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Assessment of the safety and toxicity of sulphur-enriched spirulina in white mice

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Abstract. The study of *Spirulina platensis* biomass enriched with sulphur is of particular relevance due to its potential as a valuable feed supplement for livestock. This study aimed to assess the safety and acute toxicity of sulphur-enriched spirulina biomass. Linear mice were used for the experiment. To evaluate the safety, the mice were administered 0.35 cm^3 of physiological saline (control) and 25% and 50% suspensions of sulphur-enriched spirulina biomass (experimental groups I and II) via intragastric administration. The animals were observed for 12 days, and protein metabolism indicators were examined. For acute toxicity assessment, laboratory animals received intragastric doses of spirulina biomass ranging from 5 to 6,000 mg/kg body weight. The observation period lasted 14 days. It was established that during the 12-day observation period following the administration of spirulina biomass suspensions, no lethal cases were recorded in the mice. No pathological or anatomical changes in the internal organs were observed in the experimental animals. No statistically significant increase or decrease in total protein levels or aminotransferase activity was detected in mice from experimental groups I and II compared with the control group. Assessment of acute toxicity indicated that spirulina biomass belongs to toxicity class 4, categorising it as a low-toxicity substance. No significant behavioural changes or notable effects on metabolic processes were observed, suggesting the potential safety of this biomass for use in animal husbandry. The findings of this study may be applied in livestock production to introduce innovative approaches to feed enrichment with beneficial elements that enhance animal productivity and health

Keywords: *Spirulina platensis*; liver; laboratory animals; feed supplement; clinical condition of animals

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Introduction

Spirulina platensis, a multicellular blue-green microalga, is widely used as a valuable feed additive and bioactive ingredient in the food industry. Assessing safety parameters is essential for determining whether sulphur-enriched spirulina is safe for consumption at various doses and by different consumer groups, including children, pregnant women, individuals with allergies, and those with chronic conditions. Additionally, the toxicity of supplements, particularly those containing sulphur, must be thoroughly investigated, as excessive sulphur consumption can lead to harmful effects, such as poisoning or impaired organ function. Scientific research in this area is crucial for understanding how sulphur enrichment alters the properties of spirulina and what potential risks may arise from its consumption, thereby contributing to public health protection. Furthermore, it will enable the development of safe dosage recommendations and guidelines for the use of this supplement, as well as establish clear regulations for the production and sale of such products on the market, considering the specific characteristics of sulphur-enriched spirulina.

According to O.M. Tytariova & O.A. Kuzmenko (2021), *Spirulina platensis* contains a significant amount of essential amino acids, polyunsaturated fatty acids, B vitamins, iron, magnesium, and other micronutrients, making it a promising feed for animals and poultry. It contains between 55% and 70% protein by dry weight, significantly exceeding similar indicators of traditional protein products such as soybeans. The biomass of this microalga can also be used as a dietary and therapeutic supplement.

Significant attention is paid to the adaptive capabilities of *Spirulina platensis* in response to changing cultivation conditions. One of the important features of this microalga is its ability to accumulate certain mineral elements in its biomass, allowing for the adjustment of its chemical composition depending on the needs of the end consumer. With an increased content of a particular mineral element in the cultivation medium, its active accumulation in the biomass of the microalga occurs (Abbas *et al*., 2024). Of particular interest is the ability of spirulina to accumulate sulphur – a vital element involved in the synthesis of proteins, enzymes, antioxidants (glutathione), as well as in the metabolism of vitamins (biotin, thiamine) and coenzymes. This is confirmed by the research of E. Henao *et al.* (2020), who found that sulphur-enriched *Spirulina platensis* biomass can acquire unique properties, including influencing the bioavailability of other micronutrients and potentially enhancing the immune status of animals. It was established that they can modulate the Nrf2 factor or other regulatory pathways that determine the body's resistance to oxidative stress.

Research by T. Clifford *et al.* (2021) has shown that sulphur is involved in the synthesis of Sadenosylmethionine (SAM), γ-glutamylcysteine glycine, and a range of hormones, enzymes, and vitamins. Sulphur-containing compounds are key components of many antioxidants that influence physiological processes in the body. This opens up possibilities for the use of sulphur-enriched spirulina biomass as a means of improving immune status and antioxidant protection in animals.

Studies on the effects of spirulina on farm animals demonstrate its positive impact. For instance, O. Tytariova *et al.* (2022) found that adding spirulina to rabbit feed reduced the accumulation of heavy metals in meat. This confirms its ability to influence mineral metabolism and improve the quality of the final product. Meanwhile, G. Kolluri *et al.* (2022) investigated the effects of spirulina added to the drinking water of broilers during cyclic chronic heat stress and found improvements in productivity, physiological status, and immunobiochemical parameters of the poultry.

The study of M. Marino *et al.* (2021) confirmed that sulphur-containing compounds influence biochemical processes in the body and can have a positive effect in the context of animal feed. Specifically, they participate in the synthesis of amino acids (methionine, cysteine), coenzymes,

and vitamins, which are essential for the normal growth and development of animals. Additionally, these compounds can positively influence the absorption of other micronutrients such as iron, magnesium, and calcium (Francioso *et al.*, 2020). This highlights the importance of controlling the level of sulphur-containing compounds in feed and their potential impact on the metabolism of other beneficial substances.

Despite numerous studies dedicated to the nutritional value and biological activity of spirulina, the question of its toxicological safety, when enriched with sulphur, remains insufficiently studied. In particular, there is a lack of comprehensive toxicological studies that would assess the impact of such biomass on the mammalian organism when used as a feed additive. This creates a need for an expanded study of the safety and acute toxicity of sulphur-enriched spirulina. Thus, the aim of this study is to experimentally assess the safety and toxicity of sulphurenriched *Spirulina platensis* biomass using a white mouse model.

Materials and Methods

Building on the known ability of *Spirulina platensis* to accumulate mineral elements, the biomass of the blue-green alga with increased sulphur content was obtained in 2024 at the Institute of Animal Husbandry and Food Technologies of the Bila Tserkva National Agrarian University. To evaluate the safety of sulphur-enriched spirulina biomass, three groups of linear mice (four individuals in each) of the same age (55 days), sex, size, and body weight (19.5-20.5 g) were formed using a random assignment. The saline solution and the tested spirulina suspensions were administered intragastrically to the animals using a metal probe. The distribution of animals into groups is presented in Table 1. This approach allowed for a standardised study with a clear consideration of the influencing factors being studied.

Table 2. *Basic physical and chemical parameters of raw materials (n = 4)*

Group	Number of animals	Investigated factor
Control	4	Physiological saline at a dose of 0.35 cm^3 per animal
Experimental I	4	25% spirulina biomass suspension at a dose of 0.35 cm^3 per animal
Experimental II	4	50% spirulina biomass suspension at a dose of 0.35 cm^3 per animal

Source: developed by the authors

After intragastric administration of the experimental samples to the mice, they were observed for 12 days. At the end of the experiment, the mice were anaesthetized and euthanised for pathological and anatomical studies of the internal organs and sampling for biochemical analysis. A homogenate was prepared from the collected liver, in which certain indicators of protein metabolism were determined. The total protein content was determined using the method of O.H. Lowry *et al.* (1951), and the activity of aminotransferases was determined using the method of S. Reitman & S. Frankel (1957).

In addition to assessing safety parameters such as total protein levels in the liver, aminotransferase activity (aspartate aminotransferase and alanine aminotransferase), and the pathological condition of internal organs, the acute toxicity of sulfur-enriched spirulina biomass in white mice was determined. The experiments consisted of two stages: preliminary and expanded. The suspension was administered to the experimental animals once and twice (depending on the dose) intragastrically. For 6 hours before the administration of the spirulina suspension prepared in a 1% starch solution, the mice were kept on a fasting diet with free access to water. Each group of mice consisted of five individuals.

In the preliminary study, doses of 5, 500, and 5,000 mg of spirulina per kg of body weight were administered intragastrically to mice. In the expanded study, doses of 3,000, 4,000, 5,000, and

6,000 mg/kg body weight were investigated. Observations of the mice were carried out for 14 days. Doses of 4,000-6,000 mg/kg body weight were divided in half and administered twice. All experimental studies were conducted following modern methodological approaches and in compliance with relevant requirements and standards, in particular, meeting the requirements of DSTU ISO/IEC 17025:2005 (2006). Animal maintenance and all manipulations were carried out by the provisions of the Procedure for Conducting Scientific Research and Experiments on Animals by Research Institutions (Law of Ukraine No. 249, 2012) and the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986).

Results

In assessing the safety of spirulina, it was established that no fatalities occurred among the experimental or control groups of white mice over the twelve-day experiment. It was found that within the first 2.5-3.5 hours after the administration of 0.35 cm^3 of a 50% suspension of sulphurenriched spirulina biomass, animals from the second experimental group exhibited lethargy. Over time, the mice regained mobility and responded to created noise, turning lights on and off, and touching. In 50% of mice, gastrointestinal disturbances were observed during the first day. Consumption of food and water resumed after 16-24 hours. Animals periodically approached feeders and drinkers.

According to observations of mice that were administered 0.35 cm^3 of a 25% suspension of spirulina biomass, no behavioural disturbances were detected during the twelve-day experiment. Upon dissection of the mouse carcasses and conducting pathological and anatomical studies, it was found that the condition of the internal organs of animals from the first and second experimental groups did not differ from the condition of the internal organs of control mice. When studying certain indicators of protein metabolism in the liver of mice during the establishment of the safety of sulphur-enriched spirulina biomass, it was established that on the 12th day after administration, the activity of aspartate aminotransferase in animals from the first experimental group was not significantly lower compared to the control. The difference was within the margin of error (Table 2).

Table 2. *Protein content and aminotransferase activity in the liver of mice exposed to Spirulina, M ± m, n = 4*

Group	Activity of AST, μmol/h/g	Activity of ALT, μmol/h/g	Content of total protein, g/kg
Control	10.3 ± 0.36	13.2 ± 0.68	44.7 ± 2.32
Experimental I	9.9 ± 0.47	12.9 ± 0.82	43.8 ± 3.56
Experimental II	10.5 ± 0.43	13.6 ± 0.76	45.5 ± 1.97

Note: AST – aspartate aminotransferase; ALT – alanine aminotransferase
Source: developed by the authors

Analysing the activity of aspartate aminotransferase in the liver of mice from the second experimental group, it was found that the increase in the indicator was also not statistically significant. Similarly, it was established that the activity of alanine aminotransferase in the liver of animals from the experimental groups did not statistically differ from the indicator in animals from the control group. The content of total protein in the liver of mice from the control group was at the level of 44.7 g/kg. Deviations from the control in the first and second experimental groups were 2% and 1.7%, respectively, which did not exceed the limits of statistical error. Thus, it was established that with a single administration of 0.35 cm^3 of 25% and 50% suspensions of spirulina biomass, no disturbances in protein metabolism were observed in the liver of mice.

Along with determining safety, the acute toxicity of sulphur-enriched spirulina biomass was investigated. According to the results of a preliminary study on the administration of *Spirulina platensis* biomass, enriched with sulphur, at doses from 5 to 5,000 mg/kg of body weight, it was established that over 14 days, no changes in the behaviour of animals were observed. Mice responded to stimuli, moved freely, and periodically consumed food and water. Also, no lethal cases were recorded (Table 3).

Table 3. *Results of observation of mice during the determination of the toxicity of sulphur-enriched Spirulina platensis biomass (preliminary study)*

Number of mice in the group	Dose of spirulina, mg/kg	Number of animals that died	Behavioural changes	Changes in body weight (g)	Gastrointestinal disorders
5	5	0	None	None	None
5	500	0	None	None	None
5	5,000	0	Temporary refusal of food and water for 1.5-2 hours after administration; normal behaviour restored within 4-10 hours	Slight weight loss (up to 5%)	None

Source: developed by the authors

For a dose of 5,000 mg/kg, mice refused food and water for 1.5-2 hours after the administration of Spirulina. After 4-10 hours, the behaviour of mice in this group was within physiological norms. Under the conditions of the expanded study, no deviations in the behaviour of mice were noted. After the administration of the second part of the dose of 5,000 mg/kg of body weight to 4 animals, temporary lethargy was observed (2-3 hours), and the mice did not eat or drink. By the 6th hour of observation, the ethological indicators of mice in this group were normal (Table 4)

Table 4. *Results of observation of mice during the determination of the toxicity of sulphur-enriched Spirulina platensis biomass (expanded study)*

Number of mice in the group	Dose of feed additive, mg/kg	Number of animals that died	Ethological indicators	Ethological changes	Body weight changes (g)	Gastrointestinal disturbances
5	3,000	0	Within normal limits	None	Slight weight loss (up to 3%)	None
5	4,000	0	Within normal limits	None	Slight weight loss (up to 3%)	None
5	5,000	0	Within normal limits	None	Slight weight loss (up to 5%)	Disturbances observed for 16-18 hours after administration; recovery of functions within 48 hours
5	6,000	0	Within normal limits	None	Slight weight loss (up to 5%)	Disturbances observed for 16-18 hours after administration; recovery of functions within 48 hours

Source: developed by the authors

When studying a dose of sulphur-enriched *Spirulina platensis* of 6,000 mg/kg in mice, gastrointestinal disorders were detected. The intensity of the movements of animals from this group was reduced. 16-18 hours after the administration of spirulina biomass, the consumption of food and water by mice resumed. By the 48th hour of the study, the functioning of the gastrointestinal tract of animals was normal. Ethological changes in mice that were administered Spirulina in amounts of 5,000 and 6,000 mg/kg are associated with the administration of a large amount of feed additive to the animals. It was proved that in an expanded study when administering sulphurenriched spirulina biomass to white mice at a dose of 3,000 to 6,000 mg/kg of body weight for a 14 day observation, no animal deaths were detected.

Discussion

The results of this study on the safety and acute toxicity of sulphur-enriched *Spirulina platensis* biomass are of significant importance for the further development of feed additives and the enrichment of animal diets with microelements. In particular, it was established that even at high doses (3,000-6,000 mg/kg body weight), spirulina biomass does not cause lethal cases in white mice. This is consistent with the findings of H.V. Merzlova (2015), according to which, when 5,000 mg/kg body weight of zinc-enriched spirulina biomass was administered to laboratory animals, no lethal cases were observed during the experimental period. It is important to note that, unlike studies with zinc biomass, the current study shows that sulphur-containing spirulina may be safer for intragastric administration.

The absence of changes in protein metabolism indicators in the liver of mice that were administered a single dose of 0.35 cm^3 per head of a 50% suspension of sulphur-enriched spirulina biomass (safety assessment) is confirmed by studies by authors G. Merzlova & O. Melnichenko (2012), which indicate that when laboratory animals were administered spirulina biomass enriched with Cobalt, no statistically significant increase or decrease in aminotransferase activity and total protein was observed. Therefore, it has been experimentally proven that *Spirulina platensis* biomass enriched with sulphur belongs to low-toxicity substances – class 4. The lethal dose (LD_{50}) of spirulina biomass for intragastric administration to laboratory animals (white mice) is greater than 5,000 mg/kg (Khan *et al.,* 2005).

Researchers M.B. Colovic *et al.* (2018) highlighted the crucial role of sulphur-containing amino acids in protecting cells from oxidative stress and the toxic effects of heavy metals. These amino acids have been shown to reduce damage to cellular structures by neutralising free radicals, playing a critical role in maintaining the antioxidant balance in the body. *Spirulina platensis* biomass, enriched with sulphur, contains a significant amount of these amino acids, which can contribute to increasing the body's resistance to the effects of exogenous toxicants. Studies of the toxicological profile of this biomass have not revealed a significant increase in the level of aminotransferases in animals receiving high doses of sulphur-enriched spirulina, confirming the absence of a negative impact on the liver and potential antioxidant effects. Given this, the application of such biomass may be promising in veterinary medicine and animal husbandry as an effective means of preventing oxidative stress, which can occur as a result of intensive animal farming, exposure to environmental pollutants, and metabolic stress.

C.A. Houghton (2019) highlighted sulforaphane as a promising nutraceutical with potent antioxidant properties. Although the mechanism of action of individual compounds was not analysed in this study, the results demonstrate a similar positive effect of sulphur-containing spirulina biomass on the physiological state of animals. Unlike sulforaphane, which activates specific antioxidant pathways, the sulphur contained in spirulina biomass is involved in general metabolic processes and provides a more prolonged effect on cellular metabolism. This could make it an effective component in animal feed, as

sulphur-enriched biomass can contribute to a stable increase in the antioxidant status of the organism and improve its overall resistance to negative external factors.

Researchers Y. Ingenbleek & H. Kimura (2013) indicated that a sulphur deficiency can significantly disrupt protein metabolism and lead to a decrease in the efficiency of energy metabolism processes. In this regard, the introduction of sulphur-containing additives to the diet is of great importance for maintaining the normal physiological state of animals. According to the obtained results, the level of total protein in the liver of animals that received *Spirulina platensis* biomass, enriched with sulphur, remained within the physiological norm. This indicates the absence of a negative impact on protein metabolism and confirms the possibility of using such biomass to support metabolic homeostasis.

K. Jankowski *et al.* (2014) studied the impact of sulphur fertilisers on the concentration of microelements in rapeseed and found that increasing the sulphur content in the soil contributes to an increase in the concentration of zinc and manganese in plant tissues. Similarly, the process of enriching *Spirulina platensis* biomass with sulphur can influence the improvement of the bioavailability of microelements for animals, contributing to a more efficient absorption of nutrients. In addition, there may be a synergistic interaction between sulphur-containing compounds and other microelements, which may have a positive impact on the overall level of mineral metabolism. Further research can help clarify how sulphur-containing biomass affects the metabolism of microelements and what concentrations of sulphur are optimal for enriching feed.

In the research of A. Maruyama-Nakashita (2017), it was established that plants can adapt their metabolism to sulphur deficiency through the activation of enzymatic pathways. The obtained results confirm that *Spirulina platensis* has a high ability to accumulate sulphur, which opens up possibilities for its use as a source of this microelement in animal feed. The variability of the chemical composition of spirulina biomass depending on cultivation methods can have a significant impact on its biological activity. I.D. Nwachukwu *et al.* (2012) emphasised the significance of sulphur-containing natural compounds in the formation of plant defence mechanisms against pathogens. Since the role of sulphur-enriched *Spirulina platensis* biomass in modulating the immune response of animals remains insufficiently studied, this aspect is a promising direction for further research. In particular, it is necessary to assess the possible impact of such biomass on the state of the animal immune system, its ability to regulate inflammatory processes and increase resistance to infectious agents.

Y. Yagishita *et al.* (2019) emphasised the importance of the form in which sulphur-containing compounds are consumed to achieve maximum efficiency. The introduction of sulphur-containing spirulina biomass in the form of a suspension ensures a uniform distribution of microelements in the animal's body, which may be an advantage compared to other sources of sulphur. This confirms the need for further research on optimal dosages and administration methods to achieve maximum efficiency.

Thus, the results of the study confirm the significant role of sulphur in supporting metabolic processes, particularly in protein and energy metabolism, as well as in regulating the antioxidant status of the organism. The absence of lethal cases in white mice when administered *Spirulina platensis* biomass enriched with sulphur at high doses (up to 6,000 mg/kg body weight) indicates its low toxicity and safety for intragastric administration. Analysis of biochemical indicators showed that the level of total protein in the liver of mice from the experimental groups did not differ from the control values, confirming the absence of a negative impact on metabolic homeostasis. The results also demonstrated the stability of aminotransferase activity, indicating the absence of a toxic effect of sulphur-enriched spirulina on liver function. Temporary behavioural changes and minor disturbances of

gastrointestinal tract functions, recorded in groups with the highest doses, were short-term and completely disappeared within 48 hours, confirming the adaptive capabilities of the organism to such dosages.

The results obtained demonstrate not only the safety of sulphur-enriched *Spirulina platensis* biomass but also its potential usefulness for feed enrichment. Spirulina's ability to accumulate sulphur can contribute to improving the bioavailability of microelements in animal diets, which is consistent with previous research on the role of sulphur in the absorption of zinc, manganese, and other important elements. Additionally, the antioxidant properties of sulphur-containing compounds can help protect cells from oxidative stress, which is particularly important in the context of intensive animal farming.

The practical significance of the obtained results includes the possibility of using sulphurenriched spirulina biomass in veterinary dietetics to increase animal productivity and as a prophylactic agent against stress factors. However, further research should be aimed at determining the optimal dosages for long-term use, assessing its impact on the performance indicators of different animal species, and the mechanisms of interaction between sulphur-containing compounds and other biologically active components of the feed ration.

Conclusions

The conducted study assessed the safety and acute toxicity of sulphur-enriched *Spirulina platensis* biomass using a white mouse model. The experimental results confirmed that spirulina biomass belongs to low-toxicity substances (safety class 4) and can be used in veterinary practice and animal husbandry as a feed additive. Under conditions of a single intragastric administration of 0.35 cm^3 of a 50% suspension of spirulina biomass, no lethal cases were recorded among white mice. In the first hours after administration, animals exhibited short-term signs of lethargy and gastrointestinal disturbances, expressed in reduced activity and temporary refusal of food. However, within 24 hours, the condition of the animals normalised, indicating the absence of a long-term toxic effect.

The study of biochemical parameters revealed that the administration of 0.35 cm^3 of 25% and 50% suspensions of spirulina biomass did not cause significant changes in protein metabolism indicators in the liver of mice. The activity of AST and ALT remained within the physiological norm and did not differ from the indicators of the control group. The content of total protein also did not undergo significant changes, confirming the absence of a negative impact of sulphurenriched spirulina biomass on the functional state of the liver of laboratory animals. Studies of the acute toxicity of sulphur-enriched spirulina biomass showed that it is characterised by a high safety margin. The administration of doses ranging from 5 to 5,000 mg/kg body weight to mice did not result in lethal outcomes, and the observed behavioural changes were temporary. Even when the maximum dose of 6,000 mg/kg body weight was administered, no serious pathological changes were observed in the animals. A slight decrease in mouse activity, short-term gastrointestinal disturbances, and a minor loss of body weight were reversible and completely disappeared within 48 hours after administration. It was determined that the LD_{50} of spirulina biomass exceeds 5,000 mg/kg, confirming its safety for use.

A promising direction for further research is the evaluation of the effectiveness of using sulphur-enriched spirulina biomass in the feeding of young dogs. An important task is to determine the optimal dosages, long-term effects on the animal's body, and possible mechanisms of the positive effect on physiological indicators. Further experimental studies can provide new data on the bioavailability of sulphur-containing compounds, their impact on metabolic processes, and the overall physiological state of animals, which will allow for a more effective application of spirulina biomass in veterinary practice and animal husbandry.

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Conflict of Interest

None.

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Перевірка показників нешкідливості та токсичності спіруліни збагаченої сульфуром на білих мишах

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Анотація. Вивчення біомаси *Spirulina platensis*, збагаченої сульфуром, є актуальним через її потенціал як цінної кормової добавки для сільськогосподарських тварин. Метою роботи було вивчення нешкідливості та гострої токсичності біомаси спіруліни збагаченої сульфуром. Для дослідження використовували лінійних мишей. Вивчаючи нешкідливість біомаси спіруліни мишам внутрішньошлунково вводили по 0,35 см^3 фізіологічного розчину (контроль) та 25 % і 50 % розчину суспензії біомаси спіруліни збагаченої сульфуром (I і II дослідні групи). Спостереження за тваринами проводили продовж 12 діб. У організмі мишей вивчали показники білкового обміну. За вивчення гострої токсичності лабораторним тваринам водили внутрішньошлунково біомасу спіруліни у кількості від 5 до 6000 мг/кг маси тіла. Спостереження за мишами тривало 14 діб. Встановлено, що, досліджуючи нешкідливість, протягом 12-добового спостереження після введення суспензій біомаси спіруліни летальних випадків у мишей не було виявлено. У дослідних тварин не виявлено патолого-анатомічних змін внутрішніх органів. Статистично значущого збільшення або зменшення вмісту загального білка, активності амінотрансфераз у мишей із I і II дослідних груп у порівнянні із тваринами контрольної групи не було встановлено. Визначаючи гостру токсичність, виявлено, що біомаса спіруліни відноситься до малотоксичних речовин – 4 клас. Значних поведінкових змін та суттєвого впливу на метаболічні процеси у тварин не зафіксовано, що свідчить про потенційну безпечність цієї біомаси для використання у тваринництві. Результати дослідження можна використати у тваринництві для впровадження інноваційних підходів до збагачення кормів корисними елементами, що покращують продуктивність і здоров'я тварин

Ключові слова: *Spirulina platensis*; печінка; лабораторні тварини; кормова добавка; клінічний стан тварин

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Efficiency of using mixed feeds with different levels of lysine and methionine for growing turkeys

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Abstract. The purpose of the study was to investigate the effect of feeding complete mixed feeds with different levels of lysine and methionine on the growth of young turkeys. Experimental studies were performed on young meat turkeys of the BIG 6 cross. Based on the method of balanced groups, five experimental groups of day-old poultry were established. The experiment lasted 126 days and was divided into two periods: equalising (7 days) and main (119 days). During the equalising period, the experimental young animals consumed mixed feed of the control group. During the main period of the experiment, the amount of lysine and methionine relative to the mixed feed of poultry of the control group for the rearing periods decreased or increased proportionally by 5% and 10%. It was found that different levels of lysine and methionine in mixed feeds for young turkeys affect their productivity in different ways. At the age of 126 days, turkeys that received mixed feed with an increase in the amount of lysine and methionine by 5% and 10% had the highest live weight – they outnumbered the analogues of the control group by 5.9% ($p < 0.01$) and 3.6%, respectively. Young animals that consumed mixed feed with a reduced amount of lysine and methionine in this indicator were inferior to their control peers by 5.6% ($p < 0.05$) and 2.7%, respectively. An increase in the level of lysine and methionine by 5% and 10% in mixed feed of turkeys at all stages of their growth helps to reduce feed costs per 1 kg of live weight gain by 4.3% and 2.1%, respectively. It is proved that the relationship

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between the levels of lysine and methionine in mixed feed for young turkeys and its costs per 1 kg of live weight gain is described by a polynomial line with a reliable approximation coefficient $R^2 = 1$. Correlation analysis shows that there is a significant ($p < 0.05$) strong inverse relationship between these two indicators ($r_s = -0.82$). The poultry liveability index in all experimental groups was close (94-96%), but the probable influence of different levels of lysine and methionine in mixed feed during poultry rearing on its liveability indicator was not established

Keywords: feeding; poultry; amino acids; feed consumption; liveability

Introduction

In the field of poultry farming, one of the main tasks is to ensure high productivity through efficient use of feed. Raising turkeys requires a detailed approach to the development of the diet, especially in terms of the level of essential amino acids such as lysine and methionine. Due to the increased productivity of modern turkey crosses, producers can get more products in a shorter period of time, which contributes to increased profitability. However, the high growth rate of birds is not always accompanied by an improvement in their health, which requires careful monitoring and optimisation of growing conditions. In industrial production at poultry farms, turkeys are exposed to various technological factors and pathogens that can be transmitted through feed, water, and air. Given the limited use of antibiotics in poultry farming, losses due to this can be minimised by increasing the immunity of birds and accelerating the development of the immune system. Amino acids are components with immune-boosting functions, and some of them (arginine, lysine, methionine) also regulate various key metabolic processes. However, the levels of various amino acids, in particular, lysine and methionine, in turkey feeding are now causing a lot of discussion and controversy. According to NRC recommendations (4), they specify lower levels of these amino acids than those offered by the manufacturer of modern turkey crosses British United Turkeys Ltd.

Numerous studies by various researchers and manufacturers have proven that different levels of lysine and methionine for feeding young turkeys at different stages of growth can significantly affect both their productivity and immune status, and the indicators of economic efficiency of production. That is why the issues of investigating the efficiency of using mixed feeds with different levels of lysine and methionine for growing turkeys of modern crosses in the industrial conditions of farms in Ukraine are relevant and important. J. Jankowski *et al.* (2020) evaluated the effect of different dietary ratios of arginine, methionine, and lysine on turkey performance, immune status, and meat quality. The results of the study showed that the correct ratio of these amino acids not only increases the growth rate and quality of meat, but also has a positive effect on the immune system, which helps to improve the overall health of birds. A.O. Oso *et al.* (2017) determined the effect of different levels of arginine and methionine in the diet of turkeys with high lysine content. They found that changes in the levels of these amino acids significantly improved the birds' performance, particularly muscle growth and bone development. Improved immunity and bird health were important additional results of this study.

P. Konieczka *et al.* (2022) attempted to assess the effect of elevated levels of arginine, lysine, and methionine in the diet of turkeys on their performance, intestinal integrity, and immune status under various conditions. The purpose of their study was to determine how increasing the levels of these amino acids in compound feeds can improve the health and productivity of birds, especially in conditions of stress or disease. The results of the study showed that increasing the levels of arginine, lysine, and methionine in the diet of turkeys has a positive effect on their

performance, in particular, on the growth rate and development of muscle mass. In addition, these amino acids help to improve intestinal integrity, which is important for the normal absorption of nutrients and maintaining the overall health of birds. D. Murawska *et al.* (2018) investigated the effect of various sources of methionine in the diet of turkeys on their productivity and meat quality. The purpose of their study was to determine how different sources of methionine affect the growth rate and quality of meat, in particular, its texture and taste properties. The results showed that methionine sources have a significant impact on the quality of meat, improving its taste characteristics and the overall productivity of birds.

N. Dyshliuk & N. Mazur (2024) evaluated the effect of different levels of lysine and methionine in mixed feed on the productivity and quality of turkey meat. The results showed that optimising the levels of these amino acids in the diet of turkeys improves their growth rate, muscle mass development, and meat quality. In particular, the study pointed to the importance of the balance between lysine and methionine in achieving high productivity and improving the physiological parameters of birds, which is crucial for poultry farming. V.S. Bomko *et al.* (2023) in their study drew attention to the efficiency of the use of feed and feed additives for animal feeding. The purpose of their study was to investigate the effect of various feed additives on animal productivity. The results showed that the use of specialised feed additives can significantly increase the efficiency of feed use, improve the growth rate and overall health of animals. The study highlighted the need for a proper selection of feed additives to ensure optimal development of farm animals. The purpose of the study by C. Chang *et al.* (2024) was to investigate the effect of total protein and lysine levels in the diet on meat quality and myofibrile characteristics in slow-growing chickens. The results showed that correction of protein and lysine levels in the diet of chickens affects the quality of meat, in particular, the texture and taste characteristics. The study also pointed to the importance of providing appropriate levels of these nutrients to improve meat quality in slow-growing birds.

However, previous studies have not fully addressed the effect of different levels of these amino acids on specific economic indicators, such as feed costs per unit of live weight gain and production efficiency at different stages of growth. In addition, there is no data on the impact of changes in lysine and methionine levels on the liveability of birds in industrial conditions. This paper fills in these gaps by investigating the relationship between lysine and methionine levels in mixed feed for young turkeys and feed costs per 1 kg of live weight gain.

The purpose of the study was to determine the efficiency of rearing young meat turkeys of the BIG 6 cross at different levels of lysine and methionine in mixed feeds.

Materials and Methods

Scientific and economic experiment was carried out according to the method of balanced groups at the Limited Liability Company "Industrial Exposition Company Adventure" of the Polonsky district of Khmelnitsky Oblast in 2024. All experimental studies were conducted in accordance with modern methodological approaches and in compliance with the relevant requirements and standards, in particular, they meet the requirements of DSTU ISO/IEC 17025:2005 (2006). The animals were kept and all manipulations were carried out in accordance with the provisions of the Procedure for conducting experiments and experiments on animals by scientific institutions (Law of Ukraine No. 249, 2012), the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986).

According to the experiment scheme (Table 1) at the day-old age, 500 turkeys were selected, of which 5 groups were formed according to the principle of analogues – control and 4 experimental, 100 animals each. The experiment lasting 126 days was divided into two periods: equalising (age of the bird – 1-7 days) and main (8-126 days).

