efficiency of hydraulic systems. These data provide a solid foundation for the development of new technologies aimed at developing sustainable agriculture. The main achievement was to reduce energy losses by up to 35% and reduce fuel consumption by up to 30%. The use of composite materials for hydraulic lines allowed significantly reducing the weight of systems by up to 45%, which increased their manoeuvrability and reduced energy costs. However, L. Solazzi (2020) noted limitations in the use of composites due to their instability in the field. The researcher proposed to use composites to avoid the variability of the stress state in the hydraulic cylinder, for which to use a multi-layer structure, in which the inner layer is made using a thin aluminium tubular part, and the coating is made of composite material. This is not consistent with the results of the study on sufficient stability of composite materials even under high loads and reducing pressure losses by up to 10%.

Environmental sustainability of technologies was achieved due to automated controllers, which allowed reducing CO_2 emissions up to 30% depending on the type of equipment. F. Mocera & A. Somà (2020) also proposed a solution that contributed to improving the environment. The researchers modelled a hybrid mechanism for efficient tractor power consumption using an energy storage system based on lithium-ion batteries. This contributed to a more efficient power distribution of the hybrid power plant under variable loads. This conclusion of F. Mocera & A. Somà (2020) is consistent with the results of the study to optimise work processes, speed up operations, and reduce energy losses through automation. Upgraded variable-volume pumps have reduced energy losses for tractors, seed drills, and sprayers. Even in less energy-intensive systems, such as seed drills, efficiency has increased to 85%. N. Kamthe *et al*. (2016) also noted the efficiency of axial piston pumps with constant pressure and variable volume, but did not consider it appropriate to use them in systems with moderate loads due to the high cost (5 times higher than radial piston pumps).

Reducing noise pollution was an additional achievement that provided more comfortable conditions for equipment operators. R. Zewdie & P. Kic (2017) also noted that agricultural machinery is characterised by high noise levels, especially during the start and deceleration of traffic, and when driving uphill. The authors recommended sealing the driver's cab with rubber seals, and when working on outdated equipment, since the noise level is higher than 80 dB, using individual hearing aids. Innovative solutions have demonstrated the resistance of equipment to temperature changes, and therefore, reliability in difficult operating conditions. This result is consistent with the findings of S. Pedersen *et al*. (2019), who also proposed the introduction of smart farming technologies and environmental solutions to reduce resource consumption. The stability of the systems has increased to 88% due to the uniform load distribution between the components. This is consistent with the findings of X. Guo *et al*. (2022), who noted that the hydraulic control system causes excessive throttling losses, resulting in low overall energy efficiency. The researchers designed an 89.8% more efficient hydraulic system with a multi-pressure rail for agricultural machinery.

The advantages of modernisation of hydraulic systems of agricultural machinery identified in the study are confirmed by conclusions of V. Ghodke *et al*. (2015), who have proven that in hydraulic systems, variable displacement pumps save electricity, increase productivity, or control movement more accurately, safely, and efficiently. The mechanism of changing the working volume and the power-to-weight ratio of the variable working volume piston pump makes these pumps most suitable for high power levels. P. He *et al*. (2019) noted that reducing fuel consumption is a key factor in improving the economic efficiency of agricultural production. Thus, the results of the study combine the analysis of energy efficiency, environmental friendliness and stability of hydraulic systems. The integration of such technologies contributes not only to increasing the productivity of the agricultural sector, but also to ensuring sustainable development.

Conclusions

The results of the study confirmed the high efficiency of implementing modern technologies in hydraulic systems of agricultural machinery. The use of variable volume pumps has significantly reduced the energy losses that occur in conventional systems due to a fixed flow rate, regardless of operating conditions. For tractors that performed heavy operations, such as deep ploughing, energy losses were reduced by 30%, and for sprayers and seed drills – by 25-35%. This decreased fuel consumption by up to 30% and reduced CO_2 emissions by 12-18 kg/h.

Automated control systems equipped with pressure and flow sensors have ensured the stability of hydraulic systems. In sprayers, a uniform pressure distribution helped to increase the efficiency of crop processing by 12%. In seed drills, automatic flow control allowed achieving high accuracy of seed dosing, which reduced seed consumption and increased the uniformity of seedlings. In general, automation reduced the execution time of operations by 12-15%, and the system stability indicator increased to 88%. The introduction of composite materials in hydraulic lines helped to reduce working fluid losses by 15% and decrease the weight of components by up to 55%, which helped to lower the load on engines and increase the service life of systems up to 8-10 years. The composites have demonstrated high corrosion resistance, which is especially important in aggressive environments where machinery is used.

Synthetic working fluids reduced viscosity at high temperatures, minimising energy losses, and polymer lines provided additional loss reduction due to their antifriction properties. All these factors contributed to a reduction in maintenance costs by 15-20% and an increase in economic benefits for agricultural enterprises. Promising areas of further study are the development of new automated control systems that can adapt the operation of hydraulic systems to various operating conditions in real-time. It is also important to investigate the impact of innovative materials on the durability and environmental friendliness of equipment during long-term use.

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Conflict of Interest

None.

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Проєктування та аналіз гідравлічних систем для автоматизованих сільськогосподарських машин

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Анотація. Дослідження присвячено проєктуванню та аналізу гідравлічних систем для автоматизованих сільськогосподарських машин із метою підвищення їхньої продуктивності, енергоефективності та надійності. Для випробувань було залучено трактори, обприскувачі та сівалки, які працювали у реальних польових умовах в різних регіонах України з урахуванням різноманітних типів ґрунтів та кліматичних факторів. Основними методами дослідження були польові експерименти, аналіз даних сенсорів та моделювання параметрів гідравлічних систем у програмному середовищі ANSYS. У ході випробувань, проведених на сучасних моделях тракторів, обприскувачів і сівалок, визначено, що автоматизовані контролери та насоси змінного об'єму забезпечують суттєве зниження енергетичних втрат і витрат пального. Для тракторів скорочення витрат пального досягло 25-27 %, в обприскувачах та сівалках – 24-26 %. Викиди CO_2 зменшилися в середньому на 15%, що відповідає цілям сталого розвитку. Оптимізація конструкції гідравлічних магістралей із використанням композитних матеріалів дозволила знизити енергетичні втрати на 15 %, порівняно з традиційними сталевими магістралями. Це стало можливим завдяки зменшенню тертя та кращій стійкості до зношування. Використання синтетичних робочих рідин забезпечило стабільність потоку в умовах високих температур, знижуючи ризик блокування системи та утворення осадів. Загалом впроваджені технології підвищили стабільність роботи гідравлічних систем на 88 %, знизили частоту збоїв на 40%. Отримані результати підтвердили ефективність впроваджених рішень у підвищенні продуктивності, енергоефективності та екологічності. Інноваційні підходи, включаючи автоматизовані системи керування, сприяли підвищенню якості агротехнічних операцій і забезпечують тривалий термін служби компонентів. Отримані результати можуть бути використані у проєктуванні сучасної сільськогосподарської техніки, впровадженні автоматизованих систем керування у виробничих процесах аграрного сектору, а також при модернізації існуючого парку техніки з метою підвищення її продуктивності, енергоефективності та екологічності

Ключові слова: аграрна техніка; оптимізація агротехнологій; енергоефективність виробництва; модернізація; інновації