Table 1. *Scheme of the scientific and economic experiment*

Age, weeks (days)	Content in 100 g of mixed feed, %	Group				
		1	2	3	4	5
Equalising period						
1 (1-7)	Lysine	1.76	1.76	1.76	1.76	1.76
	Methionine	0.63	0.63	0.63	0.63	0.63
Main period						
2-3 (8-21)	Lysine	1.76	1.58	1.67	1.85	1.94
	Methionine	0.63	0.57	0.60	0.66	0.69
4-6 (22-42)	Lysine	1.57	1.41	1.49	1.65	1.73
	Methionine	0.56	0.51	0.54	0.59	0.62
7-10 (43-70)	Lysine	1.33	1.2	1.27	1.39	1.46
	Methionine	0.49	0.44	0.47	0.51	0.54
11-12 (71-84)	Lysine	1.09	0.98	1.03	1.14	1.19
	Methionine	0.42	0.38	0.40	0.44	0.46
13-14 (85-98)	Lysine	0.97	0.87	0.92	1.02	1.07
	Methionine	0.40	0.36	0.38	0.42	0.44
15-18 (99-126)	Lysine	0.86	0.77	0.82	0.90	0.95
	Methionine	0.37	0.33	0.35	0.39	0.41

Source: compiled by the authors

During the scientific and economic experiment, rations were used that ensured normal viability and high productivity of poultry, in accordance with the established norms and recommendations of the producer (Nutrient Requirements of Poultry..., 1994; Feeding guidelines for..., 2015; Management guidelines for..., 2022). In the experiment, the free-range feeding was used, meaning that the bird regulated its total feed intake. Multiplicity of feed distribution – twice a day (morning and evening) with simultaneous accounting of the remaining feed. The ratio of lysine to methionine in mixed feeds was regulated by the introduction of synthetic amino acids.

Experimental livestock was kept indoors on the floor with a density of 5 turkeys per 1 m^2. The bedding was made of peat. Access to water was free. Starting from Week 7, young turkeys were released from the premises during the day to paddocks, the area of which was at the rate of 7 m^2 per animal. The live weight of turkeys was determined by individual weighing. The liveability of the livestock was determined daily by the number of culled and dead birds.

Feed consumption was accounted daily, for each period of growth and for the entire period of experiment. At the end of each period and experiment, the total consumption of mixed feed per 1 kg of live weight gain was calculated using the equation:

$$C_F = \frac{A_F}{I}, \quad (1)$$

where C_F – feed consumption per 1 kg of live weight gain, kg; A_F – amount of feed fed for the accounting period, kg; I – gross increase in live weight for the accounting period, kg. Data processing was carried out using MS Excel and STATISTICA software using built-in statistical functions.

Results and Discussion

During the scientific and economic experiment young turkeys were fed complete mixed feeds (Table 2), with the following nutritional value (Table 3). The level of lysine and methionine in mixed feeds at all stages of growth was different and this was regulated by the introduction of synthetic amino acids. It was found that different levels of lysine and methionine in mixed feeds for young turkeys during rearing affect their growth indicators in different ways. Thus, at the end of the experiment at the age of 126 days, turkeys of the Group 4 (13.45 kg) and the Group 5

(13.15 kg) had the highest live weight, which exceeded the analogues of the control Group by 753 ($p < 0.01$) and 455.5 g, respectively. Turkeys of Group 2 and Group 3 had a lower live weight compared to the control Group by 706.3 ($p < 0.05$) and 337.2 g, respectively.

Table 2. *Composition of complete mixed feeds for young turkeys of the control group, % by weight*

Component	Period, weeks					
	1-3	4-6	7-10	11-12	13-14	15-18
Wheat	29.30	25.66	24.59	24.00	24.99	24.00
Corn	13.00	20.01	26.00	29.94	38.00	45.12
Soybean oilcake	45.82	41.40	37.46	29.89	24.30	15.22
Sunflower oilcake	-	3.88	4.91	9.64	6.00	9.23
Fish meal	6.80	4.29	1.63	-	-	-
Soybean oil	-	0.50	1.41	2.81	3.02	3.55
Lysine monochlorohydrate	0.26	0.25	0.26	0.18	0.21	0.29
DL-methionine	0.22	0.15	0.17	0.10	0.15	0.11
L-threonine	0.04	0.05	0.04	0.03	-	-
Table salt	0.3	0.13	0.21	0.24	0.25	0.24
Monocalcium phosphate	1.26	1.22	1.29	1.31	1.08	0.82
Lime flour	2.30	1.76	1.36	1.21	1.36	0.78
Sodium bicarbonate	0.10	0.10	0.10	0.10	0.10	0.10
Mycosorb A+	0.10	0.10	0.07	0.05	0.04	0.04
Natuzyme (enzyme+phytase)	0.005	0.005	0.005	0.005	0.005	0.005
Premix	0.495	0.495	0.495	0.495	0.495	0.495

Source: compiled by the authors

Table 3. *Content of essential nutrients and energy in 100 g of mixed feed, %*

Indicator	Period, weeks					
	1-3	4-6	7-10	11-12	13-14	15-18
Exchange energy, MJ	11.91	12.21	12.74	13.19	13.45	13.83
Crude protein	27.43	26.00	23.30	20.98	18.02	16.00
Crude fat	5.60	7.00	7.17	7.82	7.58	8.47
Crude fibre	3.11	4.21	3.80	4.50	4.60	4.73
Calcium	1.45	1.29	1.14	0.96	0.86	0.77
Phosphorus	0.74	0.65	0.51	0.47	0.43	0.39
Lysine*	1.76	1.57	1.33	1.09	0.97	0.86
Methionine*	0.63	0.56	0.49	0.42	0.40	0.37

Note: * content of lysine and methionine in poultry feed of experimental groups varied according to the experiment scheme
Source: compiled by the authors

During the entire growth period, there is a change in the feed composition depending on the age of the birds. For example, the content of wheat decreases, while corn, on the contrary, increases, which indicates a shift in focus on more energy components, as the energy needs for turkey growth increase over time. Soybean oilcake decreases in the feed composition, while sunflower oilcake appears only at later stages, which allows meeting protein needs. Fish meal, which is an important source of protein, is gradually reduced and eliminated from the diet in the last stages, which is normal, since birds can get protein from other sources.

The levels of amino acids, in particular lysine and methionine, are adjusted depending on the age of birds. In the early stages of rearing, the content of lysine and methionine in feed is higher,

and with the age of birds, this level decreases, as the needs for these amino acids change. This allows optimising the feed, providing birds with the necessary amount of amino acids at each stage of their development. Changes in the content of additives such as table salt, monocalcium phosphate, and lime flour are also adjusted depending on the needs of birds for calcium and phosphorous substances, which is important for bone development, especially during periods of active growth. Microelements and premix used throughout the entire period support the stability of physiological processes and the health of birds.

The cost of mixed feed for the production of any product, including in turkey growing, significantly affects its cost and significantly depends on the level of poultry productivity and the amount of mixed feed consumed (Kidd & Kerr, 1998). The data provided (Table 4) showed that with an increase in the content of lysine and methionine in mixed feed, its consumption decreases by 1 kg of live weight gain.

Table 4. *Feed consumption per 1 kg of live weight gain of turkeys, kg, n = 100*

Experiment period, days	Group				
	1	2	3	4	5
1-7	1.605	1.644	1.593	1.674	1.589
8-14	1.279	1.319	1.318	1.245	1.291
15-21	1.488	1.555	1.508	1.440	1.466
22-28	1.414	1.440	1.429	1.383	1.404
29-35	1.499	1.588	1.568	1.446	1.481
36-42	1.628	1.581	1.551	1.557	1.643
43-49	1.456	1.476	1.484	1.403	1.437
50-56	1.758	1.813	1.801	1.650	1.682
57-63	1.773	1.932	1.868	1.782	1.706
64-70	2.317	2.195	2.132	1.913	2.057
71-77	2.461	2.648	2.540	2.392	2.504
78-84	3.023	3.239	3.104	3.054	2.968
85-91	3.067	3.157	3.033	2.650	2.741
92-98	3.531	4.022	3.902	3.449	3.685
99-105	3.462	3.757	3.696	3.461	3.350
106-112	4.718	5.902	5.111	4.418	4.487
113-119	4.926	5.897	5.539	4.553	4.696
120-126	5.392	5.656	5.600	4.536	4.833
For the entire period of experiment	2.691	2.850	2.765	2.537	2.597

Source: compiled by the authors

Analysis of Table 4, which provides data on the consumption of mixed feed per 1 kg of live weight gain of turkeys for different groups during the entire experiment period, shows an interesting trend in the relationship between the level of lysine and methionine in mixed feed and the efficiency of bird feeding. The costs of mixed feed per 1 kg of live weight gain for five groups of turkeys that were at different feeding levels are presented. The most noticeable trend is a decrease in feed costs with an increase in the level of lysine and methionine in mixed feeds, which indicates an improvement in the efficiency of feed use when optimising these amino acids. For example, Group 4, which probably had the most optimised lysine-methionine ratio, had the lowest feed consumption per 1 kg of live weight gain during all experiment periods. This confirms the conclusion that the correct balance of amino acids allows reducing feed costs, which directly affects the cost of production.

During the entire experiment period, feed costs per 1 kg of live weight gain were lowest in Group 4, which is 6.1%, 12.3%, 9.0%, and 2.4% less than in groups 1, 2, 3 and 5, respectively. This indicates that Group 4 had the best results in terms of feed efficiency, which can be attributed to proper correction of lysine and methionine levels in the diet. Groups with lower levels of these amino acids had higher feed costs for live weight gain. In general, the table confirms that increasing the lysine and methionine content in mixed feed is an effective strategy for reducing feed costs and increasing the economic efficiency of turkey rearing, as they provide more efficient use of feed for poultry growth. The high feed costs observed in some groups indicate the need to optimise amino acid levels to achieve better results.

The efficiency of using mixed feed is supplemented by determining the relationship between the level of lysine and methionine in mixed feed and its consumption per 1 kg of live weight gain (Fig. 1).

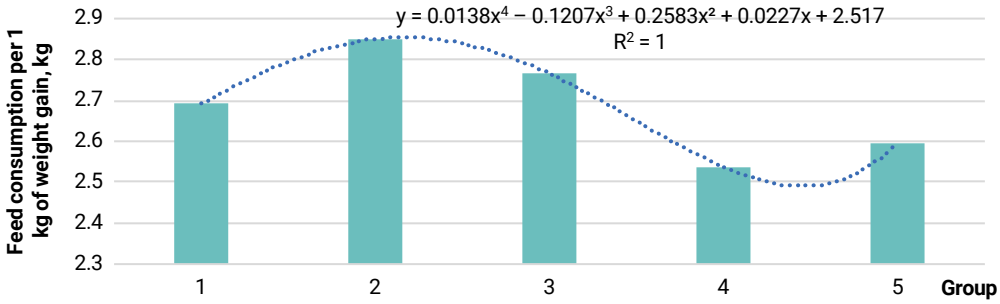

Figure 1. *Relationship between lysine and methionine levels in mixed feed and feed costs in young turkeys*

Source: compiled by the authors

From the data in Figure 1, it can be seen that there is a significant inverse relationship between the level of these amino acids in mixed feed and feed costs. In particular, correlation analysis indicates a strong inverse relationship ($r_s = -0.82$), which is statistically significant ($p < 0.05$). This means that with an increase in the level of lysine and methionine in mixed feed, the amount of feed required to achieve an increase of 1 kg of live weight in young turkeys decreases. In other words, the higher the level of lysine and methionine in the diet of birds, the more efficiently they use food for growth. This confirms the efficiency of increasing the content of these amino acids in mixed feeds to achieve more economical rearing of turkeys. This inverse relationship is a useful indicator for poultry farming, as it reduces the cost of mixed feed, which helps to reduce production costs and increase production efficiency (Kogut, 2009). The figure highlights the importance of optimising lysine and methionine levels to achieve maximum results with minimal feed costs.

Notably, the liveability of experimental young turkeys during the entire experiment period was quite high and ranged from 94-96% (Table 5).

Table 5. *Liveability of young turkeys, % of the number at the beginning of the experiment, n = 100*

Experiment period, days	Group				
	1	2	3	4	5
1-7	98	99	99	98	98
8-14	98	98	97	98	98
15-21	97	97	97	97	97

Table 5. *Continued*

Experiment period, days	Group				
	1	2	3	4	5
22-28	96	97	97	97	97
29-35	96	96	97	97	97
36-42	96	96	96	97	96
43-49	96	96	96	96	96
50-56	96	95	96	96	96
57-63	96	95	95	96	96
64-70	95	95	95	96	96
71-77	95	94	95	96	96
78-84	95	94	95	95	96
85-91	95	94	95	95	96
92-98	95	94	95	95	96
99-105	95	94	95	95	96
106-112	95	94	95	95	96
113-119	95	94	95	95	96
120-126	95	94	95	95	96
For the entire period of experiment	95	94	95	95	96

Source: compiled by the authors

The liveability of young turkeys remained quite high over time, which indicates the overall stability and good condition of the birds in the rearing process, regardless of the group. Throughout the experiment, Group 5 showed the highest bird liveability, retaining 96% at the final stage. Group 2 had the lowest liveability rate, which was 94% by the end of the experiment. Other groups (1, 3, and 4) had intermediate results, which also indicates fairly stable bird survival rates in these groups. Despite these differences in liveability among the groups, the study did not reveal a significant effect of lysine and methionine levels in mixed feed on this indicator. That is, changes in the levels of these amino acids did not have a significant effect on the level of bird survival, which indicates their irreplaceable role in improving other aspects of productivity, such as growth and development, but does not affect the survival of birds as much.

Discussion of the results shows that the results of the current study are in the context of scientific advances in poultry farming and feed efficiency, in particular, regarding the effects of amino acids such as lysine and methionine on poultry productivity. Research by C.-C. Fang *et al.* (2021) demonstrated a positive effect of increased methionine levels on the growth and development of muscle mass in fish, which correlates with the results of the current study, where an increase in lysine and methionine levels in compound feeds had a positive effect on live weight gain in young turkeys. Both studies point to the importance of optimising amino acids in animal diets to achieve better growth outcomes. The study by N. Yousefi & S. Abbasi (2022), which focuses on improving the solubility and thermal stability of feed proteins, can also be consistent with the results of the current study in the context of the importance of feed quality to ensure high productivity. Although the focus of this study on protein stability was not part of the current analysis, high feed quality is an integral part of successful animal rearing, which is supported by the results of both studies.

The study by M. Li *et al.* (2022), who investigated the relationship between collagen characteristics and meat tenderness, is also important for comparison, although the main focus of the current study was on performance indicators. However, both studies highlight the importance

of feed additives to improve final products, in this case, to achieve high poultry productivity, and in the case of these researchers – to improve meat quality. The relationship between lysine and methionine levels and product quality is an important aspect for further research in both directions. The study by M. Hastie *et al.* (2022), which focused on consumers' perception of meat and the impact of ageing methods on its quality, has a different focus and is more concerned with consumer preferences than the production aspects explored in the current paper. The results of the current study, which focuses on productivity and cost-effectiveness, can help in further work that considers the perception of final products by consumers.

The effect of quercetin on meat tenderness and apoptosis and autophagy signalling pathways described by T. Wang *et al.* (2022) and Y. Wang *et al.* (2022), supplemented the understanding of the efficiency of feed additives. Although the study focused on antioxidant properties and effects on autophagy in chickens, its results may be consistent with the results of the current study in the context of overall feeding efficiency, which includes not only amino acids, but also other supplements that affect the health and productivity of animals. The researchers noted that quercetin can improve meat tenderness due to its effect on metabolic processes in muscle tissue, in particular, by regulating apoptosis and autophagy, which are important for maintaining muscle health and overall health in birds. This study also highlights the importance of an integrated approach to the selection of feed additives, which includes not only amino acids, but also antioxidants and other bioactive components that can positively affect the productivity and quality of meat. In the current study, increased levels of lysine and methionine in turkey feed have shown a positive effect on live weight gain and feed consumption, but it is also important to consider additional additives, such as antioxidants or other biologically active components, which may have an additional impact on improving meat quality and overall health of birds.

According to C. Werner *et al.* (2008), feed additives are important for improving the efficiency of animal feeding, which is consistent with the results of the current study, which showed a positive effect of increased levels of lysine and methionine on the productivity of turkeys. The study by these researchers confirms the need to optimise feed to improve animal productivity, which is the main goal of the current study, where the effect of different levels of amino acids on live weight gain and feed consumption are investigated. According to the results of the current study, increasing the level of lysine and methionine in mixed feeds contributes not only to better growth of poultry, but also to optimisation of feed costs, which directly affects the reduction of production costs. These factors are critical for improving the economic efficiency of production and ensuring sustainable growth of turkeys in industrial conditions.

C. Chang *et al.* (2024) investigated the effect of protein and lysine levels on meat quality and myofibrile characteristics in slow-growing chickens. Although their study focused on the meat qualities of poultry rather than its performance, the results confirmed the importance of adjusting lysine levels in the diet to achieve the desired results. This is consistent with the current study, where it was demonstrated that an increase in lysine levels in mixed feed has a positive effect on live weight gain in turkeys. Although the study focuses on aspects of meat quality, these results can be useful for improving turkey feeding to improve the quality of meat products and feed efficiency, which ensures optimal results at different stages of growth.

The study by I. Cherevko (2023) and T. Vahsen *et al.* (2021) examined the effects of increased arginine, lysine, and methionine levels on turkey performance, health, and immunity. Both studies demonstrated a positive effect of increased amino acid levels on improving bird growth, which is consistent with the results of the current study. Increasing the level of lysine and methionine in mixed feeds really helps to improve live weight gain and feed efficiency,

which is confirmed by research results. However, the studies note that the effect of increasing amino acids may depend on the keeping conditions, which is an important aspect for further research.

P. Glatz & B. Rodda (2013) addressed the welfare and maintenance of turkeys, in particular focusing on the conditions of keeping, feeding, and the impact of these factors on bird productivity. The importance of creating comfortable conditions for turkeys, including appropriate temperature conditions, sufficient space for movement, and a balanced diet, was emphasised. It was noted that physical and psychological stress can significantly affect the health and productivity of birds, so special attention should be paid to the well-being in the process of raising them. This study is related to the current research, as it also examines feeding and its impact on turkey productivity.

The current study focuses on the effect of lysine and methionine in mixed feed on live weight gain and feed consumption, whereas P. Glatz & B. Rodda (2013) focuses more on an integrated approach to keeping conditions and feed efficiency in terms of animal welfare. Both studies highlight the importance of a balanced approach to keeping and feeding turkeys to achieve high productivity. An important aspect is that although the researcher focuses on creating comfortable conditions for birds, the current study focuses more on optimising feed composition and the effect of specific amino acids, such as lysine and methionine, on physiological growth and productivity indicators. The results of both studies are consistent with the need to provide turkeys with a balanced diet to achieve the best growth and health results.

The results of the current study are consistent with other papers confirming the importance of optimising lysine and methionine levels in mixed feeds to achieve high productivity and cost-effectiveness. In particular, the data provided confirm that changes in the levels of these amino acids can positively affect live weight gain and reduce feed costs. Comparison with other studies allows expanding the understanding of the impact of feed additives on various aspects of cultivation and product quality, which can become the basis for further research in this area.

As a result of the scientific and economic experiment, the effect of various levels of lysine and methionine in mixed feed on the productivity and health of young turkeys was investigated. An increase in the content of lysine and methionine in mixed feed contributed to an improvement in the growth rate of birds, in particular, turkeys of groups 4 and 5 reached the highest live weight at the end of the experiment. Optimisation of the levels of these amino acids helped to reduce feed costs by 1 kg of live weight gain, which increases the economic efficiency of cultivation. The most cost-effective feed was Group 4, where the optimised lysine-methionine ratio showed the best results.

The liveability of birds throughout the experiment remained high (94-96%), which indicates stable keeping conditions. However, lysine and methionine levels did not significantly affect this indicator, confirming that these amino acids do not directly affect the survival of birds, but significantly improve other aspects of their performance. The results of the study highlight the importance of adjusting the levels of lysine and methionine in mixed feeds to achieve high growth rates and reduce feed costs, which contributes to improving the efficiency of poultry farming.

Conclusions

The results of the study confirmed that an increase in lysine and methionine levels by 5% and 10% in mixed feed for young turkeys leads to a significant increase in their live weight at 126-day age. In particular, an increase in lysine levels by 5% provided an increase in live weight by 5.9%, and an increase in methionine by 10% – by 3.6% ($p < 0.01$). A decrease in these amino acids in mixed feed by 10% and 5% led to a decrease in the live weight of birds by 5.6% and 2.7%, respectively ($p < 0.05$). This demonstrates the importance of a balanced approach to adjusting dietary amino acid levels for optimal bird growth.

The study also indicates that an increase in lysine and methionine levels in mixed feeds by

5% and 10% at all stages of cultivation contributed to a reduction in feed costs per 1 kg of live weight gain by 4.3% and 2.1%, respectively. Analysis of the relationship between the level of lysine and methionine in mixed feed and feed costs per 1 kg of growth showed a strong inverse relationship (rs = -0.82), confirming that with an increase in the content of these amino acids, the amount of feed required to achieve bird growth decreases. However, correlation analysis revealed a significant inverse relationship between the level of amino acids and feed costs for live weight gain, which demonstrates the importance of the right balance for reducing feed costs and improving economic efficiency. As for the liveability indicators, the study did not reveal a significant effect of different levels of lysine and methionine on this parameter, since the level of liveability of birds remained consistently high and did not depend on changes in amino acid levels. This suggests that amino acids may have a positive effect on bird productivity, but their effect on survival is not significant.

Prospects for further research may focus on investigating the effects of different levels of lysine and methionine in mixed feed on the yield and quality of slaughter products, and on the possibilities of optimising the levels of these amino acids to improve the quality of meat and other indicators important for poultry farming. In addition, it is necessary to investigate the effect of various methods of introducing synthetic amino acids into mixed feeds on their efficiency and on the possibility of integrating such approaches into industrial production to reduce costs and increase the overall productivity of birds.

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None.

Conflict of Interest

None.

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Ефективність використання комбікормів з різними рівнями лізину і метіоніну за вирощування індиків

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Анотація. Метою статті було дослідити вплив згодовування повнораціонних комбікормів з різними рівнями лізину та метіоніну на ріст молодняку індиків. Експериментальні дослідження виконано на молодняку індиків м'ясного напряму продуктивності кросу BIG 6. За методом збалансованих груп у добовому віці було сформовано п'ять піддослідних груп птиці. Дослід тривав 126 діб та поділявся на два періоди: зрівняльний (7 діб) та основний (119 діб). У зрівняльний період піддослідний молодняк споживав комбікорми контрольної групи. В основний період досліду кількість лізину і метіоніну відносно комбікорму птиці контрольної групи за періодами вирощування зменшувалась або збільшувалась пропорційно на 5 і 10 %. Встановлено, що різні рівні лізину і метіоніну у комбікормах для молодняку індиків позначаються на його продуктивності по-різному. У 126-добовому віці найвищу живу масу мали індики, які отримували комбікорм із збільшенням кількості лізину і метіоніну на 5 і 10 % – вони переважали аналогів контрольної групи відповідно на 5,9 ($p < 0,01$) і 3,6 %. Молодняк, який споживав комбікорм із зменшеною кількістю лізину і метіоніну за згаданим показником поступалася перед контрольними ровесниками відповідно на 5,6 ($p < 0,05$) і 2,7 %. Збільшення рівня лізину і метіоніну на 5 і 10 % у комбікормі індиків на усіх етапах їх вирощування сприяє зниженню витрат корму на 1 кг приросту живої маси відповідно на 4,3 і 2,1 %. Доведено, що залежність між рівнями лізину й метіоніну у комбікормі для молодняку індиків та його витратами на 1 кг приросту живої маси описується поліноміальною лінією з коефіцієнтом достовірної апроксимації $R^2 = 1$. Кореляційний аналіз свідчить, що між цими двома показниками існує достовірний ($p < 0,05$) сильний зворотній зв'язок ($r_s = -0,82$). Показник збереженості птиці у всіх піддослідних групах був близьким (94-96 %), проте вірогідного впливу різних рівнів лізину і метіоніну у комбікормах за вирощування птиці на показник її збереженості не встановлено

Ключові слова: годівля; птиця; амінокислоти; витрати корму; збереженість

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International experience and strategies for forest management in the context of growing forest pollution

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Abstract. The study aimed to analyse the foreign experience of forestry management and to address the latest strategies for managing forest resources. The positive experience of foreign countries in managing the forestry sector in the context of increasing forest pollution is highlighted. The possibilities of using this experience to improve legislation in the relevant field are considered. The study established that in the developed countries of the world forest resources are among the most important national values that have significant economic and socio-cultural significance. To effectively conserve and restore these resources, multilevel governmental mechanisms for managing forest resources in the face of increasing forest pollution have been introduced abroad. The study indicated that many developed countries use forest management strategies through an integrated approach to address this issue, the main essence of which is based on control measures carried out by both public authorities specialising in forestry and environmental safety authorities and services. The study noted that forest management in the world is becoming an increasingly urgent task due to the growth of pollution, climate change and other environmental challenges. Several international approaches and strategies used to preserve and restore forests are considered, namely: Sustainable Forest Management (SFM); forest certification; international treaties and initiatives; rehabilitation and restoration of forests; involvement of local communities; and technological innovations. Several important points of foreign experience in forest management that should be used and implemented in Ukraine are highlighted: the development of an agroforestry approach, the introduction of biodiversity conservation programs, the European Union's forestry development strategy, and others. The results obtained can be used to develop national and local forest management strategies, implement eco-standards, adapt pollution control plans, and raise awareness and education among citizens and government officials

Keywords: environmental sustainability; forest ecosystems; environmental policy; EU; environmental protection

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Introduction

The management of Ukrainian forest resources is an urgent issue of state regulatory policy, as they are an exhaustive and limited natural resource of the national economy. Furthermore, forest is an important component of the natural ecosystem of territorial communities, as it provides an opportunity to develop the economic and social sphere of many territories and sectors of the country, contributes to the conservation of biodiversity and provides a unique environmental microclimate (Ozkaya & Erdin, 2020). In the modern world, where technological and technical development is growing every day, forest resources are actively used for industrial purposes, which causes excessive deforestation, a decrease in the species composition of flora and fauna, pollution, and disruption of the natural balance of ecosystems. Incompetent management of forest resources leads to several negative consequences: soil depletion, reduced water retention function of territories, air and environmental pollution, and other negative factors for ecosystems and humanity in general.

Notably, state forest management strategies significantly impact the entire national economy, as these resources are the raw material base for many industries, such as forestry, fuel and energy, medical, cosmetics, pharmaceutical, food and other industries, which provides job creation in local communities, and a significant share of forest resources form a large part of Ukrainian exports (Shi *et al*., 2022). The Ukrainian forestry sector remains in a critical situation. Forest resources do not meet economic and environmental requirements. Over the past 1000 years, the forest area has decreased by more than three times, forest landscapes have been subjected to anthropogenic changes, natural productivity has declined, and biodiversity has been reduced. Forest plantations have been destroyed by excessive deforestation in the past, so their natural protective functions are lower. Due to a lack of investment, reforestation and afforestation rates remain low, and the mismatch between the forest resource base, forest development opportunities, and forest consumption is deepening (Torres *et al*., 2021).

The study of the newest component of the strategy for the rational use of forest resources has been a part of research at the foreign and national legislative levels, as well as in the works of many scientists. There are many views among researchers on the strategy of the modern development of the forest industry, as well as the experience of their implementation abroad. O.V. Boyko (2021) believed that the creation of a modern, innovative forestry complex is possible only when the right legislative framework is created, a wide range of various subsidies is used, long-term programmes for the careful use of forest resources are created, and modern innovations in the forestry complex are monitored on an ongoing basis. M. Dyachenko *et al*. (2021) indicate that for the optimal functioning of the forestry sector, it is necessary to create free access to timber, but only if fair competitive conditions are created, a favourable climate for investment in innovative development is created, and positive dynamics of change is introduced, guided by the experience of European countries. Y.V. Muravyov *et al.* (2023) recommend changing the plan for creating strategies for the development of forestry institutions. This plan has a regional overtone, addressing the main features of the forestry sector in the Zakarpattia region. As a result of the study, a scheme of a modern strategy for the development of the forestry sector in the Zakarpattia region was proposed. The researchers also focused on international experience. O. Oshurkevych-Pankivska *et al.* (2023) have similar views, believing that in the process of creating an innovative policy for the development of the forest industry, it is necessary to address the uneven areas of forest plantations in different regions of Ukraine, which determines the necessity of keeping the focus on the regional levels.

D. Wuepper *et al.* (2023) argue that it is advisable to use a variety of approaches to the development of the forestry sector, accounting for the experience of foreign countries. They believe

that their implementation is justified in the face of risks and uncertainty of modern realities. The scientists believe that the following schemes for the development of this industry would be appropriate: export orientation, import substitution, and organisational and legal regulation. Similar views are shared by Y. Polishchuk *et al.* (2020). They believe that regional policy should be based on the experience of European partners, taking into account the following points: human capital development; subsidies for small and medium-sized businesses; modernisation of research by increasing investment; and forestry is seen as an object of modern smart specialisation. L. Malyuta & Y. Spyrydonova (2011) insist on the special importance of the forest, so it is necessary to use the latest methods in the forestry industry, which will have a positive impact on the production of fixed assets, money in circulation, increase productivity, reduce existing costs, and, of course, increase the estimated amounts. Scientists advise simulation, modelling, optimisation and digitisation of forest data, all of which will allow for the modelling of the latest forest systems.

Thus, the literature review shows that forest management issues have been considered by many researchers, but over time, forest management approaches and strategies have become outdated and need to be modernised. The study aims to analyse international experience in improving the forestry sector and to study modern forest management strategies, which will improve the forestry complex of Ukraine.

Materials and Methods

The study of international experience and strategies of forest management was based on natural materials and methods: a comparative analysis - to investigate investment and regulation of forestry opportunities in a market economy; analysis and synthesis of statistical information collected and processed to illustrate the current situation and trends in forestry in Ukraine; economic and statistical – to assess the current situation with forestry in Ukraine and its regions; cause and effect – to create and analyse tools related to the creation of strategies for the development of forest potential and the effective reproduction and use of forest resources; graphs for displaying the results of scientific research; assessment of the effectiveness of organisational and economic instruments of state regulation of forestry activities in the region.

Geographic Information Systems (GIS) technologies were used in the course of this study. Notably, the main purpose of GIS was to produce and maintain databases with spatially coordinated information. Among the databases of this type were digital atlases created for different countries and published by Delorme Mapping Systems as part of the Domesday project (Lausch *et al.*, 2017), including the Digital World Atlas and the Digital Atlas of the United Kingdom. These databases also contained a digital format of the National Atlas of Ukraine, developed by the Institute of Geography of the National Academy of Sciences of Ukraine in cooperation with "intelligent geographic systems" (Massey *et al.*, 2023). The second important component of such a database is an observational system, such as the UNESCO-led Global Resource Information Data Bank (GRID) or the European Community Geographic Information System CORINE (Carvalho *et al.*, 2021). GIS functions also included the production and operation of cadastre systems integrating various fields: municipal automated information systems (MAIS), automated land information systems (ALIS), and spatially distributed automated information systems for cadastres (water, forestry, real estate). The spatial data software included GIS packages such as MGEIntergraph, ILWIS (Netherlands), MapInfo (USA), Arc/INFO, SICAD (Germany), ArcView GIS, and QGIS (USA).

Modern approaches, methods and materials based on the latest scientific studies were used to obtain the available results on the analysis of foreign experience and the most recent forest management strategies to use the positive experience gained in the forestry sector of Ukraine (Table 1).

Table 1. *Regulations and forest management strategies of leading countries*

Country	Primary regulatory acts	Primary forest management strategies
Canada	Forest Stewardship Council (FSC) (2024), Canadian Standards Association (2024)	Sustainable forest management, forest certification, investment in new technologies, cooperation with indigenous peoples
Finland	Programme for the Endorsement of Forest Certification (PEFC) (2024), FSC	"Cut down one tree – plant two", bioenergy investments, local community participation, environmental legislation.
Sweden	Forest Stewardship Council, PEFC	Sustainable forest management, investments in the latest technologies, environmental legislation, reforestation
Germany	National Forest Act (1975), Forest Stewardship Council, PEFC	Sustainable forest management, research, certification, forest rehabilitation, stakeholder engagement
France	Code Forestier (2024, November), National Wood Production Strategy (2024)	Sustainable forest management, certification, community engagement, research, climate change adaptation
Great Britain	The Forestry Commission (2024), UK Government's England Tree Strategy Consultation (2024)	Sustainable forest management, certification, community participation, education, climate change adaptation
USA	National Forest Management Act (NFMA) (1976), Forest Legacy Program (FLP) (1990), Forest Stewardship Program (2024)	National forest management, certification, fire management strategies, climate change adaptation

Source: compiled by the author

Acts of the Cabinet of Ministers of Ukraine and the Verkhovna Rada of Ukraine were used in the study, namely Forest Code of Ukraine (1994); the Law of Ukraine No. 1264-XII "On Environmental Protection" (1991); Resolution of the Cabinet of Ministers of Ukraine No. 303-2007-p "On Approval of the Rules for Forest Reproduction" (2007); Resolution of the Cabinet of Ministers of Ukraine No. 976-2009-p "On Approval of the Regulation on State Forest Protection, Forest Protection of Other Forest Users and Forest Owners" (2009) were employed in the study. Moreover, Statistical information from the State Committee of Forestry of Ukraine and regional forestry management institutions were used in this paper, namely the Public Report of the Head of the State Agency of Forest Resources of Ukraine for 2023 (2023) and reports of the State Statistics Service of Ukraine were employed in this research.

Results

The development of the forestry industry is an important component of many economies, and some of them have achieved significant success in this area thanks to effective strategies. Here are some examples of the most successful countries and their strategies. Canada, which has some of the largest forest resources in the world, has several leading strategies for managing these resources (Yousefpour *et al*., 2020). Canada is actively implementing sustainable forest management practices. Many Canadian forests are certified according to the Forest Stewardship Council (2024) and Canadian Standards Association (2024) standards, which guarantee environmentally responsible, socially beneficial and economically sound forest management. Canada is making significant efforts to preserve biodiversity. Government agencies are creating national parks, protected areas, and protected areas where deforestation is limited or prohibited. Canada is investing in research and development of new technologies for sustainable forest management, such as bioenergy projects, development of new wood materials and innovative methods of logging and forest management. Canada actively cooperates with indigenous peoples, involving them in the management of forest resources. Indigenous communities have the right to participate in decision-making on forest use, as well as to benefit economically from forest

resources. The country supports a policy of planting new trees in areas where deforestation has taken place to ensure forest regeneration. The country is conducting genetic research to grow more resilient and productive forest stands. Through these strategies, Canada not only conserves its forest resources but also provides economic benefits to its citizens.

Finland is a role model for forest management. The country contributes significantly to green forest preservation. The main aspect of forest management in Finland is deforestation, which is always accompanied by planting new trees. The "Cut down one tree, plant two" is the basic principle that Finland follows in managing forest resources. Most Finnish forests are certified according to PEFC or FSC standards. This ensures that forest management meets environmental requirements, and social principles and is economically viable. To improve the forestry industry, financial institutions are actively investing in new technologies and research. The main areas of investment include bioenergy, the creation of new materials from wood waste, and much more. Local communities are actively involved in the proposal and decision-making processes for forest management. They can express their opinions and participate in various activities, which improves their understanding of the value of forests. Finland has developed strong environmental legislation that has played a major role in shaping forest management strategies. High standards and strict laws regulate logging and forest management. This contributes to biodiversity conservation and ecosystem protection. Finland's forest management strategies include biodiversity protection, i.e., they create protected areas and operate various environmental programmes to preserve endangered and rare species of flora and fauna. Finland is indeed a role model for forest management (Dufour-Kowalski *et al*., 2011).

Sweden is one of the countries that pioneered the principles of sustainable forest management. The basic principle is that deforestation should be compensated by reforestation. This ensures a balance between deforestation and reforestation and preserves ecological systems and biodiversity. This principle is similar to the Finnish example of forest management. Most Swedish forests are certified according to the Forest Stewardship Council (2024) and the Programme for the Endorsement of Forest Certification standards. This guarantees that forest management is carried out responsibly, respecting environmental and social aspects, as in many European Union countries. One of the areas of sustainable forest management in Sweden is investment in research and development of the latest technologies in the forest industry. The country is developing new wood products, such as bioplastics and textile fibres, and is researching new wood processing methods to improve quality and reduce waste. The national environmental laws are strict, controlling deforestation, protecting water resources and monitoring biodiversity. The laws set strict limits and requirements for forest users to ensure the sustainability and longevity of forest ecosystems. The Swedish reforestation programme is quite robust and includes planning for the planting of new trees in the areas where deforestation has occurred. These measures preserve forest areas and contribute to balancing the carbon cycle. Sweden uses the latest technologies to monitor the state of forest resources, involves non-governmental organisations and ordinary citizens in making management decisions, and promotes the development of small and medium-sized forestry enterprises, which supports regional economic development and creates additional jobs. Sweden's forest management strategies are export-oriented, which brings large revenues to the country. Adaptation of forestry to climate change and strategies to reduce emissions of harmful gases are important ideas in Swedish forestry legislation. Large areas of forests absorb carbon, which means that Sweden uses forests as a tool to combat its large carbon footprint in the atmosphere. Sweden's forest management strategies are quite effective, helping to conserve forest resources and ensure their sustainability and economic efficiency (Jourdan *et al*., 2021).

The development of the forestry industry is an important component of the economy of many countries, and some of them have achieved significant success in this area due to effective forest management strategies. Analysis of international experience highlighted an example of the successful implementation of forest policy and its successful implementation at the external and internal levels in the European Union. It is worth noting that the basic principles of forest management in Europe were created several centuries ago by German experts, which is why Germany is called the "trendsetter" among the European Union countries.

Germany is one of the world's leading countries in the field of sustainable forest management. Its approach and strategies are extremely systematic and include measures and approaches. Here are some of the main aspects of the German forest management strategy:

1. Sustainable forest management: Germany is boldly implementing the principle of sustainable forest management, which means that it strikes a balance in the environmental, social and economic spheres when managing forest resources. The country regularly monitors the state of its forests, plans deforestation and reforestation, and takes measures to protect flora and fauna.

2. Legislative framework: forest management is regulated at both the federal and state levels. The main laws of sustainable management are enshrined in the National Forest Act (1975).

3. Forest certification: many forestry enterprises in Germany are certified by the Forest Stewardship Council and the Programme for the Endorsement of Forest Certification. This ensures compliance with high environmental, social and economic requirements.

4. Rehabilitation and restoration of forests: degraded forests in Germany are being actively restored. Much attention is devoted to the use of local tree species to preserve biodiversity and make ecosystems more sustainable.

5. Research and innovation: the development of technological innovation and scientific research is a priority for Germany as it contributes to effective forest management, and Germany is investing heavily in the scientific sector. This includes the use of satellite imagery, drones and geographic information systems for forest monitoring.

6. Stakeholder engagement: an important part of the strategy is to involve various stakeholders, from local communities to private forest owners, environmental organisations and businesses. This contributes to a more integrated and harmonious approach to forest management.

7. Education and awareness-raising: a major role is played in education and awareness-raising about the importance of forest conservation and restoration. This includes training programmes, educational campaigns and cooperation with schools and universities.

8. Economic incentives: to support sustainable forest management, Germany uses various economic incentives, such as additional benefits for forest owners and subsidies, as a sustainable management practice. The country has also always been actively involved in international cooperation in forest management, exchanging experience and knowledge with other countries (Schneider *et al*., 2021).

It is worth noting the positive experience of managing the forestry complex in France. According to French law, the environment, landscapes, flora and fauna, their varieties and bio-balance are part of the national heritage, and the protection, restoration and management of natural resources is a task aimed at protecting and preserving the environment from possible threats of destruction.

France has a wealth of experience and a comprehensive approach to forest management that combines all the above principles. France is actively implementing the principles of sustainable forest management, which are aimed at preserving flora and fauna, productivity and environmental sustainability of forests. This includes regulating deforestation, reforestation and protection against soil erosion. The National Wood Production Strategy (2024) defines the main

priorities of forest management policy until 2026. The main goals include the conservation of forests, increasing their productivity, strengthening the links between forests and the economy, and enhancing adaptation to climate change. The legal framework and regulation of forestry in France is carried out through laws and regulations, including the Code Forestier (2024). This provides a legal framework for sustainable forest management and the protection of forest resources. As in Germany, many forests in France are certified by the Forest Stewardship Council (2024) and the Programme for the Endorsement of Forest Certification, meaning that France is also actively pursuing a forest certification policy. This helps ensure compliance with high standards of sustainable management.

The country actively involves local communities, private forest owners, environmental organisations and businesses in the forest management process. This contributes to a more harmonious approach and consideration of all interests. Public awareness and education are an important part of the strategy, and France invests in training programmes for foresters, public education campaigns and cooperation with educational institutions. It also actively supports scientific research in forestry and introduces technological innovations for forest monitoring and management. This includes the use of satellite imagery, drones and geographic information systems. There are various economic incentives to support sustainable forest management, including financial support for reforestation, subsidies and tax breaks for forest owners. It is worth noting that France is developing and implementing measures to adapt its forests to climate change, including the selection of drought- and pest-resistant tree species and the introduction of new management practices, which will help forests adapt to new conditions. France is also actively involved in international initiatives on forest governance, knowledge sharing and cooperation with other countries to support global forest resilience (Grünig *et al.*, 2024).

The UK has its unique forest management strategy based on the principles of sustainable development, biodiversity conservation and consideration of environmental challenges such as climate change. The UK is actively implementing the principles of sustainable forest management, which are aimed at maintaining an ecological, social and economic balance in forest management. This includes regular monitoring of forest conditions, control of deforestation and reforestation measures. Forest policy and strategy are coordinated by the Forestry Commission (2024), which is responsible for developing and implementing forest management strategies. It also provides advice to the government and private forest owners. The UK actively supports certification programmes, such as the Forest Stewardship Council (2024) and the Programme for the Endorsement of Forest Certification, which promote sustainable forest management and ensure compliance with high standards. The UK government has also developed the UK Government's England Tree Strategy Consultation (2024), which includes measures to increase the area of forests, conserve existing forest resources and increase their resilience to climate change. The UK actively engages local communities, private forest owners and various stakeholders in the forest management process. This includes consultations, joint projects and support programmes for local initiatives. The UK raises awareness of the issue and invests in educational programmes to help raise awareness of the importance of sustainable forest management. This includes training courses, online resources and cooperation with educational institutions, as well as supporting research in forestry and introducing the latest technologies for forest monitoring and management. Satellite imagery, drones and geographic information systems are used to detect changes in forests and plan conservation measures. The UK is developing and implementing measures to adapt forests to climate change. This includes the selection of resilient tree species, changes in forest management practices, and measures to increase the resilience

of forests to extreme weather. There are a variety of economic incentives to support sustainable forest management, including grants, subsidies and tax breaks for forest owners who adopt sustainable practices. The UK actively participates in international initiatives on forest governance, sharing knowledge and best practices with other countries. This contributes to the global sustainability of forests and the maintenance of international environmental standards. These measures and strategies help the UK to effectively manage its forest resources, preserve them for future generations, and adapt to new environmental challenges (Ligot *et al*., 2023).

Analysis of the development of the forestry sector in the United States of America demonstrated a significant emphasis on the national economy, contrary to Ukraine. This conclusion is based on the fact that the country is one of the largest timber producers in the world. The United States of America (USA) has a variety of forest management strategies that include public, private and local initiatives, as forests are owned by different entities, as shown in Figure 1.

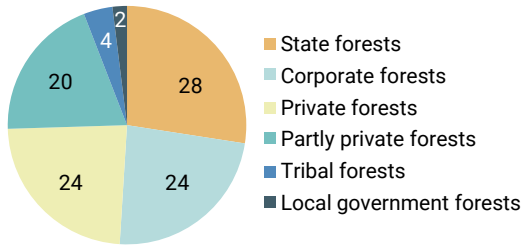

Figure 1. *Ownership structure of US forests, %*

Source: compiled by the author

These strategies aim to conserve wildlife and plants, use resources sustainably, and adapt to climate change. The US Forest Service is the primary agency responsible for managing 193 million acres of national forests and rangelands. It develops long-term forest management plans that consider environmental and societal considerations. The National Forest Management Act (NFMA) (1976) controls the management of public forests, dictates requirements for forest resource planning, and ensures public participation in decision-making. The National Park Service manages a system of national parks and wildlife refuges that include large areas of forests, which helps to preserve natural landscapes and biodiversity. The Forest Legacy Programme (FLP) (1990) is unique in that it aims to preserve private forest lands that have high ecological, recreational or historical potential. The programme provides financial support to protect forests from deforestation. There is also the Forest Stewardship Programme (2024), which provides technical and financial assistance to private forest owners to develop and implement sustainable forest management plans. Like other countries, the US actively uses forest certification systems such as the Forest Stewardship Council (2024) and the Sustainable Forestry Initiative. This helps to ensure that forest resources are used appropriately. As fires are a serious threat to US forests, the National Forest Service and local governments are actively working to develop fire management strategies that include fire prevention, controlled burns and emergency response, as this is a national concern. The United States is developing and implementing measures to adapt forests to climate change, including the selection of drought- and pest-resistant tree species, as well as the introduction of forest management practices that increase their resilience to atypical weather conditions. Forest management in the United States also involves cooperation between various federal, state and local agencies. This ensures that efforts are directed towards the conservation and sustainable use of forests

(Guignabert *et al*., 2024). These countries demonstrate how effective strategies can contribute to the sustainable development of the forest industry, providing economic benefits and conserving natural resources.

As for Ukraine, the national forestry policy places greater emphasis on direct government intervention and the use of economic incentives for sustainable forestry. The main components of the forestry industry are woodworking, forestry, furniture, forest chemicals, and pulp and paper. The economic crisis of 1990 significantly reduced the production capacity of these industries. Therefore, to restore the sustainable potential of the processing units of the forestry complex, it is necessary to create a modern design of state regulation of institutional changes. The nature of state control over the use of natural resources and environmental protection is determined by the state environmental policy. In the context of attracting foreign experience, this system should be aimed at restructuring relations in the human-society-environment system. Today, there is a need to restructure administrative institutions with a methodology for implementing the principles of integrated environmental management. The state policy in the field of environmental management should be based on a stable system of regulations, but in the context of martial law and constant changes in the domestic and foreign policy situation, this system should be resistant to changes in environmental components and avoid potential crises. This is an effective way to overcome economic and environmental problems and regulate environmental management.

Forest resources are a set of resources that includes timber, fruits, berries, medicinal plants, mushrooms, honey, firewood and other useful forest products, as well as the natural conditions in which forests grow, such as water, soils, climatic conditions, air and water pollution, and biodiversity. Forest resources are of great importance for the economy, as they are important sources of food, materials for construction and manufacturing, and energy resources, and they provide other useful functions, such as biodiversity conservation, water and air purification, climate regulation, and others. A huge part of the global forest resources is used to produce timber, which is widely used in construction, furniture and paper industries. In addition, forests provide habitats for more than 80% of the global species. Forest ecosystems also have the potential to reduce emissions and contribute to the fight against global warming (Marfina, 2011).

Ensuring sustainable forest management has a significant impact on creating a sustainable economy and preserving the environment. Efficient use of forest resources and protection of forests from careless use is a key challenge for the sustainable development of our planet. A specific feature of forest and ecosystem management in Europe is the concept of integration, which implies the need for different approaches to the potential for intensive timber production from forests designated for nature protection or recreation. In the European Union, forests are multifunctional, thus, when managing forest potential, ecological, economic and social functions of forests are addressed, all factors are analysed and management decisions are made to identify and achieve the specified goal (Fournier *et al*., 2022). Analysis of the experience of the world's leading countries identified main principles of forest management, as shown in Figure 2. A detailed description of each principle is provided below.

Conservation of forests and biodiversity: this principle involves the preservation of natural ecosystems, protection from pollution, protection from human interference and other negative impacts on the ecosystem. Biodiversity conservation is important because forests are home to a large number of different species of animals and plants. Conservation of natural processes is also relevant as they contribute to soil fertility, water balance and other ecological processes. Ensuring the conservation of forests and biodiversity is important for sustainable development and securing the natural resource potential for future generations (Karas *et al*., 2021).

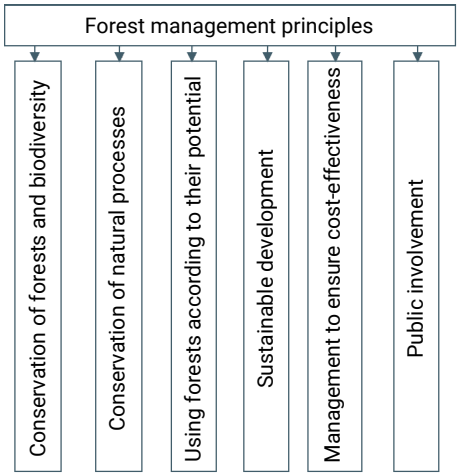

Figure 2. *Basic principles of forest management*
Source: compiled by the author

Use of forests according to their potential: this principle calls for the use of forests according to their purpose and capabilities. For instance, a forest can be used as a source of wood for furniture, paper and other materials, or as a recreational resource. This principle also requires consideration of the specifics of a particular area and forest. For instance, forests with more oak may be more profitable for furniture production, while forests with more pine may be better for paper and other materials. Analysis of the potential of forests allows to maximise the efficiency of their use and ensure the sustainable development of forest resources.

Sustainability: this principle implies that forests should be used at a rate that allows them to regenerate and maintain their ecological functions, including water and air purification, climate control, and biodiversity conservation. This principle is very important in forest management. Ensuring sustainable development means preserving natural resources for the long term, ensuring their use at a rate that does not exceed their natural ability to regenerate (Janová *et al*., 2024). This helps to maintain ecological balance and ensure access to forest resources not only for current generations but also for future generations. To achieve this goal, it is necessary to apply scientifically sound forest management methods that ensure their restoration and conservation. In addition, consideration of the impact of forestry on the environment and adherence to the principle of environmental safety are essential.

Management for economic efficiency: this principle implies ensuring maximum efficiency of forest resources use at minimum cost and maximum profit. The principle of management for economic efficiency implies that forest resources management should be aimed at ensuring maximum efficiency of their use with minimum costs and maximum profit. This implies the rational use of forest resources, optimisation of their extraction and processing, and increasing the competitiveness of the forest sector of the national economy. To achieve this goal, it is necessary to develop and implement effective forest management strategies, accounting for economic, social and environmental factors. It is essential to ensure effective control over the use of forest resources and the fulfilment of contracts for their extraction and processing, as well as to ensure transparency and openness in the process of resource allocation and control. Managing forest resources in an economically efficient manner can contribute to increasing forest revenues and developing the forest sector of the national economy. However, it is necessary to consider and consider environmental and social aspects, ensure the sustainability and conservation of forest ecosystems, and protect the rights and interests of local communities and forest users (Muys & Messier, 2023).

Public participation: this principle is essential to forest governance and involves the public in decision-making on forest management. This ensures that a wide range of diverse interests and perspectives, including economic, social, cultural and environmental, are represented, which are important for sustainable development. Public participation can take place through various forms of consultation, discussion and cooperation with stakeholders, including residents, representatives of civil society organisations,

academia and research institutions, industry and other interested parties. Public involvement helps to ensure broad support for decisions and builds trust in forest management processes. It also contributes to more effective and sustainable solutions that consider the needs and interests of different stakeholders and ensure the conservation and sustainable use of forest resources (Girma *et al*., 2023).

Ukraine has several forestry management problems that affect the quality of the forest industry. The main problems of forest management are Illegal deforestation, one of the biggest problems of forest management in many countries, including Ukraine. It leads to loss of biodiversity, disruption of ecological balance and reduction of CO_2 absorbed by forests. A major problem is insufficient protection of forests, which leads to a decrease in their natural value and deterioration of biodiversity. It also reduces the opportunities for sustainable use of forest resources and reduces the economic efficiency of forestry. Climate change is also a significant issue that has a negative impact on forests, in particular on their ability to store carbon and biodiversity. As a result, the risks of forest fires and diseases may increase, which can lead to increased forest loss. Unauthorised development of forest areas is quite popular in Ukraine, leading to a deterioration in the quality of forest resources and a decrease in their quantity, which leads to a decrease in the profits of forestry enterprises. Unauthorised development of forest areas is one of the most serious problems of forest management. This includes illegal deforestation, timber extraction without the necessary permits, the use of forests for illegal mining and other violations not provided for by law. The lack of alternatives to forest use can lead to unauthorised deforestation, which can be a barrier to sustainable development. For example, in certain regions of Ukraine, forests are the only source of firewood needed to heat domestic buildings in winter. In such cases, it is necessary to find alternative energy and fuel sources to reduce pressure on forest resources.

Discussion

The study demonstrated that international experience in managing forest resources against the backdrop of increasing pollution includes several effective strategies. Key outcomes include the introduction of air and water quality monitoring technologies, the use of innovative reforestation methods, and the integration of environmental standards into management policies.

The research showed that effective forest management strategies in the face of pollution often combined technological innovation with an integrated approach to resource management. For instance, the use of satellite data to monitor forest health has helped reduce pollution in the United States. NASA satellites such as Landsat have helped to reduce the percentage of pollution caused by deforestation and degradation, and in the state of California, Landsat data revealed a 20% reduction in pollution due to the control of forest fires and illegal logging. Sentinel-2 project in Australia is based on the use of the European Space Agency's Sentinel-2 satellites to help Australian researchers assess the condition of forests after forest fires. The data from these satellites allowed for a rapid assessment of the extent of damage and the implementation of restoration measures, which contributed to the restoration of 60% of the affected areas within the first year after the fires. Indonesia, in turn, uses satellite data to monitor forest changes and combat deforestation, so since 2015, thanks to satellite monitoring, the level of illegal logging in the country has decreased by 50%. Brazil has an Amazon forest monitoring programme, which uses satellite data to track deforestation, and thanks to data collected from satellites, deforestation in the Amazon decreased by 70% between 2004 and 2012 (Storch *et al*., 2023).

The use of satellite data for forest monitoring is gaining popularity in Ukraine, and there are several notable examples: The National Forest Monitoring Project, launched in 2020, uses satellite data to track changes in forest cover. According to the project, from 2020 to 2023, more than

30,000 hectares of illegal logging and spontaneous deforestation were identified and documented. The Forest Map system, implemented as part of an initiative to improve forest governance, is also operating on our territory, and it is worth noting that satellite imagery helped to identify and assess a 15% reduction in forest area in Ukraine in 2022 due to military operations and illegal activities. Thanks to satellite data from the Copernicus project, 35 large forest fires were quickly detected and extinguished in 2021, helping to prevent further damage to over 5,000 hectares. These examples demonstrate that innovative satellite data technologies are helping to manage forests and respond to environmental challenges in Ukraine as well. This supports the hypothesis that monitoring technologies are key to effective forest management (European Forest Institute, 2024).

The conclusions are consistent with the research of modern scientists, both foreign and domestic. T.V. Vu *et al.* (2019), paid attention to the impact of air pollution on various aspects of forest ecosystems, including tree health and biodiversity. I.Z. Gitas *et al.* (2014) explored the latest remote sensing technologies for forest health monitoring and pollution assessment. In turn, S. Cunningham *et al.* (2015) analysed successful cases of forest restoration as a means of pollution control and environmental quality improvement. E. Muller (2024) compared environmental norms and standards in forest management in different countries. Also, D. Karnosky *et al.* (2003) reviewed the impact of pollution on the biodiversity of forest ecosystems at the global level. They also emphasised the importance of monitoring technologies in forest management.

D. Zadykhailo *et al.* (2023) addressing the impact of military operations on the state of forests and the possibility of satellite monitoring for damage assessment. R. Elijah (2023) analysing the role of satellite data in the processes of forest restoration after natural disasters and pollution. In turn, O.I. Bandurka *et al.* (2021), investigating the effectiveness of satellite technologies for detecting and responding to forest fires. O.H. Chaskovskyy & H.H. Hrynyk (2020) examined the capabilities of Sentinel-2 satellites to assess the state of forests and their changes in recent years. Also, Y.S. Rajabova (2024) focused on the use of satellite imagery to monitor changes in forest cover and detect illegal logging. These studies show how Ukrainian scientists are using satellite technology to monitor and manage forests and assess environmental impacts. However, the study found that today, the war has a major impact on forest pollution. In Ukraine in particular, it has a significant impact on forests, causing physical damage through bombing and shelling, soil degradation and pollution, as well as increasing illegal logging and pressure on resources due to population displacement. The hostilities also reduce the capacity to manage and protect forests, leading to long-term environmental problems and requiring comprehensive efforts to restore forest ecosystems.

Despite the high relevance of this study, it is worth noting that certain limitations may affect its generality and applicability: first, the analysis was focused primarily on Ukraine and the European Union, which may limit the transferability of the findings to other regions of the world. Consequently, the results may not be fully reflective of the situation in other countries or continents where environmental, social and economic conditions may differ significantly. Secondly, data on forest pollution in some regions may have been incomplete or outdated, which may affect the accuracy and reliability of our findings. Future research should focus on the effectiveness of integrating different monitoring technologies in real-world settings, as this can significantly improve the quality of data collection and analysis, and it is important to investigate the impact of specific political and economic contexts on the success of forest management strategies in the face of pollution, which would allow for a better understanding of how different factors can interact and influence management decision outcomes. In summary, this study confirms that

effective forest management strategies in the face of increasing pollution can be achieved through the integration of technological innovations and a holistic approach. This is important for the development of new policies and practices that can be adapted to the specific conditions of different regions, which will not only contribute to the conservation of forest ecosystems but also increase their resilience to climate change and anthropogenic impacts.

Conclusions

Forest management is an important aspect of the national economy, as forests are a source of many resources, including timber used in construction and furniture production, as well as berries, mushrooms and other forest products used in the food industry. However, illegal deforestation and negligent management of forest resources can lead to environmental problems, such as reduced biodiversity, disturbance of ecological balance and reduced CO_2 absorption by forests, which in turn affects the climate.

In the process of analysing the international experience of forest management, the strategies of several countries were considered, namely: Canada, Finland, Sweden, Germany, France, the United Kingdom and the United States. Therefore, the following conclusions can be drawn: Canada focuses on sustainable forest management, forest certification, cooperation with indigenous peoples and investments in new technologies; Finland practices the principle of "cut down one tree – plant two", active involvement of local communities and high environmental standards; Sweden implements the principle of compensating deforestation with new plantations and investments in innovation, emphasising the importance of environmental legislation; Germany demonstrates a systematic approach to sustainable forest management, including monitoring, certification, reforestation and stakeholder engagement; France is noted for its comprehensive policy, including forest conservation, climate change adaptation and active education and research; The UK focuses on biodiversity conservation, investment in research and international initiatives; the US focuses on a combination of public, private and local forest management initiatives.

For Ukraine, these strategies can serve as useful examples for improving national forestry policy, especially in terms of sustainable forest management, certification, environmental monitoring and local community engagement. The prospect of further research is a detailed analysis of the possibilities of adapting international experience to Ukrainian conditions, to develop specific recommendations for the implementation of effective forest management strategies in Ukraine.

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Conflict of Interest

None.

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Міжнародний досвід та стратегії управління лісовими ресурсами в умовах зростання забруднення лісів

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Анотація. Метою даного наукового дослідження було ознайомлення з закордонним досвідом управління лісовим господарством та вивчення новітніх стратегій управління лісовими ресурсами. Виокремлено позитивний досвід іноземних країн щодо управління лісовою галуззю в умовах зростання забруднення лісів. Розглянуто можливості використання цього досвіду для покращення законодавства у відповідній сфері. Встановлено, що у розвинених країнах світу лісові ресурси відносяться до найважливіших національних цінностей, що мають значне економічне та соціокультурне значення. Для ефективного збереження та відновлення цих ресурсів закордоном запроваджені багаторівневі владні механізми управління лісовими ресурсами в умовах зростання забруднення лісів. У науковому дослідженні вказується, що в багатьох розвинених країнах використовують стратегії управління лісовими ресурсами за рахунок комплексного підходу до вирішення даного питання, основна суть якого, ґрунтується на заходах контролю, які здійснюються як органами державної влади, що спеціалізуються на питаннях лісового господарства, так і органами та службами з питань екологічної безпеки. У дослідженні зазначено, що управління лісовими ресурсами у світі стає все більш актуальним завданням через зростання забруднення, зміни клімату та інших екологічних викликів. Розглянуто кілька міжнародних підходів та стратегій, які використовуються для збереження та відновлення лісів, а саме: сталий лісовий менеджмент (Sustainable Forest Management, SFM); лісова сертифікація; міжнародні договори та ініціативи; реабілітація та відновлення лісів; залучення місцевих громад; технологічні інновації. Виокремлено декілька важливих моментів зарубіжного досвіду управління лісовими ресурсами, які варто використати та реалізувати в Україні: розвиток агролісомисленого підходу, запровадження програм збереження біорізноманітності, стратегія розвитку лісового господарства Європейського Союзу та інші. Отримані результати можуть бути застосовані для розробки національних і локальних стратегій управління лісами, впровадження екостандартів, адаптації планів боротьби зі забрудненням, а також для підвищення обізнаності та освіти серед громадян і представників влади

Ключові слова: екологічна стійкість; лісові екосистеми; екополітика; ЄС; охорона довкілля

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Influence of biologics on the development of soybean productivity elements in the conditions of the northern Forest-Steppe of Ukraine

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Abstract. The purpose of the study was to determine the effectiveness of the use of biostimulants for improving growth processes and increasing soybean yields in the region. The studies were conducted on chernozem soils of medium fertility, optimal for growing legumes. The sites were divided into four groups: a control group, a group with the introduction of Bioglobin, a group with Rizohumin, and a group with the combined use of both drugs. The main parameters for evaluating the effectiveness of drugs were the number of beans per plant, the number of seeds in the bean, the weight of 1,000 seeds, and the protein and oil content in the seeds. It was found that a separate application of Bioglobin improves the photosynthetic activity of plants, contributing to intensive growth and development of leaf mass, while Rizohumin actively stimulates the development of root nodules, increasing the efficiency of nitrogen fixation and providing the plant with nitrogen. The combined use of Bioglobin and Rizohumin gave the best results, significantly increasing the overall yield and quality of soybean seeds. The synergistic effect of the drugs contributed to an increase in the weight of 1,000 seeds, the number of beans per plant, and the protein and oil content in the seeds. This showed that the use of Bioglobin and Rizohumin in a complex is an effective strategy for improving soybean productivity, reducing the need for chemical fertilisers and improving the environmental sustainability of agricultural production. The results obtained indicate a significant potential of biologics to increase soybean yields in the region and are valuable for agricultural producers who seek to optimise growing conditions without additional costs for mineral fertilisers

Keywords: nitrogen fixation; fertility; inoculation; yield; plant nutrition

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Introduction

Soy is one of the most important crops in global agriculture, as it provides a high content of protein and oil, which makes it valuable for the food, feed, and industrial sectors. The demand for soybeans is constantly growing, and, accordingly, there is a need to increase its yield. However, conventional methods of increasing productivity through the use of mineral fertilisers have a number of negative consequences, in particular, environmental pollution, reduced soil fertility and increased production costs. In the conditions of modern agriculture, there is a need for efficient, ecological, and cost-effective methods of increasing crop productivity, which contributes to the search for alternative solutions. The relevance of the study is conditioned by the need to increase soybean yields in the northern forest-steppe of Ukraine using biological methods that are environmentally safe and cost-effective. Despite the growing popularity of biologics, the impact on soybean productivity in specific climatic conditions has not been sufficiently explored, which makes this study important for developing practical recommendations for farmers.

The problem of growing soybeans is related to the need to increase the yield and quality of products in conditions of limited resources and growing requirements for the environmental friendliness of agricultural technologies. Conventional methods of production intensification, which involve the active use of mineral fertilisers, cause a number of negative consequences: soil depletion, water pollution, increased acidity and reduced biological activity of the soil. This practice reduces the long-term productivity of agroecosystems and requires alternative approaches to maintain sustainable soybean production. Analysis of previous studies confirms the importance of biologics and other organic methods for improving soybean productivity.

For instance, G. Jat *et al*. (2021) investigated the effect of zinc application on soybean yield and quality in haplustepts-type soils. The researcher found that zinc supplementation improves the protein content of seeds, which increases their nutritional value and profitability. This highlights the importance of trace elements in soy nutrition systems, which contributes to its optimal development. M.D. Orozco-Mosqueda *et al*. (2021) pointed to the role of bacteria that stimulate plant growth and the benefits of increasing crop yields and stress resistance. The researchers note that these bacteria activate physiological processes, which contributes to better absorption of nutrients by plants and increases their resistance to adverse conditions, such as drought or lack of nutrients. B. Ramakrishnan *et al*. (2021) examined the role of organic farming in improving the quality of agricultural products and environmental safety. The researchers showed that organic farming methods contribute to increasing soil biodiversity, and reducing environmental pollution, which makes this approach beneficial for sustainable agricultural production. S. Bhunia *et al*. (2021) reviewed the effectiveness of animal-based organic fertilisers that improve biological activity and soil fertility. The researchers note that such fertilisers can significantly increase the organic matter content in the soil, ensuring a sustainable increase in plant productivity and reducing the need for chemical fertilisers. The study by H. Elhalis *et al*. (2024) was devoted to the fermentation processes of soy products that affect the quality of final products. The researchers emphasised that the high quality of soy seeds is the basis for obtaining products with improved nutritional properties and increased protein content.

M. Ghoroghi *et al*. (2024) investigated the properties of soybean oil-based bioplastics and their significance for the food industry. The researchers note that high-quality soybean oil contributes to the production of plastics for food packaging, which emphasises the importance of high-quality raw materials. J. Suman *et al*. (2022) reviewed the role of the soil microbiome in ensuring sustainable agricultural development. The researchers emphasise that the soil microbiome plays an important role in plant nutrition and

increases resistance to stress factors, which is key to improving yield and product quality. A. Raimi *et al*. (2021) considered the problems and prospects of biofertiliser production in Africa, noting that the use of biologics contributes to increasing crop yields and ensures the sustainable development of agricultural production. The researchers note that effective strategies for implementing biofertilisers can significantly improve yields while reducing environmental risks.

H. AbdElgawad *et al*. (2020) studied the effect of actinomycetes on improving soil quality and legume productivity. The researchers found that these microorganisms significantly increase the level of available nitrogen, which contributes to optimal nutrition of plants and an increase in the protein content in seeds. W. Elhaissoufi *et al*. (2022) focused on phosphate-soluble bacteria that increase the efficiency of phosphorus use by plants, which primarily improves yields. The researchers note that the increased availability of phosphorus stimulates the development of the root system and the overall productivity of crops. Previous studies confirm that the use of biologics and organic methods in soybean cultivation helps to increase yield and quality, improve soil composition and reduce environmental stress. The effectiveness of biologics is manifested in activating plant growth, improving stress resistance, and increasing the availability of essential nutrients such as nitrogen and phosphorus. Organic methods also contribute to the preservation of soil biological activity and ensure the stability of agroecosystems in the long term.

The purpose of this study was to investigate the effectiveness of the combined use of biologics Bioglobin and Rizohumin to increase the productivity and quality of soybeans in the agroclimatic conditions of the northern forest-steppe of Ukraine. The objectives of the study were: to determine the effect of combined use of Bioglobin and Rizohumin on soybean growth, development, and yield; to assess the effect of biologics on seed quality indicators, such as protein and oil content.

Materials and Methods

Study of the influence of biologics Bioglobin and Rizohumin on soybean productivity, which corresponded to the agroclimatic conditions of the northern forest-steppe of Ukraine characterised by a temperate continental climate with sufficient precipitation and favourable temperatures for growing legumes. The study was in line with the ethical standards set out in the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973). Bioglobin is a biological preparation used in agriculture to stimulate plant growth and development. The main function of Bioglobin is to increase the resistance of plants to stressful conditions, improve productivity and crop quality. It belongs to the group of biostimulants that help to optimise the physiological processes of plants, such as photosynthesis, mineral nutrition, protein synthesis, and substances necessary for growth. Rizohumin is a biological preparation that stimulates the development of root nodules on the roots of legumes, such as soy, which helps to increase the efficiency of nitrogen fixation. The study area was located in a region where the average annual temperature is about 8-10°C, and the annual precipitation varies from 500 to 700 mm, which provides acceptable conditions for plant development. The long growing season under these conditions allowed investigating the effectiveness of growth stimulants, Bioglobin and Rizohumin, at different stages of soybean development.

Areas with typical chernozems of medium fertility for this zone, rich in humus and well-supplied with trace elements necessary for normal plant development were selected for the study. The soils had a good structure, which contributes to the development of the root system, and a high level of organic matter, which increases the water retention capacity. The soil pH was 6.5-7, which is optimal for legumes, since it ensures the effective activity of nitrogen-fixing bacteria. Climatic conditions during the study period were stable, with an average daily temperature of about 20°C

during the active growing season and moderate fluctuations in precipitation, which ensured uniform plant growth throughout the cycle. The study was conducted using several treatment options: a control group without adding drugs; a group with Bioglobin treatment in concentrations of 0.5 l/ha, 1 l/ha, and 1.5 l/ha; a group with Rizohumin in the same concentration; and a group where both drugs were used in concentrations of 0.5 l/ha, 1 l/ha, and 1.5 l/ha. Treatment of seeds and seedlings was carried out according to the instructions for the preparations, which ensured a uniform effect of each variant on all prototypes. Variants with Bioglobin were aimed at improving photosynthetic activity and overall plant growth, while variants with Rizohumin focused on stimulating nitrogen fixation, which is key to providing the crop with nitrogen without the additional use of chemical fertilisers.

Several basic parameters that were measured during the study were used to determine performance. The number of beans per plant was determined by counting all formed beans on each plant after the end of the growing season. The number of seeds in beans was measured by counting the average number of seeds for each bean, which allowed assessing the effectiveness of generative organ development under the influence of biologics. In addition, an important indicator of yield was the weight of 1,000 seeds, which was measured based on weighing a sample of seeds from each treatment option. This indicator allowed assessing not only the quantitative, but also the qualitative characteristics of the crop, since a larger seed mass indicates the best development of each seed sample.

To determine the nutritional value of the seeds, a protein and oil content analysis was performed for Bioglobin. In particular, Rizohumin focused on the impact on root nodule development and increased nitrogen fixation efficiency, which are key indicators for assessing the effectiveness of soybean application. With the combined use of Bioglobin and Rizohumin, the study focused on combining indicators that allow assessing the complex effect of both drugs. In this case, such indicators as the total number of beans per plant, the number of seeds per bean, the weight of 1,000 seeds, and the nutritional value of seeds (protein and oil content) were considered. These parameters are critical for determining product quality, as the high protein and oil content increases the economic value of soybeans, which is of great importance for the production of feed and food products.

The general approach to the study helped to comprehensively assess the effect of each biological product on all aspects of soybean productivity, which enabled a comparison of the effectiveness of Bioglobin and Rizohumin both separately and in combined use.

Results

The northern forest-steppe of Ukraine is characterised by various types of soils that have specific properties that affect the cultivation of soybeans. Among them, there are grey forest soils with a low humus content (1.5-3%), which have an average fertility and require additional fertilisation to maintain soybean productivity, and also have a limited ability to retain moisture, which becomes critical in dry periods. Leached chernozems are among the most fertile soils in the region due to their high humus content (3-6%), retain moisture well and provide plants with nutrients, so they are favourable for growing soybeans, although they need to maintain biological activity to preserve fertility. Podzolic chernozems with a humus content of 2-5% are less productive due to podzolisation processes, which reduce fertility and require organic fertilisers to restore the balance of nutrients (AgroStory, 2024). Meadow-chernozem soils that are formed in low-lying areas with high groundwater levels have good fertility and moisture capacity, but sometimes require regulation of the water regime due to possible waterlogging. Meadow soils formed in floodplains are rich in organic matter and moisture, but require drainage to grow soybeans, as excessive humidity can negatively affect growth.

Each of these soil types requires a special approach in agricultural technologies adapted to specific conditions. The use of biologics is becoming an effective tool for improving soil quality and soybean growing conditions in these diverse soil types. Biologics stimulate microbiological activity, improve soil structure, and increase the availability of nutrients, which is especially useful for soils with a low humus content or limited ability to retain moisture.

All indicators were studied in different dosage options of the drug. Studies have shown that the use of Bioglobin significantly improves key indicators of soybean productivity, including the number of beans per plant, seed weight, and protein and oil content in seeds. Table 1 provides detailed data on these indicators and shows the percentage increase for each dose of the drug. The main results of the effect of Bioglobin on these parameters are shown in Table 1.

Table 1. *Effect of Bioglobin on soybean growth and productivity*

Indicator	Control	Bioglobin (0.5 l/ha)	Bioglobin (1 l/ha)	Bioglobin (1.5 l/ha)
Number of beans per plant	24	30	34	32
Seed weight, g/plant	12.5	14.8	16.5	15.7
Protein content in seeds, %	32	34.5	35.7	35
Oil content in seeds, %	18	19	19.5	19.2
Increase in the number of beans, %	-	25	41.7	33.3
Increase in seed weight, %	-	18.4	32	25.6
Increase in protein content, %	-	7.8	11.6	9.4
Increase in oil content, %	-	5.6	8.3	6.7

Source: compiled by the author

Analysis of the table shows that at a dosage of Bioglobin of 1 l/ha, the maximum positive effect on all productivity indicators was observed. The number of beans per plant at this dosage increased by 41.7% compared to the control, reaching 34 beans per plant. This indicates a significant increase in the efficiency of photosynthetic processes and nutrient absorption, which contributed to more active plant development.

Seed weight, which is an important indicator of overall yield, also increased significantly when using Bioglobin. The highest rate – 16.5 g per plant – was achieved at a dosage of 1 l/ha, which is 32% more compared to the control option. This suggests that Bioglobin effectively stimulates the metabolic processes of plants, which leads to improved growth and greater accumulation of biomass in seeds.

The protein content, as one of the most important indicators of soy quality, also increased when using the drug. The control group had a protein content of 32%, while Bioglobin at a dose of 1 l/ha increased this figure to 35.7%, which is 11.6% more. This increase in protein is conditioned by the activation of nitrogen fixation, which helps to improve the absorption of nitrogen, which is necessary for protein synthesis in plants. The oil content of seeds has also undergone positive changes due to the use of Bioglobin. The highest oil content – 19.5% – was observed at a dose of 1 l/ha, which is 8.3% more compared to the control.

A general analysis of the data shows that the optimal dose of Bioglobin for achieving the highest soybean productivity is 1 l/ha. This dose provides the best results in all indicators, including the number of beans, seed weight, and protein and oil content, which increases both yield and seed quality. The use of Bioglobin is an effective method for increasing soybean productivity, making this drug profitable and promising for use in the conditions of the northern forest-steppe of Ukraine.

Nitrogen fixation is a key process for plants, as it allows them to obtain nitrogen in a form

suitable for assimilation. Nitrogen is one of the most important elements for plant growth and development, as it is a part of proteins, nucleic acids, and chlorophyll. Efficient nitrogen fixation improves nitrogen uptake from the air, reducing the need for chemical fertilisers, making the growing process more environmentally friendly and cost-effective (Komok & Pirig, 2014; Didur & Tsyhanskyi, 2023).

The use of Rizohumin led to a significant increase in the number and activity of root nodules. In control plants, an average of 10-12 nodules per plant were observed, while in plants treated with Rizohumin, the number of nodules increased to 18-25, depending on the dosage of the drug. Nodules formed under the influence of Rizohumin had a larger diameter and a denser structure, which is an indicator of high activity of the nitrogen fixation process. Observations showed that the optimal dosage of Rizohumin for the development of nodules is 1 l/ha, at which the number of nodules on the roots was the highest (Table 2).

Table 2. *Effect of Rizohumin on root nodule development and nitrogen fixation efficiency in soybeans*

Indicator	Control	Rizohumin (0.5 l/ha)	Rizohumin (1 l/ha)	Rizohumin (1.5 l/ha)
Number of nodules, units/plant	11	18	25	23
Average nodule diameter, mm	1.2	1.5	1.8	1.6
Nitrogen content in tissues, %	2.3	2.7	3.1	3
Leaf mass gain, %	-	15	25	20
Chlorophyll content, mg/g	1.8	2	2.3	2.2
Efficiency of nitrogen fixation, %	-	+20	+40	+35

Source: compiled by the author

Along with an increase in the number of nodules, an improvement in nitrogen-fixing activity was also observed. Plants treated with Rizohumin had significantly higher levels of available nitrogen in their tissues compared to the control group. This is conditioned by the activation of symbiotic bacteria, such as Rhizobium, which multiply in nodules and convert atmospheric nitrogen into forms suitable for assimilation by the plant. An increase in the amount of nitrogen in plants contributed to more intensive growth of the aboveground part, in particular, the development of leaf mass, which improved the process of photosynthesis. It also contributed to increased plant productivity and higher yields, as plants had access to more nitrogen, which is necessary for the synthesis of proteins and other important components.

It was also noted that plants treated with Rizohumin showed higher resistance to stressful conditions, such as drought and nitrogen deficiency in the soil. Due to effective nitrogen fixation, plants could provide nitrogen even under adverse conditions. This is especially important for growing soybeans in regions with variable climates and uneven supply of nutrients to the soil.

The use of Rizohumin also reduced the use of chemical nitrogen fertilisers in experimental sites. This has led to lower fertiliser costs and reduced the negative impact on the environment. The study showed that under conditions of adequate use of Rizohumin, optimal nitrogen fixation indicators can be achieved, which provides plants with the necessary nitrogen without additional sources. This is a cost-effective solution for farmers, as it allows reducing the cost of mineral fertilisers and maintaining high yields.

Table 3 shows the effect of Bioglobin and Rizohumin on key indicators of soybean growth and productivity at different stages of its development, and the results of combined use of both drugs.

Table 3. *Comparative analysis of the effect of Bioglobin and Rizohumin on soybean productivity in different growth phases*

Growth phase	Indicators	Control	Bioglobin (0.5 l/ha)	Bioglobin (1 l/ha)	Bioglobin (1.5 l/ha)	Rizohumin (0.5 l/ha)	Rizohumin (1.0 l/ha)
Germination	Leaf surface, cm^2/plant	250	280	300	310	260	255
	Number of nodules, units	4	4.5	5	5.5	6	7
Root system development	Number of nodules, units	10	10.5	11	11.5	16	17
	Nitrogen content, %	1.8	1.9	2.0	2.1	2.4	2.6
Budding and flowering	Protein content in tissues, %	28	29	30	31	32	33
	Number of flowers, units	15	16	18	19	16	17
Bean development	Number of beans, units/ plant	18	20	22	24	21	23
	Average weight of 1,000 seeds, g	150	155	160	165	158	162
Filling and ripening of beans	Nitrogen content in seeds, %	2.2	2.3	2.5	2.6	2.7	2.8
	Yield, t/ha	2.5	2.6	2.8	3	2.9	3

Growth phase	Indicators	Control	Rizohumin (1.5 l/ha)	Bioglobin + Rizohumin (0.5 l/ha)	Bioglobin + Rizohumin (1 l/ha)	Bioglobin + Rizohumin (1.5 l/ha)
Germination	Leaf surface, cm^2/plant	250	270	300	320	330
	Number of nodules, units	4	7.5	8	9	9.5
Root system development	Number of nodules, units	10	18	18	20	21
	Nitrogen content, %	1.8	2.7	2.7	2.8	2.9
Budding and flowering	Protein content in tissues, %	28	33	34	35	36
	Number of flowers, units	15	18	19	20	21
Bean development	Number of beans, units/ plant	18	24	24	25	26
	Average weight of 1,000 seeds, g	150	165	168	170	172
Filling and ripening of beans	Nitrogen content in seeds, %	2.2	2.9	2.9	3	3.1
	Yield, t/ha	2.5	3.2	3.2	3.3	3.4

Source: compiled by the author

In the germination phase, it was recorded that Bioglobin contributes to an increase in the leaf surface, which has increased from 250 cm^2 in the control group up to 300 cm^2. Rizohumin at this stage had a minimal effect on the leaf surface (255 cm^2), but affected the number of root nodules, increasing their number to 7, while in the control it was only 4. The combined use of Bioglobin and

Rizohumin showed the highest results, reaching 320 cm^2 of leaf surface and 9 root nodules.

In the phase of active root system development, Rizohumin demonstrated its greatest effectiveness, ensuring the formation of 17 nodules, which is 70% more than in the control group. Bioglobin also improved this indicator (11 nodules), but the effectiveness at this stage was inferior to Rizohumin. The combination of both drugs reached the highest rate – 20 nodules per plant and an increase in nitrogen content in tissues up to 2.8%, which is 55.6% more compared to the control.

During budding and flowering, both drugs showed a positive effect on the protein content and number of flowers. Bioglobin increased the number of flowers by 3 units (up to 18), and Rizohumin increased this indicator to 17 flowers, which also had a positive effect on yield. However, the combination of drugs showed the maximum number of flowers – 20 units, and the highest protein content in tissues (35%), which is 25% more than in the control group. In the bean development phase, the effect of Rizohumin on nitrogen fixation contributed to the appearance of more beans (23 units), which was slightly higher than in plants treated with Bioglobin alone (22 units). The combined use of drugs provided the maximum number of beans – 25 units per plant, and the largest weight of 1,000 seeds, which was 170 g, which is 13.3% more compared to the control.

At the stage of filling and ripening of beans, the combined use of Bioglobin and Rizohumin gave the best result: the nitrogen content in seeds reached 3.0%, which is an important indicator for the final quality of seeds. This provided a yield of 3.3 t/ha, which is 32% higher than in the control group. Bioglobin and Rizohumin used separately also increased yields, reaching 2.8 t/ha and 3.0 t/ha, respectively, but did not exceed the result of combined use.

The general analysis of Table 3 confirms that the combined use of Bioglobin and Rizohumin provides a synergistic effect in all phases of soybean growth, increasing its productivity at all levels – from the development of the root system and leaf surface to the formation of more beans and increased yield.

One of the most important indicators that characterise the quality of the crop is the average number of seeds in a bean. Since seed development directly affects the productivity and market value of the crop, it is important to consider the effect of these drugs on this indicator (Murach *et al.*, 2020; Berdin *et al.*, 2024). Figure 1 shows the effect of Bioglobin, Rizohumin, and their combination on seed development in beans. This helped to assess how effective these drugs are in improving crop quality, which is important for increasing yields and economic benefits when growing soybeans.

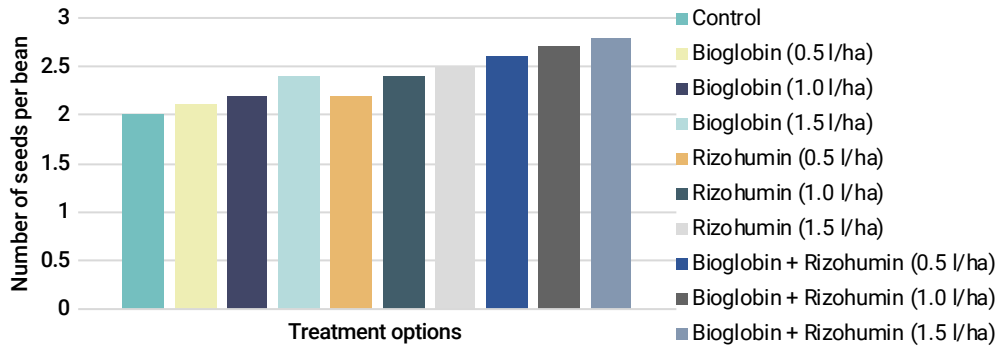

Figure 1. *Influence of biologics on the development of the number of seeds in beans in soybean plants*

Source: compiled by the author

The Figure 1 shows that the use of Bioglobin and Rizohumin significantly improves seed development in soybean beans. In the control group that was not treated with biologics, the average number of seeds per bean was only 2. The introduction of Bioglobin led to a noticeable increase in this indicator to 2.3 seeds per bean, which indicates the stimulating effect of the drug on seed development and overall productivity. The use of Rizohumin showed even greater effectiveness, increasing the average number of seeds to 2.4, which may be due to its effect on nitrogen fixation and providing the plant with available nitrogen, critical for seed development.

The combined use of both drugs – Bioglobin and Rizohumin – gave the greatest result, providing an average number of seeds in the bean at the level of 2.6. This confirms the synergistic effect of drugs, when the combined effect significantly exceeds the effect of each individual (Chaika *et al.*, 2023; Krutilo & Volkohon, 2024). This effect creates optimal conditions for the development of more seeds, which as a result has a positive effect on the yield of soybeans.

In general, the use of biologics, especially in combination, significantly increases the efficiency of seed development in soybean beans, which is an important factor for increasing the overall yield of the crop. The results obtained indicate the high efficiency of biological stimulants that can be recommended for use in agricultural production to increase the productivity and quality of the soybean crop, and to reduce dependence on chemical fertilisers.

Discussion

The results obtained demonstrate significant advantages of using microbial inoculants in increasing the productivity of crops, in particular soybeans, in modern agricultural production. These data indicate an annual increase in yield by 15-20% due to active nitrogen fixation, which reduces the need for chemical fertilisers and contributes to an increase in the biological activity of the soil. It was also found that the use of inoculants in combination with organic approaches provides long-term maintenance of soil fertility by reducing erosion and improving water retention properties. This is significantly different from conventional approaches based on chemical fertilisers, which can negatively affect the ecosystem (Fedoruk, 2021).

The results of this study confirm the effectiveness of inoculants, but they differ from the data obtained by L. Liu *et al.* (2022), who focused on fermented soy products and their biological activities. L. Liu *et al.* (2022) investigated the effect of traditional fermentation processes on the nutritional value and biological activity of soybean products, while this study is more focused on the agronomic aspect – the effect of inoculants on soil yield and environmental indicators. This suggests that this approach is more environmentally oriented and aimed at the sustainable development of agricultural systems.

A.A. Tammam *et al.* (2023) focused on vermicompost to reduce salt stress and improved nutrient absorption, which helped plants under stressful conditions. However, this study does not cover the productivity of a particular crop or the impact on yield. Unlike A.A. Tammam *et al.* (2023), this study directly concerns soybeans and shows that the use of biologics Bioglobin and Rizohumin improves yields by 25-30% and increases the protein and oil content in seeds. These results also show that these biologics reduce the need for chemical fertilisers, while maintaining the ecological stability of the soil. This makes this study more valuable for the agricultural sector due to its direct impact on soybean productivity in specific agroclimatic conditions.

Regarding the physiological processes associated with seed formation, the results of this study coincide with the conclusions of J.T. Vogel *et al.* (2021), which emphasise the importance of stimulating photosynthetic processes to increase yields. However, this study goes further, proving that the combination of Bioglobin and Rizohumin provides more intensive seed development in beans, which has been confirmed at different

stages of growth. This combined approach contributes to a synergistic effect on soybean growth and development, which was less emphasised in the study by J.T. Vogel *et al*. (2021). The results obtained for increasing the number of seeds in the bean are also consistent with the results of J.-S. Cai *et al*. (2021), who investigated the benefits of various biological methods for improving the nutritional value of soybeans. This study demonstrated that the use of Bioglobin and Rizohumin not only increases the number of seeds, but also increases the content of protein and other nutrients. This allows obtaining high-quality products, which is an additional advantage of the authors' approach in comparison with the study by J.-S. Cai *et al*. (2021).

The results of this study show a significant increase in soybean productivity due to the use of biologics Bioglobin and Rizohumin, especially when used in combination. Both drugs have a positive effect on the development of root nodules and overall yield, but the combined action has a synergistic effect, which improves the results compared to previous studies. To better understand the effectiveness of the authors' approach, it is useful to compare it with previous studies that used other methods to increase soybean yields, such as fertiliser treatment and the use of growth stimulants.

The data obtained indicate a significant increase in the number of root nodules and an increase in the level of nitrogen fixation in soybean plants treated with Rizohumin. These results are consistent with the conclusions drawn in the study by M.A. Khan *et al*. (2021), which also notes an improvement in soybean productivity under the influence of beneficial bacteria. However, this study is more complex, since not only activated symbiotic bacteria, but also additionally used Bioglobin to stimulate photosynthetic activity, which helped to achieve higher yield indicators. The combined use of both drugs provided improvements in photosynthesis and nitrogen nutrition, which was less discussed in detail by M.A. Khan *et al*. (2021).

For example, in the study P. Tripathi *et al*. (2021) examined the effect of silicon fertilisers on nodule formation and soybean yield. The researchers emphasise that silicon fertilisers stimulate the development of nodules and increase the efficiency of nitrogen fixation, which has a positive effect on yield. However, in this study, the use of Rizohumin was found to be more effective in stimulating nodules due to its direct effect on the activity of Rhizobium bacteria. In addition, the additional use of Bioglobin contributed to an increase in the photosynthetic activity of plants, which was not achieved with silicon fertilisers in the study by P. Tripathi *et al*. (2021). This suggests that the authors' approach provides better comprehensive stimulation of soybean growth.

I.B. Laskar *et al*. (2020) paid attention to the efficiency of soybean oil transesterification for biodiesel production using bio-waste as a catalyst. Although this study is not directly related to soybean cultivation, the results highlight the importance of optimising processes that contribute to improving the profitability of soybean production. This study focuses on increasing the yield and quality of soybean seeds, which can have a positive impact on the economic feasibility of biodiesel production, since increasing the number of seeds and increasing the protein and oil content of seeds contribute to improving the final quality of products for processing.

G.Y. Rahimova (2023) focused on the agrobiological properties of bentonite and its impact on crop growth. The use of bentonite improves the structure of the soil and provides better conditions for the development of the root system. However, this study focused on the effects of biologics, such as Rizohumin, which not only promote the development of the root system, but also provide a direct increase in the number of nodules responsible for nitrogen fixation. Unlike bentonite, Rizohumin provides the plant with nitrogen, which reduces the need for external nitrogen fertilisers and increases nutritional efficiency. The combined use of Rizohumin and Bioglobin in this study allows for higher yields without the

need for additional soil additives such as bentonite, making this method more cost-effective and environmentally friendly.

The study by N.E. Korres *et al*. (2020) examined the impact of soybean crop density and emergence time of *Amaranthus palmeri* on weed biology, soybean yield, and economic profitability. The researchers emphasise that the high density of soybean crops can significantly reduce the competitiveness of weeds, such as *Amaranthus palmeri*, which is one of the most aggressive weeds in the United States. This study showed that regulating crop density can be an effective means of reducing the number of weeds and minimising crop losses. However, while this increase in crop density can reduce the negative impact of weeds, its effectiveness depends on the growing conditions and time of weed emergence. In comparison with the results of this study, where biologics were used to increase soybean productivity, the paper by N.E. Korres *et al*. (2020) shows an alternative approach to crop optimisation through agronomic practices. This study complements the conclusions of N.E. Korres *et al*. (2020), showing that the use of biologics can also help in weed control, since a healthy and powerful plant that is actively developing due to the use of Bioglobin and Rizohumin has a better competitive ability against weeds. In addition, biologics increase the resistance of soybeans to stressful conditions, creating favourable conditions for high yields even in the presence of weeds. This highlights the added benefit of this approach, which not only provides a direct increase in yields, but also helps to reduce the need for mechanical and chemical weed control, which can have a positive economic and environmental impact.

B. Guo *et al*. (2022) focused on soy's genetic resources that contribute to sustainable protein production. The researchers emphasise the importance of genetic diversity in improving soybean productivity, in particular, in adapting to climate change, increasing disease resistance, and improving protein quality. B. Guo *et al*. also noted that genetic resources can help solve problems with reducing the nitrogen content in the soil and adapting plants to changing growing conditions. This study is particularly useful for long-term planning of soy protein production, as it shows that the use of genetic resources can increase soy's resistance to various stresses. The use of biologics Bioglobin and Rizohumin in this experiment showed that biological stimulants can significantly increase the resistance of soybeans to stress and improve its performance in difficult conditions. In contrast to the genetic approach by B. Guo *et al*. (2022), this method achieves faster results without the need for long-term breeding and genetic testing processes. In addition, the use of biologics can increase the content of protein and other nutrients in seeds, which is useful for the food industry, similar to B. Guo *et al*. (2022), who proposed to improve the protein content through genetic modifications.

Unlike agronomic practices and genetic modifications, this method demonstrates effectiveness in increasing the yield and quality of soybeans by stimulating photosynthesis and nitrogen fixation, creating a synergistic effect. This provides stable results regardless of growing conditions, reducing the need for chemical fertilisers and weed control, which makes this approach cost-effective and environmentally friendly.

Conclusions

The study showed that Bioglobin and Rizohumin have a significant positive effect on soy productivity, especially when used in combination. Bioglobin, as a growth stimulator, increases photosynthetic activity, leaf mass and total plant biomass, which contributes to the active development of plants in the early stages of vegetation. This ensures rapid accumulation of energy necessary for the development of generative organs, and improves productivity by increasing the number and weight of seeds. Rizohumin, in turn, actively stimulates the development of root nodules, which provides effective nitrogen fixation. This allows plants to use nitrogen from the air, reducing the need for chemical fertilisers, which

reduces costs and improves the environmental friendliness of cultivation.

For farmers working in the northern forest-steppe of Ukraine, it is recommended to use Bioglobin at a dose of 1.0 l/ha in the early stages of soybean development, which will ensure active growth and strengthening of plants. Rizohumin should also be used in the early stages, but the main effect of the drug is manifested in the phase of nodule formation and subsequent nitrogen nutrition. The combined use of both drugs allows achieving the best results, since it provides the plant with both energy support and the necessary nitrogen throughout the growing season. This approach improves the yield and quality of seeds, which makes it an effective and cost-effective method for agricultural producers in this region.

Further research may focus on optimising dosages and developing comprehensive schemes for using different biologics for different soybean varieties and growing conditions. Because different varieties may respond differently to biological stimulants, future research will help to identify more specific recommendations for each variety and region. In addition, a promising area is to study the effects of these drugs in combination with other organic methods, such as mulching or bioinoculants, which can increase effectiveness. Studying the long-term effects of biologics on soil quality and microbiota can also provide useful results for the development of sustainable agricultural technologies.

One of the limitations of the study is that it was conducted in specific agroclimatic conditions of the northern forest-steppe of Ukraine, which may limit the generalisation of results for other regions with different climatic conditions. In addition, the study covered only certain doses of Bioglobin and Rizohumin, so additional experiments with different concentrations and application schemes may be required to optimise the use.

In general, the results of the study confirm the effectiveness of Bioglobin and Rizohumin as stimulants that not only increase soybean productivity, but also reduce dependence on chemical fertilisers, which is a significant advantage for modern agriculture.

Acknowledgements

None.

Conflict of Interest

None.

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Вплив біопрепаратів на формування елементів продуктивності сої в умовах північного Лісостепу України

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Анотація. Метою роботи було визначити, наскільки ефективним є застосування цих біостимуляторів для покращення ростових процесів і підвищення врожайності сої в регіоні. Дослідження проводилися на чорноземних ґрунтах середньої родючості, оптимальних для вирощування бобових культур. Ділянки було поділено на чотири групи: контрольну, групу з внесенням біопрепарату Біоглобін, групу з Ризогуміном та групу з комбінованим застосуванням обох препаратів. Основними параметрами для оцінки ефективності препаратів були кількість бобів на рослину, кількість насіння у бобі, маса 1000 насінин, а також вміст білка та олії в насінні. Встановлено, що окреме застосування Біоглобіну покращує фотосинтетичну активність рослин, сприяючи інтенсивнішому росту та розвитку листкової маси, тоді як Ризогумін активно стимулює утворення кореневих бульбочок, підвищуючи ефективність азотфіксації та забезпечуючи рослину азотом. Комбіноване застосування Біоглобіну та Ризогуміну дало найкращі результати, значно підвищивши загальну врожайність та якість насіння сої. Синергічний ефект препаратів сприяв збільшенню маси 1000 насінин, кількості бобів на рослину та вмісту білка й олії у насінні. Це дозволило зробити висновок, що використання Біоглобіну та Ризогуміну в комплексі є ефективною стратегією для покращення продуктивності сої, знижуючи потребу в хімічних добривах та покращуючи екологічну стійкість агровиробництва. Отримані результати свідчать про значний потенціал біопрепаратів для підвищення врожайності сої в регіоні та є цінними для агровиробників, які прагнуть оптимізувати умови вирощування без додаткових витрат на мінеральні добрива

Ключові слова: азотфіксація; родючість; інокуляція; урожайність; живлення рослин

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Retrospective analysis of the dynamics of spruce drying in different forest conditions Gorgan

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Abstract. The study aimed to assess changes in the intensity of spruce drying in different forest types and at different altitudes, addressing the time factor. The research was conducted in the central part of the Gorgan Mountain range in its foothills (the Bystrytsia Solotvynska river basin) on an altitude-typological profile. The degrees of decomposition of dead wood were characterised to determine the following types of trends in the spruce drying process in different types of forests and tree species composition: fading with a decrease in intensity over time; weakly expressed with significant fluctuations in drying out in individual years; intense with an annual increase in the phenomenon. The duration and dynamics of these trends for different forest vegetation conditions were noted. On the example of three forestries, the annual dynamics of spruce drying areas in the period from 2016 to 2024 for the spectrum of vertical vegetation belts available in the Gorgany was presented in the following sequence: foothill fir-oak, mountain beech-fir, beech-fir-spruce and pure spruce forests. The results of the statistical analysis indicate that spruce drying processes are multidirectional, depending on the gypsometric levels of the relief and the associated altitudinal zonation. The study determined that in foothill fir-oak forests, the intensity of spruce drying decreases. This pattern was somewhat less pronounced in the lower mountainous zone of beech and fir forests (500-600 m). In the altitudinal range of 650-1000 m (the upper part of the beech-fir belt and the lower part of beech-fir-spruce forests), the intensification of spruce drying is notable. The study demonstrated that at altitudes above 1000 m, patterns in the drying of spruce forests are not pronounced, as this phenomenon is sporadic. The practical significance of the research results is reduced to their use in differentiated measures to enhance the sustainability of stands in different altitudinal zones

Keywords: altitudinal zones; forest types; stand composition; dead wood; empirical dependencies

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Introduction

One of the biggest challenges for forestry in the Ukrainian Carpathians is the intensification of spruce drying out due to climate warming. The widespread occurrence of this phenomenon creates critical situations regarding the loss of valuable timber and a decrease in the sustainability and protective role of forests in the ecologically unstable mountainous and foothill conditions of the region. The drying out of spruce forests in the Ukrainian Carpathians has been considered a natural disaster, with the main causes being a decrease in its resilience and weakening of stands as a result of increasing above-zero temperatures and past forestry activities. This process is especially relevant for the Gorgan Mountain range, where European spruce (*Picea abies* (L.) H. Karst.) accounts for approximately 70% of the forest stock. The decline covers approximately 13% of the forest area and 39% of the spruce forests, and in some forestries with a significant distribution of this species, 12-18% and 53-85%, respectively (Zeinalian, 2021). According to the research by Y.S. Shparyk & T.V. Parpan (2020), in wet conditions of Ukrainian Carpathian spruce forest, the average drying rate of medieval and medium-sized stands with a spruce proportion of 6-7 units was 3%, for wet beech-fir forest – 1%, and for wet beech-spruce forest – 2% per year. The identified drying trends were used to compile a calculation framework for the area and stock of spruce for the next 20 years. The forecast until 2040 showed that the average loss of spruce area in spruce forest types of the Ukrainian Carpathians will be 28%, with a decrease in the number of trees in the first tier and the accumulation of significant reserves of dead spruce wood – up to 300 m^3/ha.

Given the widespread distribution of spruce stands in Central Europe, the research by J. Krejza *et al.* (2021), which assessed their growth under climate change, is noteworthy. This publication presents data demonstrating that the most intensive drying was observed in the experimental plots located at an altitude of ≈ 600 m above sea level. E. Bowditch *et al.* (2021) and R. Bace *et al.* (2023) provided evidence that the existing climatic conditions in the Central European region are not suitable for growing European spruce at lower and middle altitudes, which should be accounted for when developing a new spruce forest growth management programme. The impact of forestry measures on the condition of spruce forests and the growth characteristics of natural spruce stands without forestry activities were studied by T. Hilmers *et al.* (2019).

The literature indicates that the processes of spruce forests drying out and their area are not the same for different forest vegetation conditions (Kramarets *et al.*, 2024), forest types and stands (Matusevych, 2022). However, the quantitative assessment of these changes is largely unexplored. First, this concerns their spatial and temporal dynamics due to the inherent variability of climate, relief and forest cover in the mountains.

The drying out of the Carpathian spruce forests, which started in the mid-1990s under the influence of global climate warming, continues to this day. Several scientific publications have been devoted to this problem, covering the factors, causes and spread of the phenomenon, the role of abiotic and silvicultural factors in its formation, forestry and environmental consequences, and proposals for strengthening forest resilience (Brodovych & Brodovych, 2023).

V.S. Oliinyk & A.M. Zeinalian (2020) studied the effect of thermal conditions on the drying of woody species, which was associated with the height of mountain slopes. The authors determined that with increasing altitude, the temperature regime changed, which directly affected the physiological state of trees. Altitude zonation affected microclimatic conditions that determined the spread and intensity of drying out. The results of the study showed that the height of the slopes was a factor that modified the manifestation of the harmful phenomenon since thermal stress in the highlands was significantly different from the conditions of the lowlands.

I. Shyshkanynets *et al.* (2021) addressed the change in the intensity of spruce drying depending on the time factor in different forest conditions. The authors noted that the dynamics of drying processes demonstrated a gradual deterioration of the trees due to the impact of climate change and biotic factors. Forest vegetation conditions, such as soil type, humidity and site exposure, were central in determining spruce resilience to adverse factors. The study highlighted the importance of long-term monitoring to understand these processes and develop adaptation measures for forest ecosystems.

Y. Shparyk *et al.* (2020) covered dead wood as an indicator of wood drying processes. The authors proved that the state of decomposition of dead wood can be used for a retrospective assessment of the time and nature of drying processes in the past. This approach was effective for making predictions on the state of forests, as information on wood decomposition could be integrated into models of forest ecosystem development. The study emphasised the importance of accounting for dead wood not only for analysing ecosystem processes but also for predicting their evolution.

In general, the current distribution and growth characteristics of spruce stands in different forest vegetation conditions of the Gorgan on a typological basis remain understudied. Factoring in the time factor when assessing changes in the intensity of spruce drying will make it possible to develop silvicultural programmes for the reproduction of native stands in the most common types of spruce forests in the study area.

The study was aimed at assessing changes in the intensity of spruce drying in different forest types and altitudinal zones depending on the time factor.

To achieve the research objective, the following tasks were defined: to analyse dead wood stocks and the degree of its decomposition in the main forest types; to assess the dynamics of annual areas of spruce forests in the altitudinal zones of foothill fir oaks, mountain beech-fir, beech-fir-spruce and spruce forests.

Materials and Methods

The study was conducted in three forestries of the Osmolodske Forestry branch in 2016-2024. The object of the study was spruce forests located in foothill fir-oak and mountain beech-fir, beech-fir-spruce and spruce forests at altitudes from 300 to 1400 metres above sea level. The study analysed the drying processes of spruce forests in different forest vegetation conditions typical for the Gorgan Mountains and their foothills. The study was conducted following the ethical standards set out in the Convention on Biological Diversity (1992) and the Convention on Trade in Endangered Species of Wild Fauna and Flora (1973).

The processes of spruce forests drying out were studied in two ways of retrospective analysis: 1) by the degree of decomposition of dead wood in five test plots in different forest types; 2) by the dynamics of annual allocation of spruce drying areas for sanitary felling in different altitude forest zones. These approaches were used to comprehensively assess the condition of spruce forests and establish the temporal patterns of their degradation.

The trial areas were laid out at relief heights of 300-900 m (SOU 02.02-37-476:2006, 2007), where spruce drying processes are most pronounced in mountainous conditions (Hudyma *et al.*, 2014; Oliinyk & Zeinalian, 2020). They are confined to the main forest types of the Gorgan; their stands are similar in age but differ in the proportion of spruce and wood stock. The deadwood and lying deadwood in the sample plots were counted according to generally accepted forest inventory methods. At the same time, A. Schuck *et al.* (2004) distinguished the stages of its decomposition – from fresh undecomposed to decayed state. Each of these stages allowed to establish the time limits of wood death: for Gorgan spruce forests, dead wood in the first stage of decomposition indicates that it was formed 2-3 years ago, the second – 5-10 years, the third – 10-15 and the fourth – 15-20 years ago (Shparyk & Parpan, 2020).

The annual dynamics of drying areas and their trend over time were studied on an altitudinal forestry profile in the Bystrytsia Solotvynska river basin, which covered three forestry units of the Osmolodske Forestry branch – Bohorodchany, Manyava and Hutyany – following the vertical differentiation of vegetation in the Ukrainian Carpathians (Stoyko, 2012; Zeinalian, 2021). These processes are consistently associated with foothill fir-oak forests, mountain beech-fir, beech-fir-spruce and partially spruce forests. Data on the drying out of spruce forests were collected and analysed based on departmental materials on the allocation of drying out areas for sanitary felling with their distribution by altitude zones and forest strips. The data on relief indicators and silvicultural and taxonomic features of the stands in the drying areas were borrowed from forest management materials. In total, more than 300 sites in the altitude range of 300-1400 m were analysed.

For high-altitude forest vegetation zones, the proportion of spruce forests, the coefficients of variation in drying out of the species over the years, and the regression equation for the dependence of its drying out on time were determined. The empirical formulas were calculated with pairwise correlation coefficients greater than 0.6 and a confidence level of more than three.

Results and Discussion

The analysis of materials on the accumulation and dynamics of dead wood on the experimental objects of high-altitude forestry profile (Table 1) shows the following features of this process.

Table 1. *Stocks and degrees of decomposition of dead wood in different forest conditions*

Characteristics of the research facilities	Height above sea, m				
	300	**600**	**680**	**850**	**900**
Silvicultural and taxation indicators stands					
Forest type	C_3-FirCo	D_3-Fb-FirSpr	C_3-Fb-FirSpr	C_3-Fb-FirSpr	C_3-Fb-FirSpr
Composition of the stand	6Spr3Sc1B+Fir,Co	5Fir3Spr1Sc1B	8Fir2Spr+Fb	6Spr3Fir1Fb+B	6Spr3Fir1B+Fb
Age, years	64	62	54	57	60
Completeness	0.7	1.0	0.7	0.9	1.1
Reserves, $m^3 \cdot ha^{-1}$	160	560	290	450	560
Stock of dead wood (dead and dead wood) *					
Total, $m^3 \cdot ha^{-1}$	144/134	83/70	73/29	144/92	104/101
By degree of decomposition:					
1	4/3	5/0	48/11	59/17	6/6
2	19/19	18/12	17/11	39/32	30/27
3	48/48	34/32	8/7	43/40	28/26
4	73/64	26/26	0/0	3/3	40/40
Trend drying spruces	pronounced 20-year decay	weak 20-year decay	weak 15-year increase	intensive growth 5-15 years ago	intensive growth 15-20 years ago

Note: Spr – European spruce; Fir – white fir; Sc – Scots pine; Cp – cedar pine; Fb – forest beech; Sy – sycamore; Co – common oak; B – hanging birch; * in the numerator – for the entire plantation, in the denominator – for spruce

Source: developed by the author

Firstly, reserves of dead wood depend on the proportion of spruce in the composition of stands. Thus, its increase from 2-3 units to 6 units contributes to a 2-4-fold increase in the volume of dead wood reserves. In mountainous conditions, they increase with the increase in gypsometric relief levels caused by an increase in the proportion of spruce forests (r = 0.83) and a slowdown in

wood decomposition due to a vertical decrease in the maximum temperatures of the growing season (r = 0.96).

The dynamics of dead wood accumulation are different in certain forest vegetation conditions. Judging by the presence of the 3rd and 4th stages of its decomposition, which respectively characterise the age of its formation over 10-15 and 15-20 years, it is possible to assume that the impetus for the drying of the species was the extreme weather conditions of the late twentieth and early twenty-first centuries, namely the hot and extremely dry periods of active vegetation in 1995-2003. According to forest meteorological studies in the Gorgan spruce forests (Oliinyk & Zeinalian, 2020), these periods were characterised by minimal precipitation, which amounted to only 55% of the norm, and in some summer months even dropped to 9.5-18% of the norm.

In general, the analysis of the dead wood condition shows that in different forest vegetation of the foothill and mountainous conditions of the Gorgan during 2016-2024, the trend of spruce forests drying out is different. Its directions are as follows: 1) fading with a decrease in intensity; 2) weak expression with fluctuations over the years; 3) increase with an increase in the area of drying.

In the foothill subboreal forests, where intensive drying of spruce stands began in the second half of the 1990s, there was a downward trend in this process (Tkachuk & Zeynalian, 2023). This is related to the small proportion of spruce derivatives and intensive sanitary felling. To a certain extent, a similar drying trend is characteristic of the neighbouring lowland spruce forests. At higher hypsometric levels (700-900 m) in mixed fir and spruce forest types, the drying of the species intensified after 2003. It is characterised by growth with slope height and maximum development 5-20 years ago.

The above-mentioned dynamics of spruce forests drying out over time is confirmed by the data on the allocation for sanitary felling of 326 forest plots affected by this phenomenon in different altitude forest zones of the three forestries of the Osmolodske Forestry branch in 2016-2024 (Table 2).

Table 2. *Dynamics of spruce drying areas in different altitudinal zones*

Years	All forests	Foothill forests (350-500 m)	Mountainous conditions						
			beech and fir forests			beech-fir-spruce forests			For mountain forests
			500-650 m	650-800 m	for the entire belt	800-1000 m	> 1000 m	for the entire belt	
2016	156	82	25	7	32	39	4	43	75
2017	112	39	22	19	41	27	5	32	73
2018	100	44	12	15	25	28	2	30	55
2019	145	58	6	21	27	45	15	60	87
2020	91	34	2	34	36	21	0	21	57
2021	52	12	0	12	12	27	0	27	39
2022	205	36	45	52	98	62	10	72	170
2023	215	29	19	35	54	114	17	131	185
2024	187	34	36	54	90	64	0	64	154
Total %	1263 100	368 29.1	167 13.2	248 19.7	415 32.9	427 33.8	53 4.2	480 38.0	895 70.9

Source: developed by the author

For the foothill spruce forests of the foothills, the decrease in drying areas in the specified time interval is notable. In the range of mountain altitudes of 650-1000 m (upper zone of the beech-fir belt and lower zone of the beech-fir-spruce belt), the opposite trends are expressed – an increase in the intensity of drying out of the rock. In the transitional, lower-mountainous zone of beech-fir forests (500-650 m) and at high hypsometric levels of mixed and pure spruce forests (above 1000 m), no clearly defined patterns of drying changes are observed. Despite the vertical variability of these processes, the phenomenon of spruce drying intensification prevails in mountain forests in general.

Dominant partial drying increases from foothill fir-beech forests (300-500 m) to mountain beech-fir forests (500-800 m), and then decreases in beech-fir-spruce forests (800-1200 m) and becomes non-existent in the upper spruce belt (at 1300 m). Continuous drying is characterised by a small proportion and a slight increase in the average area with increasing altitude. These patterns are caused by two factors:

1) the growth from the foothills to the upper boundary of the lower mountain belt of areas of spruce forests that are intensively exposed to drying out;

2) the slowdown of these processes from 800 m above sea level is caused by changes in meteorological conditions. At this level, the temperate climate zone with July temperatures of +17, +19° moves to the lower temperature zone, where they are 2-3° lower, and even higher, in the cold zone with pure natural spruce forests, temperatures drop to 12° or less.

The area of partial drying increases from 1.8-2.8 ha at 300 m to 4 ha at 600-800 m and then decreases, disappearing at 1200-1300 m. Areas of continuous drying increase evenly from 300 m (0.6 ha) to 1300 m (1.9 ha). In general, plantations at altitudes of 400-900 m are most vulnerable to drying out. In this altitude range, 87% of the centres and 84% of the area of this harmful phenomenon are concentrated.

In quantitative terms, the dynamics of spruce drying are characterised by the following results of statistical processing of materials in the context of the altitudinal zonation of mountain forests. In the foothill fir-oak forests, the proportion of spruce derivatives and the coefficient of variation of their drying areas over the analysed years are the lowest in Gorgan and amount to 20% and 45%, respectively. Changes in annual drying (S, ha) in Bohorodchany forestry over time (A, annual indices; 11-19 years of the 21st century) are characterised by a reliable inverse regression equation of the following type:

$$S = 112 - 4.71 \cdot A \quad \text{at } r = -0.66 \pm 0.18, \quad (1)$$

which shows that in 2016-2024, the area of spruce drying out decreased by three times. The data on the area of spruce forests in the Bohorodchany forestry and the annual regression coefficients show that, if current climatic conditions remain unchanged, in 2022-2032, the main areas of spruce forests will be covered by sanitary felling, minimising the area of this derivative species.

Specific trends in the drying out of spruce derivatives are observed in the lower mountain belt of beech-fir forests in the Maniava and Hutia forestries, which is adjacent to the foothill conditions. The proportion of spruce plantations varies with altitude from 18 to 38%, and the coefficient of variation of the drying area of the species ranges from 61-100%. In the strip of beech spruce forests (500-600 m) adjacent to the foothill conditions, the spruce stands in the analysed years had a certain tendency to decrease in drying out ($r = -0.50$). The dependence of the species drying on the time factor is weak ($r = 0.28$) for the entire lower part of this belt at altitudes of 500-650 m. Only in the upper part of the belt (650-800 m) with 38 % spruce, there is a clear dependence of the intensification of rock drying on changes in the time factor:

$$S = 6.9 \cdot A - 50 \quad \text{at } r = 0.80 \pm 0.12. \quad (2)$$

Such patterns of drying out of spruce derivatives in different altitudinal bands of beech spruce forests determine a positive trend towards

a general belt-wide increase in this process, the empirical formula of which is as follows:

$$S = 6.7 \cdot A - 54 \quad \text{at } r = 0.62 \pm 0.21. \quad (3)$$

It indicates that the area of drying out quadrupled between 2016 and 2024. The patterns of drying of derivative and native spruce forests are different in the high-altitude zones of beech-fir-spruce and pure spruce forests (800-1400 m). In these two forestries, the share is 57 and 85%, respectively. The belt of mixed spruce forests (800-1000 m) is characterised by a relatively small coefficient of variation of drying areas – about 59 % and their reliable positive dependence on the time factor:

$$S = 6.9 \cdot A - 56 \quad \text{at } r = 0.64 \pm 0.19. \quad (4)$$

In this altitudinal range, the growth of spruce drying areas is similar to that of the beech spruce belt. At higher hypsometric levels (>1000 m asl), the coefficient of variation of drying areas by year is quite variable (≈ 104%), and their relationship with time is extremely low (r = 0.15). In certain years, this process is insignificant or even absent (Table 2). This is caused by significant relief heights with a corresponding decrease in air temperature and an increase in precipitation, which prevents the rock from drying out. In general, natural spruce forests at altitudes of 800-1400 m are characterised by a general tendency to dry out over time ($r = 0.58 \pm 0.22$), but it is not sufficiently expressed in quantitative terms due to the influence of relief and meteorological factors.

In mountainous conditions, the current intensification of spruce drying is most clearly manifested at altitudes of 650-1000 m (upper strip of beech spruce forests and lower part of mixed spruce forests). This pattern is reinforced by drying tendencies at other altitudes, and therefore the dependence of increased drying of the species dominates in mountain spruce forests (500-1400 m) at the present stage of climate warming. It is expressed by the following equation:

$$S = 13.9 \cdot A - 109 \quad \text{at } r = 0.70 \pm 0.17. \quad (5)$$

Due to the different vectors of spruce drying in foothills and mountainous conditions, there is no general picture of this process in the region over time ($r = 0.45 \pm 0.27$). The analysis of the forest fund of the Manyava and Hutia forestries and the empirical dependence (5) suggests that under current climatic conditions, the main areas of spruce forests may be covered by sanitary felling in the next 7-8 years due to the drying out process.

Numerous studies revealed the influence of various environmental factors that can cause spruce forest degradation and drying out, particularly in mountainous conditions. Climatic and edaphic conditions have an impact on the specificity and intensity of spruce drying processes. To prevent spruce dieback, it is necessary to develop systems of forest protection measures that consider natural conditions and regional peculiarities of forest management.

According to European scientists, namely E. Gordeeva *et al.* (2022), the processes of spruce drying are observed in both native and derivative stands, but the situation in derivative spruce stands is currently more critical. Other researchers H. Spiecker & H.-P. Kahle (2023) noted that dieback processes are present in spruce stands of different ages but are most pronounced in pure medieval monocultures and older stands, as well as in sparse stands that have emerged on the site of natural oak and rock oak groves. V. Lavnyy & O. Pelyukh (2019) determined that the largest areas of spruce forests are concentrated in Ivano-Frankivsk region – 47.8% of the total area of spruce forests. Among the forest types, spruce-fir forests are most often found in wet spruce-beech successional forests. The authors also noted a decrease in the biotic and abiotic stability of spruce derivative stands.

The relationship between silvicultural and climatic factors and their impact on the sanitary condition of spruce stands was studied by H. Hrynyk *et al.* (2010). The analysis of the impact of climate change on the sanitary condition of spruce stands in the Ukrainian Carpathians was studied by H. Hrynyk & O. Hrynyk (2022). Due to changing

climatic conditions in European countries, spruce forests are weakening, their sanitary condition is deteriorating, and plantations are drying out over large areas (Vyshnevskyi & Donich, 2021).

As spruce forests decline, the carbon storage of wood decreases and the amount of carbon released into the atmosphere during the decomposition of dead wood increases. Climate change has affected the condition and productivity of forest ecosystems, including mountain spruce monocultures, which were created in the 19th century in Europe and the Carpathians to produce ripe timber quickly – as a result of climate change, they began to dry out en masse. The most intense drying affected the spruce forests created on the site of fir and beech forests (Tkachuk & Zeynalian, 2023).

C. Yue *et al.* (2023) believe that in the second half of the twenty-first century, forest conditions will deteriorate further. It is expected that there will be even less precipitation during the growing season, and droughts will be more frequent and longer. Such climate change will contribute to an even greater spread of forest drying. This will result in significant changes in the species composition of forests. A. Taccoen *et al.* (2019, 2022) investigated the impact of climate stresses and dry periods on spruce drying in the Vosges and Ardennes, using remote sensing to monitor forest change.

The intensive die-off of spruce forests can be influenced by their age. According to L.M. Beley *et al.* (2022), the massive decline of mono-dominant dark coniferous forests is a normal phenomenon in the process of their age development. First of all, these processes are manifested in stands that have reached the age of old age for this species under certain conditions (Synek *et al.*, 2020).

The dominant feature of the distribution of forest vegetation in mountainous conditions is the altitude zonation, according to which the plantations are divided into zones: foothill oak forests (100-220 m asl, pure oak, beech-oak stands), beech forests (300-1450 m asl, pure beech, fir-beech, fir-fir-beech stands), spruce forests (700-1450 m asl, pure spruce, beech-fir, fir-spruce, beech-fir-spruce-spruce stands), subalpine belt (1300-1500 (1800) m asl, coniferous and deciduous shrubs), alpine belt (above 1800 m asl), which is primarily due to the climatic conditions of the mountainous terrain (Matusevych, 2022). In the context of modern climate change, which is accompanied by a global increase in air temperature, forest plantations are forced to adapt to new conditions. Therefore, identifying the current limits of spruce plantations and comparing them with the previously established ones will be used to assess the dynamics of the high-altitude distribution of European spruce stands. Therefore, spruce stands were grouped by altitude within the study area, the main silvicultural and taxation indicators, and dead wood stock.

To prevent the drying out of spruce forests and the formation of stable indigenous stands, a set of forest health measures (various types of felling, monitoring and protection of the forest, and reforestation) should be conducted, primarily in a timely manner: in mountainous conditions – up to the altitude range of 450-900 m above sea level, mainly on the southern slopes, as well as on all steep slopes with stony soils, regardless of their exposure; in foothill conditions – in forest areas adjacent to treeless lands. To prevent spruce stands from drying out, attention should be devoted to plantations with a spruce proportion of more than 3-5 units, 35-60 years old and with a fullness of 0.6-0.8, as they are most prone to drying out. Foothill sub-alpine conditions are not suitable for growing spruce derivatives, while lower mountain spruce forests are more promising. The best conditions for the formation of spruce forests are observed in spruce forest types, regardless of forest management systems.

Conclusions

Based on comprehensive silvicultural studies for different forest vegetation conditions, the stability of spruce forests in the Gorgan Mountains is assessed. The altitude-belt and silvicultural-taxation features of spruce forests drying out, their influence on structural changes in plantations and the dynamics of dead wood formation in

them are revealed. The silvicultural condition of such stands and the processes of natural regeneration are highlighted. The leading abiotic factor of spruce drying is the relief height, which determines the dependence of these processes on mixed oak, fir and beech forest types in the altitude range of 350-1150 m above sea level. Plantations at altitudes up to 900 m are most vulnerable. At higher levels (spruce forest belt), these phenomena are insignificant. A retrospective analysis of the accumulation of dead wood in drying spruce forests shows that its reserves depend on the proportion of spruce in the stand composition and the height of the mountainous terrain, and the state of its decomposition indicates the subsequent trends in the drying of the species: 1) attenuation; 2) weak expression; 3) intensification. They have altitude-belt patterns.

In the fir subboreal forests of the foothills, the intensive drying of spruce derivatives that occurred at the turn of the twentieth and twenty-first centuries has been replaced by processes of slowing down this phenomenon. To a lesser extent, similar changes in spruce drying are characteristic of the neighbouring lowland strip of beech-fir forests. In the altitude range of 650-1000 m (the upper band of beech-fir forests and the lower part of the belt of beech-fir-spruce forests), processes of intensification of the species drying are observed. At altitudes above 1000 m, the dependence of spruce drying on time is insignificant.

Estimates show that if current climatic conditions remain unchanged, with the inherent drying out of spruce forests, in the next 8-10 years, sanitary felling will have to cover the main areas of spruce forests in the altitude range of 300-1000 m above sea level.

Spruce cultivation is not very promising in foothill spruce sub-forests. In lowland fir forests, silvicultural measures can control spruce drying out, reducing the high competitiveness of fir. In mountain-mixed spruce forests, properly implemented silvicultural measures contribute to the formation of indigenous highly productive spruce stands. In the absence of harvesting, spruce retains its position in the upper tier, while fir and beech spread in the subordinate tiers. In sub-arid conditions, native spruce stands of low productivity are formed. In general, spruce retains its viability in spruce forest types under different management systems.

In different forest vegetation conditions, the drying out of spruce forests in time is ambiguous. In foothill subboreal forests, it was highest in 2000-2010, after which it gradually decreased. Similar dynamics are typical for spruce in lowland fir forests. In mountain spruce forests, there are no clear patterns of spruce drying out over time. In spruce forests, this phenomenon intensified in 2005-2010 and continues to this day on steep slopes of southern exposures with gravelly soils. In sub-boreal conditions, spruce drying is similar to the process in birch forests.

Further research could identify the key factors that influenced the change in the intensity of the process, including climatic conditions, anthropogenic impact, changes in soil properties and stand structure.

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Conflict of Interest

None.

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Ретроспективний аналіз динаміки всихання ялинників у різних лісорослинних умовах Ґорган

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Анотація. Метою роботи було оцінити зміни в інтенсивності всихання ялинників у різних типах лісу та на різних висотах з урахуванням фактора часу. Дослідження проводилися у центральній частині гірського масиву Ґорган із його передгір'ям (басейн річки Бистриця Солотвинська) на висотно-типологічному профілі. Охарактеризовано ступені розкладу мертвої деревини, за якими визначено наступні види трендів процесу всихання ялини у різних типах лісу та породним складом деревостанів: затухаючий із зменшенням інтенсивності по мірі плину часу; слабко виражений із значним коливанням всихання по окремих роках; інтенсивний із щорічним збільшенням площ явища. Відзначено тривалість та динаміку цих трендів для різних лісорослинних умов. На прикладі трьох лісництв висвітлена річна динаміка площ всихання ялини у період з 2016 по 2024 роки для наявного у Ґорганах спектру вертикальних рослинних поясів у такій послідовності: передгірних ялицево-дубових, гірських буково-ялицевих, буково-ялицево-ялинових і чистих ялинових лісів. Результати статистичного аналізу свідчать про різновекторність процесів всихання ялини залежно від гіпсометричних рівнів рельєфу і пов'язаної з ним висотної поясності. Виявлено, що у передгірних ялицево-дубових лісах інтенсивність всихання ялини затухає. Дещо слабше ця закономірність виражена у нижньогірській смузі буково-ялицевих лісів (500-600 м н. р. м.). У висотному діапазоні 650-1000 м (верхня смуга буково-ялицевого поясу і нижня частина буково-ялицево-ялинових лісів) досить чітко виражена інтенсифікація всихання ялини. Наведено дані, що на висоті більше 1000 м н. р. м. закономірності у всиханні ялинників не виражені, оскільки це явище тут спорадичне. Практична значущість результатів досліджень зводиться до їх використання у диференційованих заходах щодо посилення стійкості деревостанів у різних висотних поясах

Ключові слова: висотні пояси; типи лісу; склад деревостанів; мертва деревина; емпіричні залежності

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Efficient winter wheat cultivation in high-productivity different-field crop rotations under the conditions of unstable moisture in the Forest-Steppe zone of Ukraine

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Abstract. The application of modern technologies for cultivating winter wheat in scientifically grounded crop rotations is increasingly important in the context of climate change. Such practices enhance its yield and production volumes, ensuring domestic market demands and the stable export of Ukrainian grain products. The study aimed to identify, synthesise, and systematise scientifically

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validated measures for effectively cultivating winter wheat in high-productivity five-field and ten-field crop rotations with varying levels of cereal saturation under unstable moisture conditions in the Left-Bank Forest-Steppe zone of Ukraine. To achieve this goal, a comprehensive system of general scientific and specialised research methods was employed, including field, laboratory-field, comparative-calculation, mathematical-statistical, and abstract-logical approaches. It was established that, on average, during the research period of 2021-2023, the highest winter wheat yield of 6.64 t/ha was achieved following peas in a five-field crop rotation with 60% cereal saturation and the application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land. In five-field crop rotations, the yield of winter wheat following peas increased by 7.1-18.1% compared with perennial grasses, spring barley, and spring wheat. A high winter wheat yield of 6.44 t/ha was achieved following peas in a ten-field crop rotation with 80% cereal saturation and the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land. In ten-field crop rotations, the yield increase of winter wheat following peas compared with annual grasses (vetchoat), soybean, perennial grasses, spring barley, oilseed radish, and silage maize ranged from 7.5% to 24.4%. The yield increase attributable to mineral fertiliser application at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land was 39-60% after peas, 43% after perennial grasses, and 36-42% after silage maize. The most economically viable option was identified as the five-field crop rotation with 60% cereal saturation and mineral fertiliser application at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land, yielding the highest net profit of 26.93 thousand UAH/ha and a profitability level of 151%

Keywords: five-field and ten-field crop rotations; cereal saturation; predecessors; mineral fertilisation; productivity; economic efficiency

Introduction

Winter wheat plays a crucial role in addressing the grain production challenge, serving as one of the best predecessors in crop rotations for key agricultural crops such as sugar beet, maize, sunflower, peas, soybean, rapeseed, and potatoes. Consequently, significant attention is directed towards employing modern cultivation technologies for winter wheat within scientifically validated crop rotations. These efforts aim to enhance its yield and production volumes, increase overall food reserves and seed security stocks, and meet the demands of the domestic market while supporting the stable export of Ukrainian grain products.

Comprehensive research into an integrated scientific and technological approach – combining scientifically grounded measures for cultivating high-productivity winter wheat varieties within different-field crop rotations under unstable moisture conditions – has not yet been fully undertaken. At the same time, individual agronomic practices highlighted in scientific publications require optimal coordination. Notably, a series of studies by Ukrainian researchers provide valuable insights into the effective cultivation of cereal crops within short-field crop rotations, which merits further attention.

For instance, Ye. Yurkevych *et al.* (2021) investigated the impact of organic and mineral fertilisers on the yield and quality of cereal crops, including under the conditions of unstable moisture in Ukraine. The authors highlighted the effectiveness of combining organic fertilisers (such as compost and manure) with mineral fertilisers (nitrogen, phosphorus, and potassium), which enhances crop productivity amidst climate change and supports the sustainable development of agriculture. Similarly, V. Ivanina & T. Prokopiuk (2024) underscored the significance of mineral fertilisers and micronutrients (manganese and silicon) in improving soil fertility and increasing grain yield

and quality, emphasising their advantages for the sustainable management of soil resources.

The research conducted by B. Mazurenko *et al.* (2021) focused on the post-sowing application of compound fertilisers in the cultivation technologies of soft winter wheat. Compound fertilisers, which contain essential macro- and microelements, were shown to improve yields, grain quality, and disease resistance, demonstrating their efficacy in enhancing winter wheat productivity. In a monograph, O. Demydenko *et al.* (2019) analysed the effects of crop rotations systems and the use of plant residues on the fertility of chernozem soils in the Left-Bank Forest-Steppe zone of Ukraine. The use of crop residues and green manure crops, such as alfalfa and peas, was found to enrich the soil with nutrients, promoting its sustainable development and maintaining high productivity.

In her study, N. Kovalenko (2024) examined innovative technologies for the effective cultivation of cereal crops, focusing on green manure and the use of plant residues. The author emphasised the importance of incorporating green manure crops, which improve soil structure and enrich it with nutrients, thereby enhancing crop yields under diverse climatic conditions in Ukraine.

These findings underscore that the use of organic, mineral, and compound fertilisers, alongside the utilisation of plant residues and green manure crops, represents effective strategies for improving soil fertility and crop productivity in contemporary agricultural systems.

Romanian researchers I. Sulea & F. Sala (2022) highlighted the significance of combined applications of biodynamic preparations for improving the physiological parameters and productivity of winter wheat. Their study demonstrated the effectiveness of such approaches in alternative cultivation systems, enhancing plant growth and yield under challenging agro-climatic conditions. Similarly, C. Iordan *et al.* (2022) investigated plant protection systems against diseases and pests in Romania and other European countries. They confirmed that the integrated application of protection measures is essential for maintaining high yields, particularly in the context of increasing pathogen pressure. Soil tillage methods are another critical aspect for improving winter wheat cultivation efficiency. Research by I. Prymak *et al.* (2023) in Ukraine and M. Nankova & S. Doneva (2024) in Bulgaria demonstrated the effectiveness of both conventional and no-till systems in preserving soil structure and enhancing productivity. These methods ensure better soil preparation for sowing and contribute to higher yields by reducing the adverse effects of erosion and improving conditions for plant root systems.

However, the specific features of integrating fertilisation systems and crop predecessors for the efficient cultivation of winter wheat in high-productivity different-field crop rotations under the unstable moisture conditions of the Left-Bank Forest-Steppe zone of Ukraine require further investigation and analysis.

The study aimed to identify, synthesise, and systematise scientifically grounded measures for the efficient cultivation of winter wheat in high-productivity five-field and ten-field crop rotations with varying levels of cereal saturation under the unstable moisture conditions of the Left-Bank ForestSteppe zone of Ukraine.

Materials and Methods

The research was conducted as part of long-term stationary experiments at the Cherkasy State Agricultural Research Station of the National Scientific Centre "Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine". This station is located in the Left-Bank Forest-Steppe zone of Ukraine, characterised by unstable moisture conditions, and is situated on typical low-humus, medium loamy chernozem soils. The study adhered to ethical standards outlined in the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992). Between 2021 and 2023, the research evaluated the efficiency of cultivating winter wheat in high-productivity five-field and ten-field crop rotations with 60-100%

cereal saturation, including 20-40% winter wheat and 10-20% spring wheat, depending on their arrangement and proportion. This analysis incorporated various predecessors and the application of mineral fertilisers (Table 1, 2). The total research area was 27 hectares, with a plot size of 230 m^2 for sowing and 100 m^2 for accounting, and each trial was conducted in triplicate.

Table 1. *Structure of sown areas of five-field crop rotations*

Variant No.	Structure of sown areas, %											
	Cereals (total)	Including:					Row crops (total)	Including:		Spring rapeseed	Annual and perennial grasses	Oilseed radish
		Winter and spring wheat	Spring barley	Oats	Maize for grain	Legumes		Maize for silage	Sunflower			
Application of mineral fertilisers at a rate of $N_{52}P_{56}K_{56}$ per hectare of arable land												
1	80	40	20	-	-	20	-	-	-	20	-	-
2	80	40	-	20	-	20	-	-	-	20	-	-
3	80	20	-	-	20	40	-	-	-	20	-	-
4	80	20	-	-	40	20	-	-	-	-	-	20
5	60	60	-	-	-	-	-	-	-	-	20	20
6	60	40	-	-	20	-	-	-	-	-	20	20
Application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land												
7	100	40	-	-	20	40	-	-	-	-	-	-
8	100	40	20	-	20	20	-	-	-	-	-	-
9	60	40	-	-	-	20	40	20	20	-	-	-
10	80	40	-	-	20	20	-	-	-	-	20	-
11	100	40	-	-	-	60	-	-	-	-	-	-
12	80	20	20	-	20	20	40	20	-	-	20	-

Source: developed by the authors

Table 2. *Structure of sown areas of ten-field crop rotations*

Variant No.	Structure of sown areas, %										
	Cereals (total)	Including:				Row crops (total)	Including:			Annual and perennial grasses	Oilseed radish
		Winter and spring wheat	Spring barley	Maize for grain	Legumes		Maize for silage	Sugar beet	Sunflower		
Without fertiliser application											
1	70	30	10	10	20	20	10	10	-	10	-
Application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land											
2	80	30	-	20	30	20	10	-	10	-	-
3	60	30	20	-	10	20	10	-	10	10	10
4	90	40	-	20	30	10	-	-	10	-	-
5	70	20	-	30	20	10	-	-	10	-	10
6	70	30	10	10	20	20	10	10	-	10	-
7	60	20	10	10	20	10	10	-	-	20	10
8	100	30	10	30	30	-	-	-	-	-	-
9	70	30	-	10	30	30	10	-	20	-	-

Source: developed by the authors

The weather conditions during the years of the study were generally favourable for the growth and development of winter wheat plants. However, the 2020/2021 and 2021/2022 growing seasons were characterised by uneven precipitation distribution and excessive drought, which adversely affected winter wheat yield formation.

The study utilised regionally adapted varieties and hybrids of agricultural crops listed in the State Register of Plant Varieties Suitable for Distribution in Ukraine (2024). To achieve the research objectives, a combination of general scientific and specialised methods was employed: field and laboratory-field methods were applied to obtain experimental data on the impact of scientifically justified measures on the efficiency of cultivating winter wheat in high-productivity fivefield and ten-field crop rotations with varying cereal saturation; comparative and computational methods were used to determine winter wheat yield, as well as the quantitative indicators of productivity and the economic efficiency of five-field and ten-field crop rotations; mathematical and statistical methods were employed to assess the reliability of the research results; the abstractlogical method facilitated the formulation of conclusions and the development of a series of scientifically substantiated measures for the efficient cultivation of winter wheat in high-productivity crop rotations under conditions of unstable moisture to ensure Ukraine's food security.

Results and Discussion

Over the 2021-2023 study period, it was determined that in five-field crop rotations, pea was the most effective preceding crop for winter wheat, yielding the highest productivity of this key strategic crop (Table 3). Specifically, the maximum yield of 6.64 t/ha was observed with the application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land in crop rotations with 60% cereal saturation, including 20% winter wheat and 20% spring wheat (Variant 9). The application of mineral fertilisers at a rate of $N_{52}P_{56}K_{56}$ per hectare of arable land in crop rotations with 80% cereal saturation, also with 20% winter wheat and 20% spring wheat, resulted in high yields of 6.33-6.43 t/ha (Variants 2, 4). Other preceding crops ranked in descending order of effectiveness were annual grasses (vetch-oat mixture), spring barley, and spring wheat. Winter wheat yields following pea cultivation were 7.1-18.1% higher compared to these alternatives.

Table 3. *Winter wheat yield in five-field crop rotations depending on preceding crops, t/ha, average for 2021-2023*

Variant No.	Preceding crop	Yield, t/ha			
		2021	2022	2023	Average
Application of mineral fertilisers at a rate of $N_{52}P_{56}K_{56}$ per hectare of arable land					
1	Pea	6.52	5.22	6.80	6.18
	Spring barley	6.48	4.24	6.42	5.71
2	Pea	6.64	5.60	6.76	6.33
3	Pea	6.19	5.43	6.62	6.08
4	Pea	6.28	5.24	7.78	6.43
5	Annual grasses (vetch-oat)	6.00	5.10	6.74	5.95
	Spring wheat	5.97	4.70	5.64	5.44
6	Annual grasses (vetch-oat)	5.80	4.90	6.30	5.67
Application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land					
7	Pea	6.42	5.38	6.65	6.15
8	Pea	6.38	5.30	8.11	6.59
9	Pea	6.63	5.30	8.00	6.64
10	Annual grasses (vetch-oat)	6.09	5.02	7.40	6.17
11	Spring wheat	6.70	5.58	7.12	6.47

Table 3. *Continued*

Variant No.	Preceding crop	Yield, t/ha			
		2021	2022	2023	Average
12	Annual grasses (vetch-oat)	5.90	4.67	6.03	5.53
	LSD_{05}	0.16	0.15	0.17	-

Source: compiled by the authors based on research findings

On average, from 2021 to 2023, the highest yield of winter wheat in ten-field crop rotations was obtained following pea cultivation with the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land (Table 4). Specifically, the maximum yield of 6.44 t/ha was recorded in a crop rotation with 80% cereal saturation, including 30% winter wheat (Variant 2). Other preceding crops can be ranked in descending order of effectiveness as follows: annual grasses (vetch-oat), soybeans, perennial grasses, spring barley, oilseed radish, and silage maize. Winter wheat yields following pea cultivation were 7.5-24.4% higher compared to these alternatives. The yield increase for winter wheat resulting from the application of mineral fertilisers was as follows: after pea – 39-60%, after perennial grasses – 43%, and after maize for silage – 36-42% (Variants 1, 6).

Table 4. *Winter wheat yield in ten-field crop rotations depending on preceding crops, t/ha, average for 2021-2023*

Variant No.	Preceding crop	Yield, t/ha			
		2021	2022	2023	2021
Without fertiliser application					
1	Perennial grasses	3.60	3.44	4.63	3.89
	Pea	3.70	3.56	4.80	4.02
	Maize for silage	3.48	3.29	3.96	3.58
Application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land					
2	Pea	5.80	5.67	7.86	6.44
	Pea	5.68	5.13	5.95	5.59
	Maize for silage	5.00	4.60	5.51	5.04
3	Maize for silage	4.90	4.34	5.62	4.95
	Annual grasses (vetch-oat)	5.40	5.56	6.27	5.74
	Oilseed radish	5.50	4.78	5.48	5.25
4	Soybeans	5.73	5.29	6.34	5.77
	Pea	6.20	5.40	6.86	6.15
	Maize for silage	4.88	4.45	5.90	5.08
5	Annual grasses (vetch-oat)	5.75	5.20	6.94	5.96
	Soybeans	5.87	4.66	6.20	5.58
6	Perennial grasses	5.49	5.00	6.21	5.57
	Pea	5.90	5.34	7.04	5.79
	Maize for silage	4.80	4.28	5.52	4.87
7	Pea	6.40	5.80	7.02	6.41
	Maize for silage	5.10	4.30	5.46	4.95
8	Spring barley	5.54	4.90	5.80	5.41
	Pea	6.60	5.48	6.46	6.18
9	Pea	6.70	5.50	7.03	6.41
	Pea	6.38	5.20	7.02	6.20
	Maize for silage	4.97	4.64	5.40	5.01
	LSD_{05}	0.15	0.14	0.16	-

Source: compiled by the authors based on research findings

The differences in weather conditions during the growing season of winter wheat in the years of the study influenced its yield, both in five-field and ten-field crop rotations. The impact of uneven precipitation distribution and drought conditions in 2021 and 2022 led to a decrease in the yield of winter wheat following all preceding crops. The most unstable data were observed in 2022, when, in the five-field crop rotations, the lowest winter wheat yield was recorded with the application of mineral fertilisers at a rate of $N_{52}P_{56}K_{56}$ per hectare of arable land following spring barley – 4.24 t/ha. In the ten-field crop rotations, the lowest yield was observed with the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land following silage maize – 4.284.64 t/ha. Due to the lack of moisture in 2021, the combined effect of agronomic measures was generally significant, leading to an increase in the yield of winter wheat compared to 2022. In the favourable weather conditions of 2023, the yield of winter wheat was significantly higher compared to 2021. The greatest increase in yield was observed in all variants where peas were used as the preceding crop. Specifically, the highest yield of 8.11 t/ha was achieved by increasing the mineral fertiliser application rate to $N_{60}P_{64}K_{64}$ per hectare of arable land in a five-field crop rotation with 100% saturation of cereal crops, including 20% winter and spring wheat. With the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land in a ten-field crop rotation with 80% cereal crop saturation, including 30% winter wheat, the maximum yield of 7.86 t/ha was obtained. Therefore, the impact of preceding crops, the placement and ratio of cereal crops, and fertilisation in five-field and ten-field crop rotations with 60-100% cereal crop saturation, including 20-40% winter wheat and 10-20% spring wheat, on the yield of winter wheat is limited by both temperature and moisture conditions.

On average, from 2021 to 2023, the application of mineral fertilisers at a rate of $N_{52}P_{56}K_{56}$ per hectare of arable land in a five-field crop rotation with 80% cereal crop saturation, including 40% maize for grain, 20% winter wheat, 20% peas, and 20% oilseed radish (Variant 4), contributed to the highest productivity indicators: grain yield of 7.22 t/ha; grain harvest of 5.78 t/ha, including 4.49 t/ha of fodder; 10.47 t/ha of feed units; 0.77 t/ha of digestible protein, alongside high winter wheat yield of 6.43 t/ha (Fig. 1). This crop rotation resulted in a reduction of grain production costs to 3.36 thousand UAH/t; feed unit costs to 1.85 thousand UAH/t, while achieving a high net profit of 22.82 thousand UAH/ha and a profitability level of 123% (Fig. 2).

With the application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land, the best results were observed in a five-field crop rotation with 80% cereal crop saturation, including 20% winter wheat, 20% spring wheat, 20% soybeans, 20% maize for grain, and 20% annual grasses (Variant 10). This crop rotation achieved the highest productivity indicators: grain yield of 6.69 t/ha; feed units of 8.71 t/ha; digestible protein of 0.75 t/ha, alongside a high winter wheat yield of 6.17 t/ha; grain harvest of 4.20 t/ha, including 2.13 t/ha of food-grade grain and 2.07 t/ha of fodder. This crop rotation ensured a high net profit of 21.92 thousand UAH/ha and a profitability level of 125%. The most economically advantageous crop rotation was one with 60% cereal crop saturation, including 20% winter wheat, 20% spring wheat, 20% peas, and 20% sunflowers and maize for silage, which resulted in the highest net profit of 26.93 thousand UAH/ha and a profitability level of 151% (Variant 9).

On average, between 2021 and 2023, the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land in a ten-field crop rotation with 70% cereal crop saturation, including 30% maize for grain, 20% winter wheat, 20% soybeans, and 10% sunflowers, oilseed radish, and annual grasses (Variant 5), contributed to achieving the highest productivity indicators: grain yield of 7.44 t/ha; digestible protein of 0.77 t/ha with a high winter wheat yield of 5.77 t/ha;

feed units of 8.54 t/ha; grain harvest of 3.92 t/ha, including 1.15 t/ha of food-grade grain and 2.77 t/ha of fodder (Fig. 3). This crop rotation resulted in a reduction in the cost of grain production to 4.99 thousand UAH/t; cost of feed unit to 2.29 thousand UAH/t, while ensuring a high net profit of 22.97 thousand UAH/ha and a profitability level of 124% (Fig. 4).

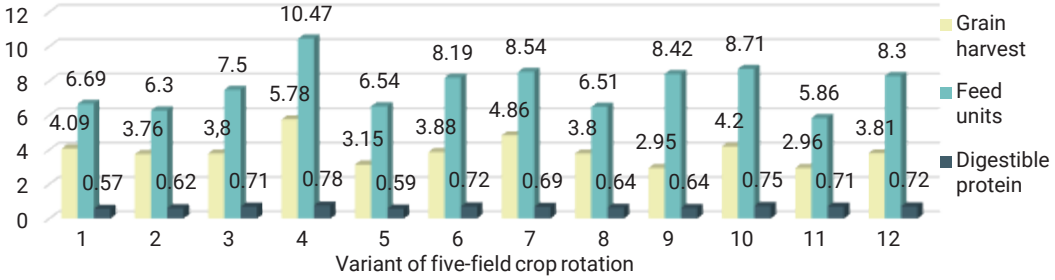

Figure 1. *Productivity of five-field crop rotations depending on cereal crop saturation, t/ha, average for 2021-2023*

Source: compiled by the authors based on research findings

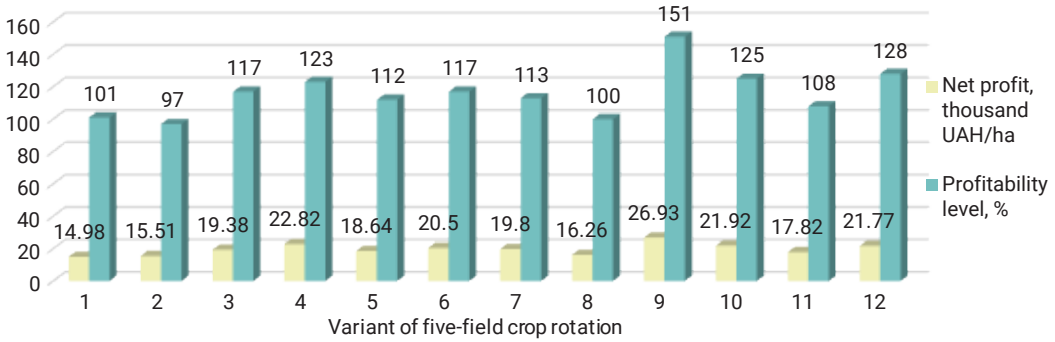

Figure 2. *Economic efficiency of five-field crop rotations depending on cereal crop saturation, average for 2021-2023*

Source: compiled by the authors based on research findings

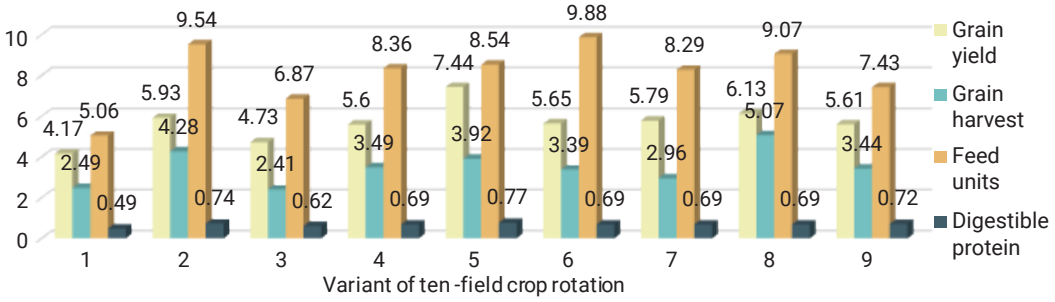

Figure 3. *Productivity of ten-field crop rotations depending on cereal crop saturation, t/ha, average for 2021-2023*

Source: compiled by the authors based on research findings

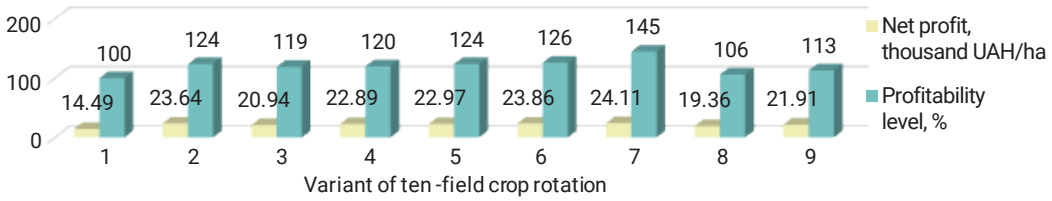

Figure 4. *Economic efficiency of ten-field crop rotations depending on cereal crop saturation, average for 2021-2023*

Source: compiled by the authors based on research findings

In a ten-field crop rotation with 60% cereal crop saturation, including 20% winter wheat, the use of two fields of perennial grasses and maize for silage resulted in the lowest cost of feed units – 2.01 thousand UAH/t, which provided the highest net profit of 24.11 thousand UAH/ha and a profitability level of 145% (Variant 7).

The increase in productivity and economic efficiency due to the application of mineral fertilisers was as follows: cereal crop yield – 26%; grain harvest – 27%, including food-grade grain – 30%, fodder – 23%; feed units – 49%; digestible protein – 29%; net profit – 39%; and profitability level – 26% (Variants 1, 6).

Based on the conducted research, it has been proven that the application of mineral fertilisers at rates of $N_{52-60}P_{56-64}K_{56-64}$ per hectare of arable land in five-field and ten-field crop rotations with 6080% cereal crop saturation ensures the highest winter wheat yield, productivity, and economic efficiency when using a leguminous predecessor.

Other researchers have also conducted similar studies. For instance, according to S. Kudria (2020), the effectiveness of using leguminous predecessors for winter wheat is fully confirmed, resulting in increased yields and productivity indicators in short-rotation four-field crop rotations. The results of the current research also align with the findings of I. Prymak *et al.* (2022), highlight the high productivity, economic, and energy efficiency of using organo-mineral fertilisers and differentiated soil cultivation when growing winter wheat after leguminous predecessors in short-field crop rotations. Specifically, the highest economic and energy efficiency indicators were achieved with the annual application of 12 tonnes of manure and $N_{95}P_{82}K_{72}$ per hectare of arable land. To improve biodiversity, the authors recommend including 20% white mustard as a green manure crop in five-field crop rotations.

Researchers M. Tkachenko *et al.* (2023) confirm the effectiveness of using leguminous predecessors for winter wheat in long-field crop rotations and the application of green manures and post-harvest residues alongside mineral fertilisers, as well as liming. They have demonstrated that the use of these technological practices contributes to an increase in productivity indicators of seven-field crop rotations by 1.2-2.5 t/ha annually. The effectiveness of growing winter wheat after leguminous crops in crop rotations with the application of mineral fertilisers and micronutrients (manganese and silicon) is examined by V. Ivanina & T. Prokopiuk (2024). The authors found that the highest yields and grain quality of winter wheat were achieved with the application of $P_{60}K_{60}$ before ploughing, ammonium sulphate N_{60} on frozen soil, and two foliar applications of urea in the phases of formation of the tube and earing ($N_{30} + N_{20}$), combined with manganese and silicon micronutrients.

Significant attention is devoted to the development and use of modern winter wheat varieties with high genetic productivity potential and resistance to adverse factors. These varieties, which have been obtained through genetic improvement and the implementation of innovative breeding methods, possess enhanced characteristics that enable them to be effectively cultivated under changing climatic conditions, ensuring

stability and high-quality yields. For example, research conducted in Ukraine (Morhun *et al*., 2022; Vakulenko *et al*., 2024) confirms that modern Ukrainian varieties exhibit increased drought resistance and can withstand significant temperature fluctuations, which is particularly important in the context of climate change. They also demonstrate good resistance to diseases, particularly brown rust and fusarium head blight, which significantly reduces the need for chemical protection measures.

In Bulgaria, the research by E. Dimitrov *et al*. (2022) focuses on the adaptation of local varieties to the specific regional climate, particularly the drought conditions observed in recent years. The authors found that the new varieties demonstrate stable productivity, maintaining high grain quality even under reduced moisture conditions, making them attractive for dissemination in other regions with similar climatic conditions.

Egyptian scientists H. Elsayed *et al*. (2022) also studied the productivity of winter wheat varieties, taking into account the challenges posed by high temperatures and limited water resources. They noted that new varieties, characterised by increased drought tolerance and the ability to efficiently utilise moisture, show promise for large-scale implementation. This is particularly important for countries with arid climates, where the rational use of water resources is a key factor in ensuring food security.

Thus, modern winter wheat varieties that have been adapted to extreme weather conditions show great potential for further dissemination in global agriculture. Their use not only enhances productivity and grain quality but also reduces dependence on agrochemicals, contributing to the development of resilient and environmentally sustainable agroecosystems. These varieties are strategically important for ensuring food security in the context of climate change and the growing demand for food.

Overall, the findings of current research align with those of O. Tonkha *et al*. (2024), who established the effectiveness of mineral fertiliser application in winter wheat cultivation within short-rotation five-field crop rotations. Their study revealed that the highest winter wheat yield was achieved with optimal mineral fertiliser application at a rate of $N_{81}P_{54}K_{62}$ per hectare of arable land, which, alongside the residual effects of organic fertilisers, helped preserve soil resources and prevent potential soil contamination. Specifically, this organo-mineral fertilisation system ensured the maximum content of available phosphorus, which ranged from 4.8 to 8.5 mg/100 g of soil.

Key aspects of the issue, particularly the pre-sowing application of complex fertilisers to optimise the parameters for wheat yield and grain quality in winter wheat cultivated in a short-field crop rotation after a legume predecessor, were discussed by B. Mazurenko *et al*. (2021). The current study established the optimal parameters and patterns for the formation of yield structure components of winter wheat depending on the fertiliser formulation DuraSOP: the number of productive stems, grains per ear, grain weight per ear, and the 1,000-grain weight.

M. Nankova & S. Doneva (2024) determined that the yield and grain quality of winter wheat in short-field crop rotations are most influenced by the application of soil cultivation systems. Specifically, the highest yield of winter wheat in a four-field crop rotation was achieved with the implementation of a soil tillage system that included conventional deep ploughing at 24-26 cm for spring crops and disking at 10-12 cm for winter wheat, which showed a 6.4% increase compared to the continuous use of conventional deep ploughing. The current study revealed that interrupting annual conventional deep ploughing with disking or a No-till system for winter wheat in a four-field crop rotation resulted in the highest output of crude protein.

Thus, addressing the issue of effectively cultivating winter wheat in high-productivity crop rotations with varying cycles is both highly relevant and complex. The role of predecessors, fertilisation systems, and soil cultivation in increasing winter wheat yield is indisputable, but it is also

crucial to establish the effectiveness of different placement and ratios of cereal crops in crop rotations concerning climate change. The conducted research revealed the impact of various predecessors and fertilisation systems on the yield of winter wheat, productivity, and economic efficiency in five-field and ten-field crop rotations with different levels of cereal crop saturation under conditions of unstable moisture.

Conclusions

It was found that, on average, from 2021 to 2023, the highest winter wheat yield was achieved after peas: in a five-field crop rotation with 60% cereal crop saturation, including 20% winter and spring wheat, and the application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land – 6.64 t/ha; in a ten-field crop rotation with 80% cereal crop saturation, including 30% winter wheat, and the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land – 6.44 t/ha. The increase in winter wheat yield was: after peas, compared to other predecessors, in five-field crop rotations – 7.1-18.1%, in ten-field crop rotations – 7.5-24.4%; from the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land in ten-field crop rotations after peas – 39-60%, after perennial grasses – 43%, after maize for silage – 36-42%.

The highest productivity rates were achieved in five-field crop rotations with 80% cereal crop saturation: 40% maize for grain, 20% winter wheat and peas, and 20% oilseed radish, with the application of mineral fertilisers at a rate of $N_{52}P_{56}K_{56}$ per hectare of arable land; 20% winter and spring wheat, soybeans, and maize for grain, as well as 20% annual grasses, with the application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land. In a ten-field crop rotation with 70% cereal crop saturation, including 30% maize for grain, 20% winter wheat and soybeans, and 10% sunflowers, oilseed radish, and annual grasses, the application of mineral fertilisers at a rate of $N_{60}P_{60}K_{60}$ per hectare of arable land was optimal. The highest net profit – 26.93 thousand UAH/ha, and a profitability level of 151% were achieved in a five-field crop rotation with 60% cereal crop saturation, including 20% winter wheat, spring wheat, and peas, as well as 20% sunflowers and maize for silage, with the application of mineral fertilisers at a rate of $N_{60}P_{64}K_{64}$ per hectare of arable land.

Further research should focus on determining the effectiveness of growing cereal crops in high-productivity different-field crop rotations, depending on fertilisation systems, soil treatment, and predecessors, based on the assessment of productivity, economic, and energy efficiency.

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None.

Conflict of Interest

None.

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Ефективне вирощування пшениці озимої у високопродуктивних різноротаційних сівозмінах в умовах нестійкого зволоження Лісостепу України

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Анотація. У зв'язку зі змінами клімату вагомого значення набуває застосування сучасних технологій вирощування пшениці озимої у науково обґрунтованих сівозмінах, що сприятиме підвищенню її урожайності та обсягів виробництва та забезпечуватиме потреби внутрішнього ринку і стабільного експорту української зернової продукції. Метою дослідження було встановлення, узагальнення та систематизація науково обґрунтованих заходів для ефективного вирощування пшениці озимої у високопродуктивних п'ятипільних та десятипільних сівозмінах з різним насиченням зерновими культурами в умовах нестійкого зволоження Лівобережного Лісостепу України. Для досягнення мети використовували систему загальнонаукових та спеціальних методів дослідження: польовий, лабораторно-польовий, порівняльно-розрахунковий, математично-статистичний та абстрактно-логічний. Встановлено, що у середньому за 2021-2023 рр. виконання досліджень, найвищу

урожайність пшениці озимої, яка становила 6,64 т/га, отримали після гороху у п'ятипільній сівозміні з 60 % насиченням зерновими культурами та внесенням мінеральних добрив у нормі $N_{60}P_{64}K_{64}$ на 1 га ріллі. У п'ятипільних сівозмінах приріст урожайності пшениці озимої після гороху у порівнянні з травами багаторічними, ячменем ярим та пшеницею ярою становив 7,1-18,1 %. Високу урожайність пшениці озимої, яка становила 6,44 т/га, отримали після гороху в десятипільній сівозміні з 80 % насиченням зерновими культурами та внесенням мінеральних добрив у нормі $N_{60}P_{60}K_{60}$ на 1 га ріллі. У десятипільних сівозмінах приріст урожайності пшениці озимої після гороху у порівнянні з травами однорічними (вико-овес), соєю, травами багаторічними, ячменем ярим, редькою олійною, кукурудзою на силос становив 7,5-24,4 %; приріст урожайності пшениці озимої від внесення мінеральних добрив у нормі $N_{60}P_{60}K_{60}$ на 1 га ріллі склав: після гороху – 39-60 %, після трав багаторічних – 43 %, після кукурудзи на силос – 36-42 %. Найбільш економічно вигідною відзначено п'ятипільну сівозміну із 60 % насиченням зерновими культурами та внесенням мінеральних добрив у нормі $N_{60}P_{64}K_{64}$ на 1 га ріллі, де отримали найвищий умовно чистий прибуток – 26,93 тис. грн/га і рівень рентабельності – 151 %

Ключові слова: п'ятипільні та десятипільні сівозміни; насичення зерновими культурами; попередники; мінеральне удобрення; продуктивність; економічна ефективність

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Suitability of crude glycerol as a substrate for biobutanol production

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Abstract. Glycerol is a natural polyol formed as a major by-product during biodiesel production. The use of glycerol, which is uniquely utilised by *Clostridium pasteurianum*, for butanol production is highly promising but requires a thorough understanding and optimisation of the process. This study aimed to determine the composition of crude glycerol and evaluate its suitability as a substrate for butanol accumulation by *Clostridium* sp. UCM B-7570. During the research, a chromatographic method was used to determine the composition of crude glycerol and the solvent content in the culture liquid. An experimental approach was employed according to a developed scheme, incorporating microbiological methods (microorganism cultivation), biotechnological methods (strain cultivation under conditions resembling industrial settings, investigation of the solvent accumulation), and statistical methods for the mathematical processing of research results. A detailed study of the composition of different crude glycerol fractions showed that the initial glycerol layer contained a relatively low proportion of glycerol itself. The identified components accounted for more than half of the mass of the glycerol layer (51.6%). It was shown that the glycerol layer was found to contain only up to 20% glycerol and approximately 17% methanol, which is an inhibitor of microbial growth and development. It was determined that the highest butanol accumulation (9 g/L) occurred at a crude glycerol concentration of 35 g/L, while culture development was inhibited at 45 g/L. During the initial phase of fedbatch cultivation of *Clostridium* sp. UCM B-7570, butanol accumulation remained unchanged. However, the subsequent fermentation of crude glycerol led to a twofold reduction in solvent by accumulation, ultimately resulting in complete inhibition of production by the eighth period, possibly due to the presence of methyl esters in the medium. To enhance butanol production technology, the use of sorbents such as activated carbon during fermentation is recommended. This study provides practical insights for biotechnologists and

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the demonstrated ability of *Clostridium* sp. UCM B-7570 to ferment crude glycerol for butanol production presents numerous research opportunities. These findings contribute to improving the feasibility of biobutanol production and advancing biomass-based industrial processes as viable alternatives to petroleum-derived products

Keywords: biofuel; waste; producer strains; fermentation; *Clostridium*

Introduction

In the modern context of increasing demand for alternative energy sources, special attention is paid to bioresources as a promising foundation for renewable fuel production. The development of biological, ecological, and biotechnological approaches to the extraction and rational use of bioresources is becoming crucial, given the need to preserve ecosystems and support sustainable natural resource use. The utilisation of industrial by-products, such as crude glycerol, for biofuel synthesis, exemplifies an innovative technology that combines biotechnology, ecology, and economic efficiency, addressing pollution reduction while generating additional resources.

Biobutanol, produced through the fermentation of glycerol, is an environmentally friendly biofuel capable of competing with traditional fuels. The use of *Clostridium* sp. cultures in biobutanol production not only enables efficient recycling of industrial by-products but also results in an energy-efficient product with minimal environmental impact. Evaluating the suitability of crude glycerol as a substrate for biobutanol synthesis is highly relevant, as it reveals the potential of this by-product from biodiesel production as a viable biofuel feedstock, as noted in the study by T. Attarbachi *et al.* (2023). Research in this area expands knowledge of bioresource processing and contributes to improving their utilisation efficiency.

In the process of biodiesel production from renewable biomass, glycerol is generated in significant amounts as a by-product of the transesterification of vegetable oils, as highlighted by Z. Pirzadi & F. Meshkani (2022). T. Attarbachi *et al.* (2024) observed that with the expansion of biodiesel production, the cost and availability of glycerol have noticeably changed due to variations in output across typical biodiesel and ethanol production processes. According to Y. Bansod *et al.* (2024), this crude glycerol is generally regarded as waste. A key challenge in using crude glycerol for industrial fermentation is the inhibitory effect caused by impurities, as noted by S. Mehariya *et al.* (2023). After transesterification, glycerol typically contains varying concentrations of methanol (a residue from the methylation process in biodiesel production), sulphate or chloride salts, residual free fatty acids, fatty acid methyl esters, and soap – by-products of the hydroxide catalyst used in transesterification, as described by M. Tomatis *et al.* (2024). One approach to mitigating this inhibitory effect, as demonstrated by Y. Wang *et al.* (2024), is the purification of crude glycerol, though this significantly increases substrate cost.

Butanol production from glycerol derived from biodiesel aims not only to utilise it as waste but also to enable large-scale chemical production for use in the chemical industry. J. Kazimierowicz *et al.* (2024) reviewed the biosynthesis of liquid fuels and other value-added products from waste glycerol, emphasising its potential as a feedstock for biobutanol and other biofuels. They highlighted technological advancements and identified future research needs to enhance glycerol conversion efficiency, contributing to a more sustainable circular economy. M.H. Moklis *et al.* (2022) investigated methods for upgrading crude glycerol into high-value products. Their study explored approaches to improve the economic feasibility of glycerol conversion, including fermentation and catalytic upgrading techniques.

They suggested that process optimisation could enhance biobutanol yields and other bio-based chemicals, positioning glycerol as a viable alternative to petrochemical products while lowering production costs and promoting sustainability in the chemical industry.

Studies such as P. Arbter *et al.* (2021) have demonstrated the potential of using crude glycerol as a substrate for fermentative butanol production by *Clostridium pasteurianum*. However, the extremely slow growth of the culture and the high toxicity of unrefined glycerol have limited its direct industrial application. Although experiments conducted by Y. Liu *et al.* (2022) showed promising results for butanol production from crude glycerol, impurities – including methanol, ash, free fatty acids, and triglycerides – likely interfered with solvent production. This was particularly evident with residual methanol and sodium or potassium salts, which are known to inhibit cell growth, as highlighted by S. Silva *et al.* (2023). M. Elsayed *et al.* (2024) emphasised that high yield and productivity are essential requirements for developing an industrial process for butanol production based on crude glycerol obtained from biodiesel.

The aim of this study was to evaluate the composition of crude glycerol from industrial biodiesel production to determine possible nutrient limitations and the influence of crude glycerol concentration on butanol accumulation by *Clostridium* sp. UCM B-7570.

Materials and Methods

The butanol-producing strain *Clostridium* sp. UCM B-7570, from the "Collection of Strains of Microorganisms and Plant Lines for Agricultural and Industrial Biotechnology" (Tigunova *et al.*, 2023) at the Institute of Food Biotechnology and Genomics of the National Academy of Sciences of Ukraine (IFBG), was used for this study. Determination of residual methanol in crude glycerol (Pharma, Belgium) was performed by gas chromatography using an Agilent 7890A gas chromatograph (USA) with a flame ionisation detector, following the international standard ASTM D7716-11a (2020). Free glycerol content was determined according to the international standard SN/T 3344-2012 (2013), while the overall composition of crude glycerol was analysed using the international standard SN/T 2995-2011 (2011).

To determine butanol accumulation using glycerol, the following medium composition (g/L) was used**:** crude glycerol (10.0-20.0), yeast extract – 1.0, $(NH_4)_2SO_4$ – 0.6, $(NH_4)_2HPO_4$ – 1.6; pH 6.5. The medium was sterilised for 30 minutes under a pressure of 1 atm. Cultivation of the butanol-producing strain *Clostridium* sp. UCM B-7570 was carried out in flasks containing liquid medium or on Petri dishes in a Crystal anaerostat (Germany) at a temperature of 35°C in a nitrogen atmosphere. After 120 hours of fermentation, the cells were pelleted using a Labofuge 400R ultracentrifuge (Germany) for 30 minutes at 13,000 rpm. Fermentation was conducted in 100 mL flasks containing 60 mL of medium. The flasks were weighed and incubated at 35°C.

Ethanol, butanol, and acetone were determined in the culture liquid using a gas chromatograph with a flame ionisation detector and a 2.4 m×3 mm column packed with Chromsorb Carbovax 6000 (Merck, Germany). The column temperature was 80 ± 5°C, while the evaporator temperature was 140 ± 10°C. The ratio of nitrogen, hydrogen, and air flows was 1:1:10. To determine the concentration of butanol in the culture liquid, a calibration curve was constructed using known butanol concentrations in distilled water. All experiments were performed in triplicate. Statistical analysis of the experimental data was conducted using Microsoft Excel 12.0, applying Student's t-test. A difference between the two mean values was considered significant at $P < 0.05$.

Results

The use of crude glycerol plays a key role in the efficient use of bioresources by promoting the recycling and valorisation of a by-product from biodiesel production. Crude glycerol, which accounts for 10% of the total volume of biodiesel produced, has traditionally been considered an unwanted

byproduct. However, with the growing focus on sustainability and resource optimisation, its conversion into valuable biofuels and chemicals has emerged as a practical solution for improving the overall efficiency of bioresource utilisation.

By using crude glycerol as a substrate for microbial fermentation, it can be converted into highvalue products, such as butanol – a renewable alternative to petroleum-derived fuels and chemicals. This not only reduces dependence on finite non-renewable resources but also contributes to the development of a more sustainable chemical industry. The process of converting crude glycerol into biofuels and other value-added products helps address environmental concerns by reducing glycerol waste, which, if left untreated, can contribute to pollution and environmental degradation. Moreover, crude glycerol serves as an ideal feedstock for various biotechnological processes due to its high organic content, which can be metabolised by microorganisms to produce biofuels, bioplastics, and other bio-based chemicals. By integrating crude glycerol into industrial applications, biodiesel producers can generate additional income streams, making the overall biodiesel production process more economically viable. This also allows for a circular production approach, where waste by-products are reintegrated into the value chain, reducing waste and optimising resource use.

The use of crude glycerol as a renewable resource also aligns with the broader goal of developing a circular economy, where waste from one process is used as an input for another. In this context, the efficient utilisation of crude glycerol reduces the environmental burden of waste disposal, lowers the carbon footprint associated with fossil fuel consumption, and encourages the use of renewable bioresources. Furthermore, it supports innovation in green technologies that foster sustainable industrial practices, promoting the responsible use of natural resources and enhancing the overall sustainability of the bioenergy sector.

Overall, the transformation of crude glycerol into valuable products not only enhances the economic sustainability of biodiesel production but also supports a broader environmental strategy by reducing waste, lowering emissions, and promoting the use of renewable bioresources in various industrial applications. By maximising the potential of crude glycerol, a more sustainable future can be achieved, where the efficient use of bioresources serves as a cornerstone of both economic development and environmental stewardship.

The composition of different crude glycerol fractions was studied in detail using chromatographic analysis. The initial glycerol layer contained a relatively low amount of glycerol itself (Table 1). In total, the identified components comprised more than half of the mass of the glycerol layer (51.6%). The remaining 48.4% may include products of incomplete transformation of triglycerides – mono- and diglycerides, alkali metal salts of fatty acids (soap), alkaline transesterification catalysts that migrated to the glycerol layer, water, or non-lipid components of the original oil. If the original oil contained a significant amount of phosphatides, then the products of their incomplete transesterification with methanol-diacylated phosphatides (esters of phosphoric acid with glycerol and choline/ethanolamine/inositol, etc.) – could also be present in the glycerol composition. It was determined that the glycerol layer from methanol transesterification contained a significant amount of an alkaline catalyst; however, the specific type of catalyst used remains unknown.

Table 1. *Component content of the initial glycerol layer*

Component	Content, %
Glycerol	21.9
Methanol	17.1
Fatty acid methyl esters	12.6

Source: developed by the author

Sodium or potassium hydroxides, as well as sodium or potassium methylates, are most commonly used (Meng *et al.*, 2023). Titration with hydrochloric acid indicated that 100 g of the glycerol layer contained 0.072 mol of monovalent alkali metal. The alkali metal may be present in its original catalyst form, partially converted into soaps, or bound in alkali metal glycerate. This amount corresponds to: 2.81 g K / 4.04 g KOH / 5.19 g CH_3OK / 7.07 C_3H_7OK or 1.66 g Na / 2.88 g NaOH / 4.04 g CH_3ONa / 5.92 g C_3H_7ONa. If the alkaline catalyst is calculated as soap, its amount in the glycerol layer is equivalent to 23.1% potassium oleate or 21.9% sodium oleate. Additionally, during the distillation of methanol, several unidentified light impurities, likely hydrocarbons, were removed, producing several small peaks on the chromatograms of the obtained methanol-water mixture. In total, 1.2-1.5% of the glycerol layer mass consisted of unidentified impurities that passed into the distillate.

Distillation of methanol from the glycerol layer of methanol transesterification was complicated by the presence of an alkaline catalyst and all the components required for the progression of individual stages in the three-stage equilibrium process of triglyceride transesterification. In addition, the presence of alkali and water in the system facilitated the saponification of both glycerides and esters, while heating significantly accelerated the process. The chemical equilibrium of each stage in the transesterification process of triglycerides can be represented by the following reaction schemes:

Stage I:

$$TG + MeOH \xrightarrow{kat} DG + FAME$$

Stage II:

$$DG + MeOH \xrightarrow{kat} MG + FAME$$

Stage III:

$$MG + MeOH \xrightarrow{kat} {}^{W}G + FAME$$

In the given scheme, *TG*, *DG*, and *MG* are triglyceride, diglyceride, and monoglyceride, respectively; *G* is the glycerol, *MeOH* is the methanol, and *FAME* is the fatty acid methyl ester.

During storage of the glycerol layer, the reaction equilibrium stabilised at a certain level, corresponding to a constant concentration of individual components. The removal of methanol from the system shifted the equilibrium towards the formation of the starting substances – methanol and glycerides – due to the reverse transesterification of methyl esters with free glycerol. Consequently, these esters were converted into glycerides, leading to the additional formation of methanol. Since the transesterification reaction exhibits a weak exothermic effect at each stage, heating the mixture during methanol distillation further shifted the chemical equilibrium towards the formation of glycerides and methanol. Reverse transesterification of 100 g of methyl oleate required 31.1 g of glycerol, yielding 120.3 g of monoolein (monoglyceride) and 10.8 g of methanol. Additionally, saponification resulted in the formation of free glycerol, producing 25.8 g of glycerol and 90 g of potassium oleate from 100 g of monooleate. Methyl esters also underwent saponification, leading to the release of additional methanol – from 100 g of monooleate, 108.1 g of potassium oleate and 10.8 g of methanol were generated.

Initially, an attempt was made to extract methanol from the glycerol layer by distillation under atmospheric pressure without neutralising the catalyst. However, the complete extraction of methanol was hindered by intense foaming of the mixture, caused by the simultaneous presence of a significant amount of glycerides and soaps. The distillation process was halted when excessive foam formation made it impossible to continue. As a result, a fraction was collected with a distillation temperature range of 70-78°C, which exceeds the boiling point of pure methanol (65°C). During condensation, the methanol-rich distillate exhibited a tendency to separate into two distinct layers: a transparent upper layer and a cloudy white lower layer. After settling, the distillate became uniformly transparent and homogeneous. The overall material balance for distillation is presented in Table 2.

Table 2. *Material balance of methanol distillation from a glycerol layer without neutralisation*

Loaded, % wt.		Obtained, % wt.	
Initial glycerol layer	100	Distillation (70-78˚C)	20.24
		Cubic residue	79.76

Source: developed by the author

It was not possible to provide a fully detailed material balance for individual components due to the absence of comprehensive quantitative data on the mixture's composition, the potential for complex transformations during distillation, and the semi-quantitative nature of glycerol content determination. The composition of the identified components in the original glycerol layers was provided earlier. The distillate contained 63.4% methanol, 5.9% unidentified organic compounds – which appeared on chromatograms as numerous peaks of unidentified components, possibly of hydrocarbon origin – and 30% water. The cubic residue contained 15.9% glycerol, 3.6% methanol, 4% fatty acid methyl esters, and the remainder consisted of glycerides and soaps.

During distillation, the concentration of methanol in the cubic residue decreased significantly, but complete extraction was not achieved. The concentration of free glycerol also declined, with its absolute amount decreasing even more noticeably, while the concentration of fatty acid esters dropped even sharply. This suggests the occurrence of reverse transesterification of esters with glycerol. Saponification of esters and glycerides likely also took place, which should have resulted in the additional formation of methanol and glycerol. The total mass of methanol in both the cubic residue and the distillate was found to be slightly lower than in the original glycerol layer. This discrepancy suggests that the concentration of methanol in the distillate may be somewhat underestimated. To prevent foaming during the distillation of transesterification products containing significant amounts of glycerides and soaps, these compounds should be decomposed using a strong acid. Therefore, prior to the next distillation, the initial glycerol layer was neutralised with phosphoric acid (as an aqueous solution with (H_3PO_4) = 85% by mass). The acid was added in the amount required to bind the alkali metal present in the glycerol layer, either through neutralisation of alkali/alcohol or breakdown of soaps, forming dihydrogen phosphate. Potassium and sodium dihydrogen phosphates are insoluble in transesterification products. After the addition of acid, the consistency of the glycerol layer became heterogeneous, with the formation of a solid phase. No foaming occurred during distillation, and methanol was extracted quantitatively. The boiling range of the volatile fraction was 72.5-100.3°C.

The cubic residue, after settling, separated into two distinct layers: a lower "salt" layer, where most of the phosphates accumulated, and an upper "salt-free" layer (though a small quantity of salts remained in the upper layer). The overall material balance for distillation with neutralisation is provided in Table 3.

Table 3. *Material balance of methanol distillation from a glycerol layer with neutralisation*

Loaded, % wt.		Obtained, % wt.	
Initial glycerol layer	92.12	Distillation (70-78˚C)	28.97
Phosphate acid (85% by weight	7.88	Cubic residue Upper layer Lower layer	70.76 41.81 28.25
		Losses	0.97

Source: developed by the author

The distillate contained 52.8% methanol, 4.6% unidentified organic compounds (which appeared on chromatograms as numerous peaks of unidentified components, possibly of hydrocarbon origin), and 40% water. The upper "salt-free" layer of the cubic residue contained 28.7% fatty acid methyl esters, trace amounts of glycerol (no more than 0.2%), and excess methanol (only in trace amounts). Chromatograms also displayed additional peaks of unidentified components, the concentration of which did not exceed 2-3%. The remaining composition included glycerides, phosphoric acid esters, and a smaller fraction of potassium/sodium acid phosphates. The lower "salt" layer of the cubic residue contained 44.7% glycerol, 1.9% fatty acid methyl esters, and no detectable methanol (only trace amounts, likely in dispersed particles). The remaining composition consisted of glycerides, phosphate esters, and the bulk of potassium/sodium acid salts.

During distillation, methanol was completely removed. The total mass of methanol in both the cubic residue and the distillate was approximately equal to that in the original glycerol layer, although it was slightly lower. This discrepancy suggests that the concentration of methanol in the distillate may be somewhat underestimated. The mass of glycerol after distillation decreased significantly, likely due to reverse transesterification via an acid-catalysed mechanism involving acid phosphates. All free glycerol migrated to the lower "salt" layer, while the methyl esters remained in the upper "salt-free" layer. It can be inferred that the majority of bound glycerol (in the form of mono- or possibly triglycerides) was concentrated in the upper "salt-free" layer. The study demonstrated that the glycerol layer contained a relatively low amount of glycerol up to 20%, and approximately 17% methanol. Distillation without neutralising the glycerol layer with phosphoric acid enabled the complete extraction of methanol. However, this process also led to the formation of acid phosphates of potassium or sodium. To investigate butanol accumulation by *Clostridium* sp. UCM B-7570, experiments were conducted using crude glycerol at various concentrations (Table 4).

Table 4. *Accumulation of solvents at different crude glycerol concentrations*

Concentration crude-glycerol, g/L	Butanol, g/L	Ethanol, g/L
10	6.23 ± 0.39	0.18 ± 0.01
15	6.72 ± 0.07	0.34 ± 0.01
20	7.92 ± 0.22	0.36 ± 0.01
25	8.28 ± 0.39	0.59 ± 0.05
30	8.87 ± 0.4	0.68 ± 0.05
35	9.0 ± 0.08	1.2 ± 0.04
40	8.5 ± 0.03	0.7 ± 0.05
45	7.9 ± 0.22	0.3 ± 0.05

Source: developed by the author

Using crude glycerol at concentrations ranging from 10 to 45 g/L, as shown in the results presented in Table 4, bioconversion to butanol occurred. The highest butanol accumulation (9 g/L) was observed at a crude glycerol concentration of 35 g/L, while culture inhibition occurred at 45 g/L. To increase butanol accumulation at lower crude glycerol concentrations, *Clostridium* sp. UCM B7570 was cultivated using a fed-batch system. The results are presented in Table 5.

Table 5. *Accumulation of solvents using fed-batch culture*

Fed-batch period	Butanol, g/L	Ethanol, g/L
0	9 ± 0.01	0.36 ± 0.01
1	8.8 ± 0.05	0.22 ± 0.05
2	4.5 ± 0.39	0.23 ± 0.03
3	4.3 ± 0.05	0.05 ± 0.01
4	4.2 ± 0.04	0.02 ± 0.01
5	1.2 ± 0.04	0.01 ± 0.01
6	0.5 ± 0.05	-

Source: developed by the author

During cultivation, butanol accumulation in the culture liquid remained unchanged during the initial period of extraction and medium replenishment. However, from the second to the fourth period, butanol accumulation decreased twofold. With continued use of the negative replenishment method, butanol accumulation decreased eightfold and eventually ceased by the sixth period.

Discussion

Glycerol purification has been identified as an expensive and energy-intensive process, as concluded by T. Arofai *et al.* (2024). In their study, they investigated methods for separating residual salts from glycerol pitch, a by-product of refined glycerol production. This process was found to be crucial for reducing both the cost and energy consumption associated with glycerol purification, which has been a major obstacle to its widespread industrial application.

Similarly, M. Oliveira *et al.* (2022) highlighted potential advancements in crude glycerol purification through computational modelling. Their research focused on optimising purification steps to make glycerol purification more economically viable. By enhancing process efficiency, their study indicated that the cost of producing high-quality glycerol could be significantly reduced, addressing the challenges posed by traditional, energy-intensive methods.

N. Armylisas *et al.* (2023) demonstrated that crude glycerol, a by-product of biodiesel production, could be effectively utilised in microbial synthesis. Their research showed that crude glycerol could serve as a substrate for biobutanol production, thereby reducing production costs and increasing the profitability of biofuel manufacturing. This approach emphasised the potential of repurposing glycerol waste into a valuable resource for industrial applications, thus enhancing economic sustainability.

Furthermore, M. Boro *et al.* (2022) and M. Zhao *et al.* (2023) explored the broader use of crude glycerol in biotechnological processes, focusing on its role as a cost-effective substrate for biofuel synthesis. Their studies revealed that crude glycerol not only reduced the cost of microbial synthesis but also contributed to the economic sustainability of biofuel production. By repurposing glycerol waste from biodiesel production, these studies demonstrated how glycerol could support the development of more environmentally friendly energy sources.

Crude glycerol poses a significant financial and environmental challenge in terms of global disposal. E. Almeida *et al.* (2023) emphasised that for the sustainable use of this resource, biotechnology must be prioritised. A. Al-Haimi *et al.* (2024) noted that glycerol, or propyne-1,2,3-triol, is a by-product in the production of fatty acid methyl esters (biodiesel). It is also traditionally formed as a by-product of oleochemical and soap production. Depending on the intended application, glycerol obtained during the transesterification of oils is purified to varying degrees: crude (30-80% pure), technical-grade distilled

(50-86%), and glycerol for use as a chemical reagent or in cosmetics and pharmaceuticals (99.0-99.9%). After transesterification and methanol removal, the crude glycerol contains various impurities, is heavily coloured, and has low commercial value as a commodity. In small-scale production, it is often discarded, contributing to environmental pollution. Given these challenges, industrial biotechnology plays a crucial role in identifying microbial strains capable of metabolising waste, including crude glycerol, as highlighted by Y. Wang *et al.* (2024). Modern biotechnology presents significant opportunities for utilising glycerol, traditionally regarded as a by-product of numerous production processes. The authors M.U. Faruk *et al.* (2023) determined that to facilitate bioconversion, it is first necessary to analyse the composition of residues from biodiesel production, as they may contain substances that inhibit microbial growth and development. The use of waste substrates introduces stress factors due to the accumulation of toxic agents in the fermentation medium, in addition to the issue of variable substrate quality even within the production process. One approach to mitigating this inhibitory effect is the purification of crude glycerol, which negatively impacts the cost of the substrate, as described in the research by V. Boas & F. Mendes (2022). A more promising strategy involves the mutation or adaptation of wild-type strains to crude glycerol, as reported for *Clostridium pasteurianum*, by I. Kushkevych (2023). R.J. Humphreys *et al.* (2023) noted that instability and culture degeneration, leading to the loss of solvent production capability, has been a significant challenge in the study of solvent production through glucose fermentation. On the other hand, D. Karayannis *et al.* (2024) investigated the adaptation of strains to a specific type of crude glycerol, noting that even well-adapted strains may still experience toxicity from different substrate batches. Similar site-directed mutagenesis techniques could be applied to generate mutants with improved stability or tolerance to impurities such as methanol. However, until a stable culture is developed, it will be difficult to determine the extent to which parameters such as pH, substrate concentration, and impurities influence solvent production.

This study aimed to determine the maximum concentrations of pure and crude glycerol that support the growth and efficient metabolism of *Clostridium sp.* UCM B-7570. Since glycerol is an osmotically active substance that significantly affects the osmotic potential of the fermentation medium, it can restrict the production capacity of microorganisms, as demonstrated by D.T. Jones (2024). *Clostridium sp*. UCM B-7570 has been shown to grow on crude glycerol and produce butanol. This is the first report on cell growth and solvent production by the domestically isolated strain *Clostridium sp*. UCM B-7570 using crude glycerol as the sole carbon source, in comparison with global studies by other researchers. These findings align with the study of P. Ponsetto *et al.* (2024) and indicate that butanol production via glycerol fermentation is a promising alternative for biobutanol production that warrants further investigation. Several articles (Koh *et al.*, 2024; Sim *et al.*, 2024) have reported the growth and product formation of other *Clostridium* species using crude glycerol as the sole substrate. The results of this study demonstrate that *Clostridium sp.* UCM B-7570 can grow on crude glycerol derived from biodiesel at concentrations up to 35 g/L, with the highest butanol production reaching 9 g/L. Although these experiments yielded promising results for butanol production from crude glycerol, impurities such as methanol and salts may interfere with solvent production, as emphasised by M.U. Faruk *et al.* (2023). Y. Gan *et al.* (2023) noted that while several *Clostridium* species can metabolise methanol (producing acetate), *C. pasteurianum* has not been identified as one of the species capable of converting this compound. Although the potential for producing butanol from crude glycerol derived from biodiesel is promising, further research is required

to fully understand and optimise the process. As D.T. Jones (2024) previously highlighted, culture stability is crucial and may be improved by developing mutant strains. Additionally, it is important to identify and quantify key parameters of the nutrient medium, such as pH, nutrient concentration and trace metal levels, which significantly influence solvent formation and product distribution. Additional research efforts should evaluate growth and solvent production using purified glycerol with added methanol to determine whether the presence of methanol (or other impurities) affects cell growth, solvent production, and long-term culture stability, as recommended by Y. Gan *et al*. (2023). At the very least, further studies should be conducted to confirm whether these initial butanol yield figures can be maintained over extended periods and with higher concentrations of crude glycerol (and, consequently, higher impurity levels). Considering that the use of crude glycerol would eliminate the need for pretreatment, the associated cost savings may compensate for the slightly lower yield. Additionally, *C. pasteurianum* does not produce acetone, which should simplify the separation and purification of butanol. Unlike *C. acetobutylicum* and *C. beijerinckii*, *C. pasteurianum* also produces significant amounts of ethanol, as demonstrated by D.T. Jones (2024). Although ethanol is far from an ideal fuel, it can be used alongside butanol for blending with petroleum fuels. Finally, A. Tyszak & L. Rehmann (2024) demonstrated that carbon recovery during glycerol fermentation by *C. pasteurianum* ranges from 75% to 90%, compared with less than 60% during sugar fermentation. As a result, less carbon is lost through CO_2 production. Industrial-scale utilisation of crude glycerol could open new prospects in the biofuel industry and reduce production waste, thereby having a positive impact on the environment and promoting the rational use of bioresources. Integrating microbiological butanol production into biodiesel production could lead to lower raw material costs. D.T. Jones (2024) noted that in sugar-based fermentation processes, raw material costs typically account for 60%-80% of total production costs and are one of the most significant factors influencing the cost of butanol production.

The use of crude glycerol enhances the rational use of bioresources by transforming a byproduct of biodiesel production into valuable bio-based products. Biodiesel production generates large quantities of crude glycerol as a waste product, which often remains underutilised. However, by repurposing this by-product for the production of high-value chemicals, biofuels, and other value-added products, both the environmental impact and overall inefficiencies in biodiesel production can be mitigated.

Conclusions

These results demonstrate that crude glycerol derived from biodiesel is a promising, low-cost, renewable feedstock for butanol production. Since crude glycerol contains impurities, including salts and methanol, the methanol concentration in these samples varied significantly. The average methanol concentration in the fermentation broth samples was 1.78 ± 2.98 g/L. No direct correlation was observed between methanol concentration and glycerol concentration (i.e., samples with the highest crude glycerol concentrations did not necessarily contain the highest methanol levels). The fermentation of glycerol by the related organism *Clostridium pasteurianum* can facilitate the reoxidation of excess NADH produced during glycerol catabolism. The results indicate that *Clostridium* sp. is capable of growing and maintaining viability on crude glycerol obtained from biodiesel at a rate comparable to that observed during growth on purified glycerol. Furthermore, *Clostridium* sp. can utilise crude glycerol for solvent production, primarily yielding significant amounts of butanol. Different concentrations of crude glycerol (an unrefined by-product of biodiesel production) were used to investigate butanol accumulation. It was shown that at low crude glycerol concentrations, conversion to butanol

is feasible. However, as crude glycerol concentrations increased, culture growth and development were inhibited, possibly due to the presence of methyl esters in the medium. Given that the use of crude glycerol eliminates the need for pretreatment, the associated cost savings could offset the slightly lower yield. This study clearly demonstrated that crude glycerol obtained from biodiesel production can be fermented at high concentrations and with rates relevant to industrial applications. The findings offer significant potential for biofuel production technology using crude glycerol, which supports the rational use of bioresources, reduces production waste, and contributes to environmental improvement.

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Conflict of Interest

None.

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Придатність гліцерину-сирцю, як субстрату для біобутанолу

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Анотація. Гліцерин – природний поліол, який утворюється як основний побічний продукт під час виробництва біодизеля. Використання гліцерину, яке притаманне лише для *Clostridium pasteurianum*, для отримання бутанолу є багатообіцяючим та має високий потенціал, однак потребує розуміння та оптимізації процесу. Метою дослідження було визначити склад гліцерину-сирцю та оцінити його придатність як субстрату для накопичення бутанолу культурою *Clostridium* sp. UCM B-7570. Під час проведення досліджень було застосовано низку методів: хроматографічний – для аналізу складу сирого гліцерину та вмісту розчинників у культуральній рідині; мікробіологічний – для культивування мікроорганізмів; біотехнологічні методи – для вирощування штаму в умовах, наближених до промислових, та дослідження накопичення розчинників; статистичний – для математичної обробки результатів. Детальне вивчення складу різних фракцій гліцерину-сирцю показало, що вихідний гліцерновий шар містив досить мало власне гліцерину. Продемонстровано, що ідентифіковані компоненти складали у сумі більше половини маси гліцеровинового шару (51,6 %). Показано, що гліцериновий шар містив досить незначну кількість власне гліцирину до 20 % та близько 17 % метанолу, який є інгібітором росту та розвитку мікроорганізмів. Визначено, що найбільше накопичення бутанолу (9 г/л) було при концентрації сирого гліцерину в середовищі 35 г/л, а пригнічення розвитку культури – при концентрації 45 г/л. Здійснено культивування *Clostridium* sp. UCM B-7570 від'ємно-доливним методом та визначено, що накопичення бутанолу протягом першого періоду не змінювалось. Послідуюча ферментація гліцерину-сирцу знижувала акомулювання розчинника у два рази до повного інгібування продукцію у восьмому періоді, що можливо пов'язано з вмістом метилових ефірів у середовищі. Для удосконалення технології накопичення бутанолу потрібно використовувати сорбенти під час ферментацію, наприклад активоване вугілля. Матеріали статті становлять практичну цінність для фахівців-біотехнологів, а показана властивість *Clostridium* sp. UCM B-7570 до вироблення бутанолу шляхом бродіння сирого гліцерину відкриває безліч потенційних дослідницьких можливостей, які можуть підвищити життєздатність виробництва біобутанолу та сприяти розвитку промислових процесів на основі біомаси, як альтернативи нафтопродуктам

Ключові слова: біопаливо; відходи; штами-продуценти; ферментація; *Clostridium*

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Comprehensive assessment of the decorative value of *Araliaceae* Juss. woody species in the collection plantations of botanical gardens of Kyiv

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Abstract. Features of decorative plants within urban ecosystems can be used to create highly decorative plantings with a long-lasting aesthetic effect that interacts harmoniously with urban systems. The study aims to determine the degree of decorativeness of dendrosozoexotics of the family *Araliaceae* Juss. Represented in the collection plantations of botanical gardens in Kyiv. A comprehensive assessment of the decorative effect of 8 species of woody plants of the *Araliaceae* family was conducted. The results of the assessment of the degree of decorativeness of the studied plant species were presented, noting that 2 species have a high degree of decorativeness (*Aralia. elata* (Miq.) Seem. and *Eleutherococcus lasiogyne* (Harms) S.Y.Hu), 5 species are characterised by a high degree of decorativeness (*Kalopanax septemlobus* (Thunb.) Koidz, *Eleutherococcus senticosus* (Rupr. & Maxim.) Maxim., *Eleutherococcus sessiliflorus* (Rupr. & Maxim.) S.Y. Hu, *Eleutherococcus trifoliatus* (L. f.) S.Y. Hu, Eleutherococcus wardii (W.W.Sm.) S.Y.Hu.) Mediocre decorativeness was noted in one species – *Eleutherococcus sieboldianus* (Makino) Koidz. The dynamics of seasonal decorativeness of dendrosozoan exotics of the family *Araliaceae* were analysed, determining a high degree of decorativeness in 87.5 % of the studied plant species. The peak of the decorative effect of dendrosozoexotics occurs in summer and lasts approximately 120 days (from 3 decades of May to 2 decades of September), which is associated with biological characteristics and

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phases of the ontogeny of introductions, in particular, long periods of flowering, fruit formation and ripening. The results obtained are the basis for optimising the species composition of urban and park plantations in megacities and increasing their decorative effect in an urban environment, accounting for the resistance of the studied plant species to anthropogenic load

Keywords: seasonal ornamentation; dendrosozoexotics; phytodesign; introductions; medicinal plants; flowering; fruiting; vegetation

Introduction

In the current conditions of urbanisation and climate change, the conservation and use of ornamental woody plants in green areas of cities is of particular importance. Species of the *Araliaceae* Juss. family are prominent among ornamental plants due to their aesthetic properties, resistance to adverse environmental conditions and ecological value. The collection plantings of botanical gardens are an ideal basis for studying these plants, which can be used to conduct a comprehensive assessment of their decorative and adaptive potential, as well as to develop recommendations for their use in landscaping.

According to V.L. Matviychuk *et al.* (2021), human perception of the environment depends on the features of the terrain and the location of different types of plantations on the territory. Representatives of the plant world are characterised by a wide morphological divergence, featuring certain decorative effects that can be assessed by measuring the strength of the emotional impact on the observer, thus plants are a key component of phytodesign. The decorativeness of plants is manifested in their external morphological features – the size and habit of the crown, the shape of leaves, flowers and fruits, the colour of flowers and leaves, the texture of surfaces, and the aroma. According to S.F. Nilufer *et al.* (2013), an equally important feature of plants is their dynamism throughout the entire period of life.

The evaluation of the decorative qualities of dendrosozophytes is relevant in Ukrainian research, especially in terms of their further implementation in the green space system. Scientists address the use of comprehensive methods for assessing decorativeness, which includes aesthetic, ecological and adaptive components. M. Matusiak *et al.* (2021) assessed the decorative properties of representatives of the *Magnolia* L. genus in the Vinnytsia region using a classical scale that incorporates such indicators as shape, structure, and colour of the main morphological elements. This study not only confirmed the high potential of plants of this genus for landscaping but also contributed to the development of recommendations for their compositional use in urban environments. Another study by T.O. Boiko (2024) addressed representatives of the *Rosaceae* Juss family. The results of this study emphasised the importance of combining species diversity with practical aspects of landscape design aimed at preserving biodiversity and improving the ecological state of the region.

The study of complex and seasonal decorativeness of dendrosophytes based on phenological observations was carried out by N. Demchenko *et al.* (2019). The study analysed the decorative qualities of representatives of the *Magnoliaceae* Juss family. The authors assessed the adaptive capabilities of these plants and their use in landscaping. V.P. Shlapak & N.P. Shpak (2018) presented the results of a study of the complex and seasonal decorative qualities of introduced plants in the Right-Bank Forest-Steppe and Steppe of Ukraine. In particular, the study included an assessment of the adaptation potential and decorative characteristics of the *Ailanthus altissima* (Mill.) species, which can determine its prospects for use in landscaping. The authors analysed the processes of introduction and acclimatisation of

this species, analysing the factors that affect its stability, growth and decorative properties in different seasons of the year.

Turkish scientists B. Mutlu & Ş. Alp (2023), studying the aesthetic characteristics of *Amygdalus* species, evaluated plants according to aesthetic components, where harmony, contrast, balance, and accent affected the perception of the composition. Y. Hu *et al.* (2023) studied the decorative characteristics of plants, in particular morphological characteristics (height and branching of the stem, size and shape of leaves, structure of flowers and fruits), colour characteristics (colour of flowers, fruits, leaves, bark), textural characteristics (bark, leaves, flowers), which are important in assessing the decorative effect of plants.

The study by K. Wang *et al.* (2018), which analysed the complex and seasonal decorative qualities of 12 deciduous representatives of the *Araliaceae* family, was devoted to the establishment of the decorative features and seasonal rhythms of the local flora. Wild ornamental plants of the South China flora, including representatives of the *Araliaceae* family, were evaluated as decorative and capable of covering vertical surfaces (Cong & Han, 2020).

The growing interest in the use of medicinal plants in landscape design is contributing to the combination of the decorative and practical value of such plantings. According to L. Ning & M. Quanfa (2020), out of 11,146 species of medicinal plants characteristic of the Chinese flora, 112 representatives of the *Araliaceae* family demonstrate high decorative properties and have significant potential for implementation in landscape compositions. They can be efficiently used in landscaping due to the combination of aesthetic and environmental functions.

A. Hangan *et al.* (2020) confirmed the potential of integrating medicinal and ornamental plants into the concept of suburban gardens to protect the environment. These gardens can create harmonious spaces that combine aesthetics with environmental benefits. Notably, researchers primarily focus on the biochemistry and pharmacology of *Araliaceae* plants, leaving aside their decorative value. Based on the literature review, most publications address the ornamental value of native species of the *Araliaceae* family in South Asia, while the issues of assessing the ornamental value of woody species of the *Araliaceae* family introduced to Ukraine remain poorly understood.

The study aimed to establish a complex of decorative qualities of dendrosozoexotics of the *Araliaceae* family for their further introduction into the system of green building in Ukraine, in particular, in Kyiv.

Materials and Methods

The assessment of the decorative effect of 8 representatives of the *Araliaceae* family was carried out visually during phenological observations (vegetation period 2018-2021) on the territory of collection plantations of unprotected soil in 3 botanical gardens of Kyiv: M.M. Gryshko National Botanical Garden of the National Academy of Sciences of Ukraine (NBG), Botanical Garden of the National University of Life and Environmental Sciences of Ukraine (NUBiP), and Fomin Botanical Garden of Taras Shevchenko National University of Kyiv (Fomin Botanical Garden). The objects of research were dendrosozoexotics of the family *Araliaceae*, in particular, *A. elata*, *K. septemlobus*, *E. senticosus*, *E. sessiliflorus*, *E.lasiogyne*,*E.trifoliatus*,*E.wardii*,*E.sieboldianus*.The study of the complex decorativeness of plants was conducted based on the results of in-house field and experimental studies (Morozko *et al.*, 2018).

The seasonal decorativeness of representatives of the *Araliaceae* family was determined by the traditional method of N.V. Kotelova & O.N. Vinogradova (1974), which was adapted for the representatives of the studied family. To correctly reflect the indicators of decorativeness of the studied plant species, use two additional separate criteria were proposed: flowering and fruiting due to the partial overlap of their terms. Each of these metrics has been assigned with conversion factor of 2.

The decorativeness of the crown, leaves, inflorescences, fruits, colour and texture of the bark of the trunk, branches and shoots of 8 woody species of plants of the *Araliaceae* family was assessed monthly on a 5-point scale and the indicators were calculated using the following formula:

$$Poverall. = \sum_{i=1}^{5} AiPi / \sum_{i=1}^{5} Pi, \quad (1)$$

where: A_1 – assessment of the architectonics of the trunk and crown; A_2 – assessment of the decorativeness of leaves; A_3 – assessment of inflorescences; A_4 – assessment of fruits; A_5 – assessment of the colour and texture of the bark of the trunk and crown; P_1, $P_{2...}$ P_5 – conversion factors that reflect the importance of each trait based on the strength and duration of emotional impact, where the coefficient of trunk and crown architectonics (P_1) is 4; for leaves (P_2) – 3; inflorescences (P_3) – 2; fruits (P_4) – 2; texture and colour of trunk bark (P_5) – 1.

The decorative qualities of the plants were assessed using a 5-point scale by Kalinichenko (2003): 1 – negative decorativeness (the appearance of plants is not attractive); 2 – zero (decorative properties are not expressed or plants do not have expressiveness on the general background of plantations); 3 – insignificant (decorative properties are noticeable, but not too expressive); 4 – sufficient (decorative properties are expressive, plants stand out well against the general background of plantations); 5 – high (decorative properties give plants significant attractiveness, cause a strong emotional feeling, admiration in the mass observer). Based on the calculations obtained, graphs of the dynamics of seasonal decorativeness of the studied plant species of the *Araliaceae*family were constructed.

To determine the decorativeness of representatives of the *Araliaceae* family, a complex methodology by A.S. Vlasenko (2016) developed for dendrosozoexotics, was used. According to the methodology proposed by the author, the assessment of decorative traits of woody plants was carried out in four main blocks: the first one is the assessment of the overall decorativeness of the plant, which includes the period of decorativeness, decorative traits of the crown (shape, density, texture) and the duration of flowering and foliage; the second one is the assessment of the decorativeness of the bark, its texture and colour; the third one is the assessment of the decorativeness of the leaves in terms of their shape, size, colour and seasonality of their changes; the fourth block is the assessment of the decorativeness of the generative organs of the plant, which is based on the results of the study. According to this methodology, the degree of decorativeness of plants ranges from 13 to 90 points with a gradation into four groups of decorativeness: IV (13-40 points) – low decorativeness, III (41-50 points) – mediocre, II (51-64 points) – high, I (65-90 points) – very high (Vlasenko, 2016). The study was conducted following the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973).

Results and Discussion

One of the most important decorative features of plants is the architecture of the trunk and crown. For the most part, the maximum expressiveness of these traits of deciduous plants is manifested in the autumn-winter period. Since the studied representatives of the *Araliaceae* family are low-branched plant species, the architectonics of their trunks and crowns were assessed at 3 points during the leafless state. Notably, the use of regular formative pruning of the crown of *E. lasiogyne* and *E. trifoliatus* in the collection plantations of the NBS named after M.M. Hryshko and the BS named after A.V. Fomin ensured high decorativeness of the aboveground part due to its orderliness, density, texture and compactness: the decorativeness of crowned specimens in autumn and winter was estimated at 4 points (Fig. 1).

Leaf decorativeness is a substantial component that forms the longest-lasting and most stable overall decorative effect of plants. In an assessment of leaf decorativeness, such qualitative

attributes as the shape and size of the leaf blade, colour and its change in autumn, the venation system, surface texture, and the method of attachment to the shoots are central.

a  b 

Figure 1. *Crown and trunk architecture of experimental plants in a leafless state in autumn and winter*

Note: *a – E. lasiogyne; b – E. sessiliflorus*

Source: photos taken by the authors

With the beginning of the growing season and budding, the overall decorative effect of *Araliaceae* increases due to the appearance of leaves. Large double-pinnate leaves of *A. elata* reach a length of more than 1 m and develop on the tops of branches. At the time of blooming, the leaves have a crimson hue, which eventually transforms into a dark green colour. In the 3rd decade of August – 1st decade of October, the green colour scheme of *A. elata* leaves is replaced by autumn colour with the predominance of warm shades from yellow to purple-red (Fig. 2). Thus, the leaves of *A. elata* are attractive, with a maximum score of 5 points for their decorative effect.

Figure 2. *Autumn leaf colour of A. elata*

Source: photos taken by the authors

The studied representatives of the genus *Eleutherococcus* are characterised by palmate and ternate leaves of different size ranges, which in autumn acquire yellow shades. Thus, the decorativeness of the leaves of 3 studied species of *Eleutherococcus* (the largest in size) was estimated at 5 points (*E. senticosus*, *E. sessiliflorus*, *E. wardii*). In turn, the leaves of *E. lasiogyne* and *E. trifoliatus* are ternary compounds, and those of *E. sieboldianus* are palmate, small (up to 10 sizes), and their decorative effect was assessed at 4 points.

In 4 plant species under study, the leaves retain their decorative effect for more than 6 months (*E. trifoliatus*, *E. wardii*, *E. lasiogyne*,

E. sieboldianus). The flowers of the studied representatives of the *Araliaceae* family are inconspicuous, small (3-4 cm in diameter), white to yellowish-green in colour, collected in inflorescences that differ in size, complexity of structure and duration of flowering (Fig. 3).

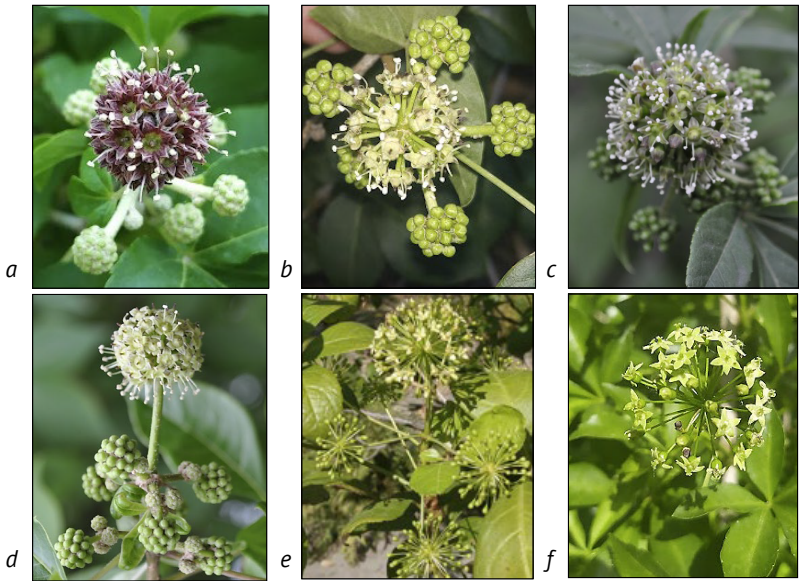

Figure 3. *Generative organs of representatives of the Araliaceae family at different stages of development*

Note: a – *E. sessiliflorus*; *b* – *E. trifoliatus*; *c* – *E. wardii*; *d* – *E. lasiogyne*, e – *E. senticosus*, *f* – *E. sieboldianuss*

Source: photos taken by the authors

It is worth noting the peculiarities of flowering and fruiting of plants of the genus *Eleutherococcus* (*E. sessiliflorus*, *E. lasiogyne*, *E. trifoliatus*, *E. wardii*, *E. senticosus*), which are characterised by the partial overlap of terms and stages of development of generative organs (Fig. 4).

Figure 4. *Generative organs of Eleutherococcus representatives at different stages of development (from flowering to fruiting)*

Note: *a – E. sessiliflorus; b – E. trifoliatus; c – E. wardii; d – E. lasiogyne*

Source: photos taken by the authors

Among the representatives studied, the largest inflorescences – panicles – are those of *A. elata* (up to 50 cm in diameter, with one individual fruit 3-4 mm in size), its primary axis has 5 to 12 lobes 20-35 cm long (Fig. 5) and *K. septemlobus* (up to 30 cm in diameter) with a similar structure.

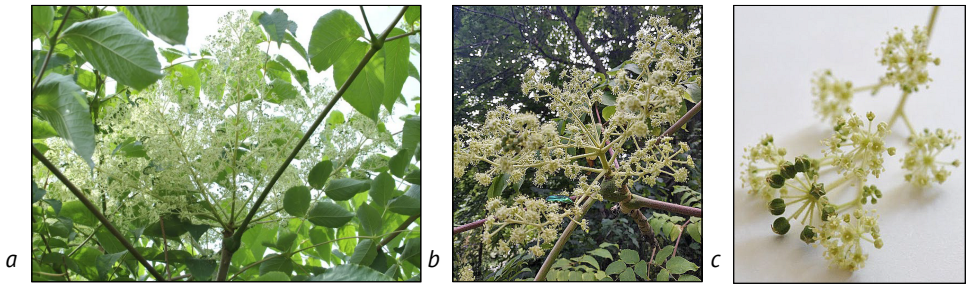

Figure 5. *Inflorescences of A. elata*
Note: *a* – general view of the inflorescence; *b* – terminal axis of the panicle
Source: photos taken by the authors

In plants of *A. elata*, flowering begins on the umbels located at the tops of the terminal panicle axes, with further records of fruit formation, while the umbels located below the inflorescence axes begin to enter the flowering phase. Thus, the timing of flowering and fruiting phases in the above representatives of the *Araliaceae* family occur simultaneously. The high decorativeness of *A. elata* fruits is observed during their ripening (III decade of August – III decade of September). During this period, the openwork axes of the inflorescences become pink, and the small spherical fruits are distinguished by a purple-black colour (Fig. 6).

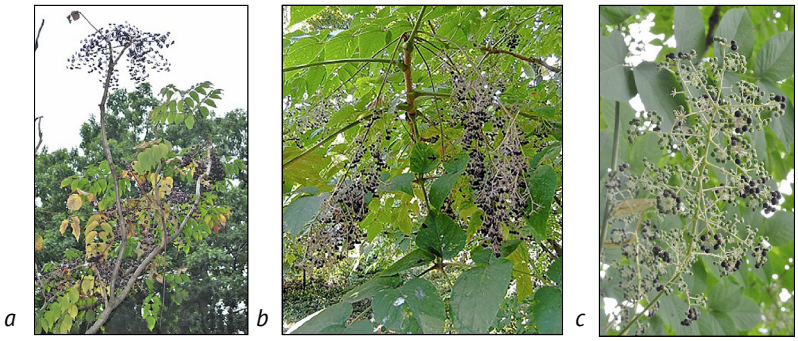

Figure 6. *Fruiting of A. elata*
Note: *a* – nature of the placement of tassels on the plant; *b* – single inflorescence; c – secondary axis of the panicle, showing the nature of fruit ripening
Source: photos taken by the authors

The results of the current study revealed that plants of all studied species of the *Araliaceae* family growing in unprotected soil of Kyiv bloom, but fruit forming is inherent only in some species. Given that *E. sieboldianus* is a monoecious plant and is represented only by single female specimens in the study areas, the fruit decorative effect was not assessed.

In the studied species of plants of the *Araliaceae* family, the fruit is a juicy drupe, which changes colour from greenish to purple and then almost black as it ripens (Fig. 7).

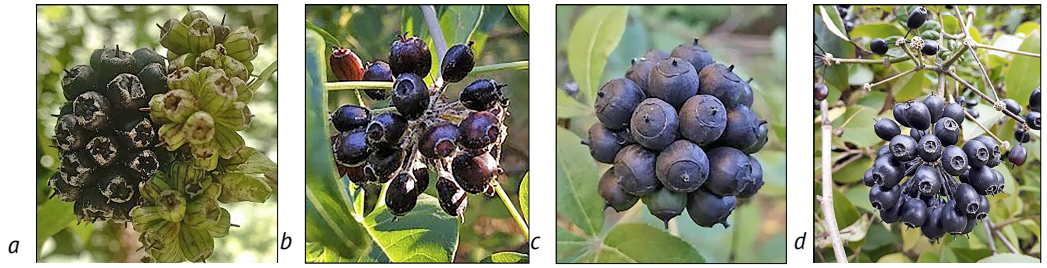

Figure 7. *Ripe fruits of plants of the Araliaceae family*
Note: a – E. *sessiliflorus*; *b – E. trifoliatus*; *c – E. wardii*; *d – E. lasiogyne*
Source: photos taken by the authors

In *E. wardii* and *E. senticosus*, only those fruits located on the tops of the main axis of the panicle reach the stage of ripeness. The fruits on the umbels of the lateral axes mostly do not ripen and fall off. In plants of *E. trifoliatus*, *E. sessiliflorus*, *and E. lasiogyne*, successful fruit ripening occurs on all inflorescence orders. When determining the decorative effect of plants, the aforementioned features of the development of generative organs are expressed in the quantitative assessment of fruiting abundance.

Members of the *Eleutherococcus* genus are characterised by long flowering and fruiting. The fruits of *E. senticosus* are the first to ripen, but they do not remain in the bushes. Fruits of *E. sessiliflorus*, *E. lasiogyne*, *E. trifoliatus*, and *E. wardii* are decorative for more than 3 months: dark purple, almost black – they are visible in winter. Notably, the plants of the *Araliaceae* family are zoo species, their fruits are the food base of some bird species, which is a positive phenomenon in the context of biocenosis in the anthropogenic environment. The colour and texture of the trunk bark of *K. septemlobus* plants varies with age from grey fine-cracked to grey-brown longitudinally deeply cracked. Young shoots are covered with green thorns with a wide base, and old branches become grey-brown in colour, with sickle-shaped leaf scars visible on them. The decorative score of the trunk bark and crown of *K. septemlobus* plants was 3 points.

The trunk bark of *A. elata* plants at a young age is light brown in colour and densely covered with thorns, later it acquires a grey-brown hue and becomes finely fissured (Fig. 8). On light brown branches, wide sickle-shaped leaf scars with a system of conductive bundles surrounding the downwardly directed thorns are visible. The decorative qualities of the colour and texture of the crown and trunk of *A. elata* plants in winter were rated at 4 points.

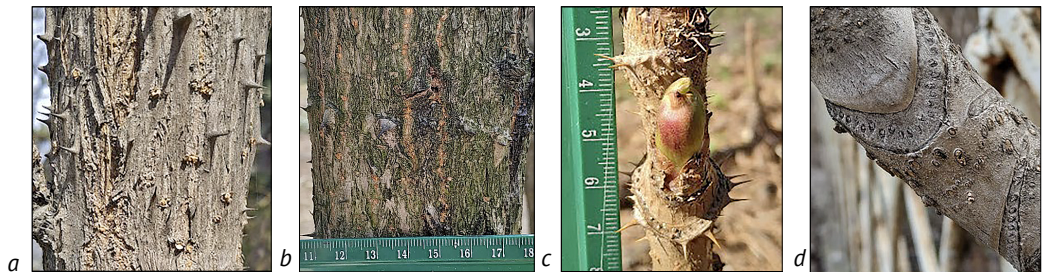

Figure 8. *Colour and texture of trunks and branches of A. elata*
Note: *a* – trunk bark of a young specimen; *b* – trunk bark *of a mature specimen*; *c* – annual shoot *A. elata*; *d* – four-year-old branch *A. elata*
Source: photos taken by the authors

Representatives of the genus *Eleutherococcus* have decorative qualities – the colour and texture of the bark and trunk are not very expressive, and the surface is covered with emergences of different structures, sizes and densities (except for *E. sessiliflorus*).

The bark of the branches of *E. senticosus* is light brown and densely covered with spines 4-8 mm long. The bark of *E. sessiliflorus* has a dark grey colour and single spines 5-10 mm long. Plants of *E. lasiogyne* and *E. trifoliatus* have light grey bark and single short spines 3-4 mm long. The branches of *E. wardii* and *E. sieboldianus* have light grey bark and a moderate number of spines up to 4 mm and 7 mm long, respectively (Fig. 9).

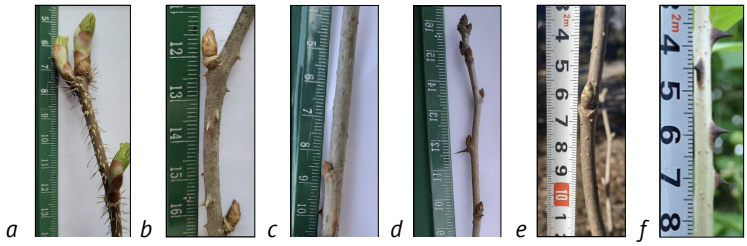

Figure 9. *Colour and texture of branches of representatives of the genus Eleutherococcus*
Note: *a – E. senticosus; b – E. wardii; c – E. trifoliatus; d – E. sieboldianus; e – E. sessiliflorus; f – E. lasiogyne*
Source: photos taken by the authors

The sequence and duration of the phenological phases of seasonal growth and development of the studied plant species are reflected in the phenospectrum (Fig. 10).

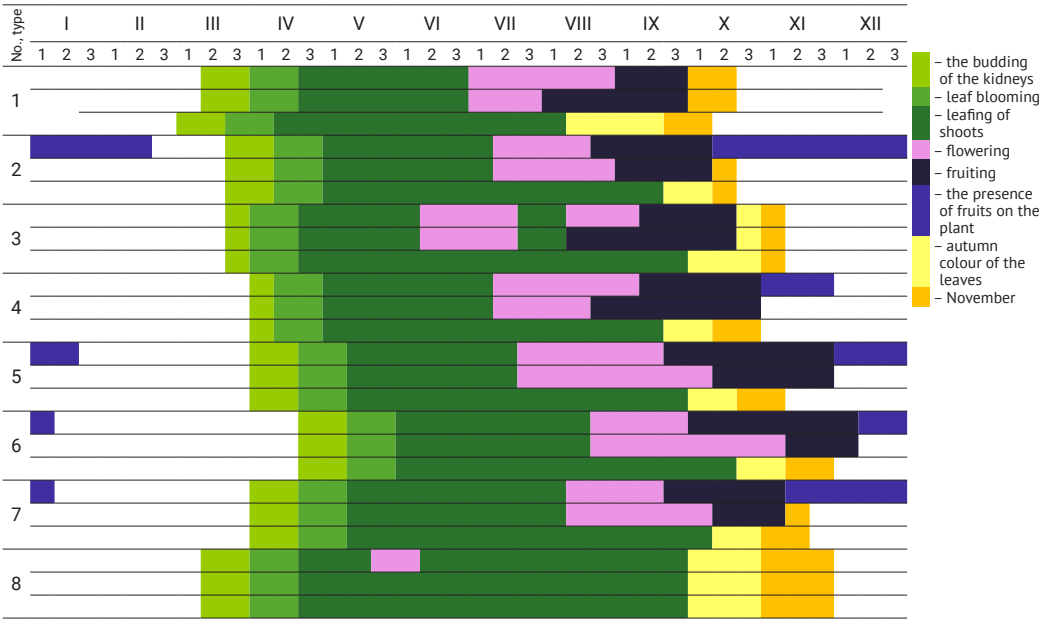

Figure 10. *Phenomenology of seasonal growth and development of dendrosozoan exotics of the family Araliaceae in the territory of botanical gardens of Kyiv (on the example of the vegetation period of 2019)*
Note: *1 – A. elata; 2 – K. septemlobus; 3 – E. senticosus; 4 – E. sessiliflorus; 5 – E. lasiogyne; 6 – E. trifoliatus; 7 – E. wardii; 8 – E. sieboldianus*
Source: compiled by the authors based on own research

The results of calculations of the total decorativeness of representatives of the *Araliaceae* family during 12 months by 5 traits for each plant species studied are provided in Table 1.

Table 1. *The decorative effect of Araliaceae throughout the year*

Species name	Month											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
A. elata	3.20	3.20	3.63	4.75	4.75	4.75	4.80	4.80	4.80	3.80	3.20	3.20
K. septemlobus	2.86	2.86	3.00	3.50	4.38	4.38	4.30	4.30	3.90	2.86	2.86	2.86
E. senticosus	3.00	3.00	3.00	3.88	4.40	4.60	4.60	4.80	4.80	4.10	3.40	3.00
E. sessiliflorus	3.00	3.00	3.00	3.80	4.25	4.75	4.80	4.80	4.30	3.70	3.58	3.00
E. lasiogyne	3.80	3.80	3.80	3.88	4.38	4.38	4.38	4.50	4.59	3.92	3.80	3.86
E. trifoliatus	3.80	3.80	3.80	3.88	4.38	4.38	4.38	4.50	4.59	4.09	3.92	3.50
E. wardii	3.00	3.00	3.00	3.50	4.10	4.75	4.80	4.80	4.50	4.10	3.40	3.00
E. sieboldianus	3.00	3.00	3.50	3.50	4.10	4.30	4.38	4.38	4.38	3.88	3.50	3.00

Source: compiled by the authors based on own research

Graphs of the seasonal dynamics of the overall decorative effect (Figs. 11, 12) were constructed based on the data in Table 1, reflecting changes in the scores of each of the studied species of plants of the *Araliaceae* family during the year.

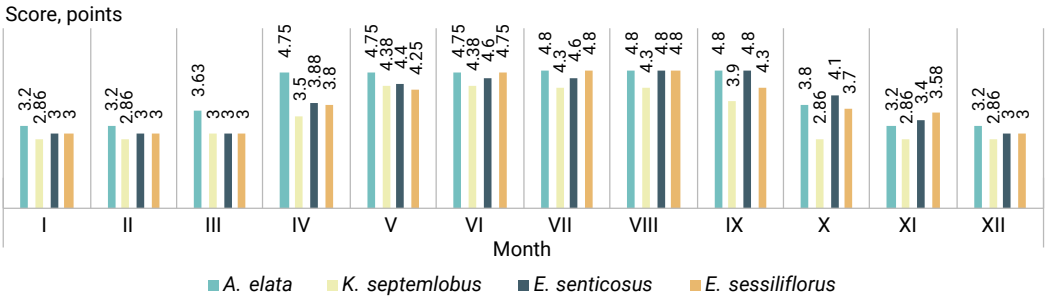

Figure 11. *Seasonal dynamics of the overall decorative effect of plant species: A. elata, K. septemlobus, E. senticosus, E. sessiliflorus*

Source: compiled by the authors based on own research

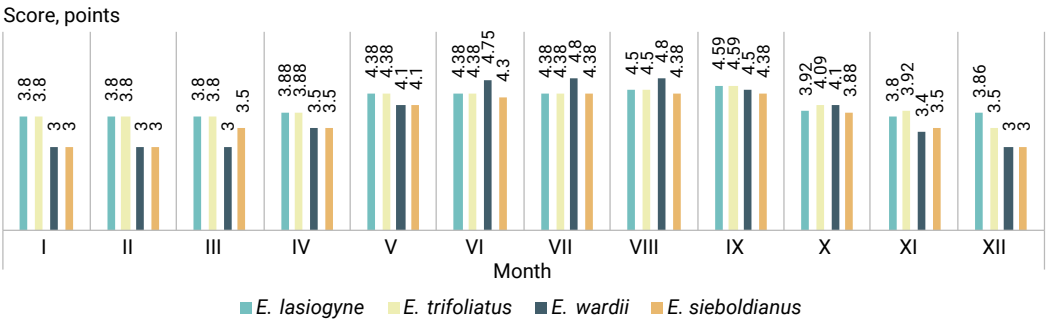

Figure 12. *Seasonal dynamics of the total decorative effect of plants of E. lasiogyne, E. trifoliatus, E. wardii, E. sieboldianus*

Source: compiled by the authors based on own research

Based on the generalised research results, plants of 8 species of the *Araliaceae* family growing in the collection plantations of three botanical gardens in Kyiv have a decorative value of 45-65 points and therefore can be divided into 3 groups according to these indicators (Table 2).

Table 2. *Quantitative assessment of the decorative value of dendrosozoexotics of the family Araliaceae in the botanical gardens of Kyiv*

	General decorativeness of plants						Evaluation of the decorative quality of the crust	Assessment of leaf decorativeness				Assessment of the decorative effect of generative organs									
		crown				longevity						flowers/ inflorescences			fruits						
Plant species by number	decorative time	form	density	structure	blooming	foliage	structure	colouration	size	form	colouration	colour changes	size	colouration	abundance	form	size	colouration	abundance	**Overall score**	**Decorative group**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
1	3	3	3	5	5	1	3	3	5	5	3	5	5	5	3	3	1	3	1	65	I
2	3	3	3	3	3	1	3	3	5	3	3	3	5	3	1	1	1	3	1	51	II
3	3	3	3	3	3	5	3	3	5	5	3	5	3	1	3	3	1	3	3	61	II
4	3	3	3	3	3	3	3	3	5	5	3	3	3	3	1	3	1	3	3	57	II
5	3	5	3	3	5	5	1	3	3	5	3	3	3	3	5	5	1	3	5	67	I
6	3	3	3	3	5	5	3	3	3	5	3	3	3	5	3	3	1	3	3	63	II
7	3	3	3	3	3	5	3	3	5	5	3	3	3	3	3	3	1	3	1	59	II
8	3	3	3	3	1	5	3	3	3	5	3	3	3	1	3	0	0	0	0	45	III

Note: 1 – *A. elata;* 2 – *K. septemlobus;* 3 – *E. senticosus;* 4 – *E. sessiliflorus;* 5 – *E. lasiogyne;* 6 – *E. trifoliatus;* 7 – *E. wardii;* 8 – *E. sieboldianus*

Source: compiled by the authors based on own research

Thus, the study revealed that a mediocre degree of decorativeness (group III) is inherent in *E. sieboldianus* plants, whose low score among the other studied species is due to the lack of points for fruiting. Five plant species were classified as having a high degree of decorativeness (group II): *K. septemlobus*, *E. senticosus*, *E. sessiliflorus*, *E. trifoliatus*, *and E. wardii*. A high degree of decorativeness (group I) is observed in plants of 2 species – *A. elata* and *E. lasiogyne*. The high quantitative indicators of the degree of decorativeness are due to the unique biological and morphological features of the studied plant species (large and complex leaves, as well as their bright autumn colour, long flowering and fruiting period).

The assessment of the decorative qualities of the *Araliaceae* family and their prospects for use in landscape design is a relevant topic that is reflected in numerous scientific studies. Representatives of this family are known for their high decorative qualities, economic value and medicinal properties, which makes them promising objects for implementation in the green building system.

Several publications indicate that the decorative characteristics of the *Araliaceae* depend on their morphological characteristics, including

habit, size, colour and texture of leaves, and colour of fruits and flowers. The study by A. Abdelnaby *et al.* (2021) in Egypt highlighted the aesthetic value of *Araliaceae* woody plants, in particular their use in urban landscapes. The authors noted that certain species of this family have significant potential for creating decorative compositions due to their high adaptability to urban conditions. C. Thakur & R. Parajuli (2024) investigated the ornamental qualities of wild plants on the Tribhuvan Highway in Nepal. The study emphasises that *Araliaceae* species growing naturally can be integrated into urban landscapes as part of sustainable design concepts. In particular, the study demonstrated that these species are well adapted to new ecotopes and contribute to biodiversity in urban environments.

The biological and genetic features of the *Araliaceae* family also attracted the attention of researchers. K. Kim *et al.* (2017) conducted a phylogenetic and evolutionary analysis of the *Araliaceae* family using complete chloroplast genomes and 45S nrDNA. The results of the study showed a significant level of genetic diversity among species and determined the mechanisms of speciation and adaptation to different environmental conditions. T. Yi *et al.* (2004) studied chromosomal evolution within the *Araliaceae* family, emphasising its importance for understanding genetic and morphological divergence that affects decorative properties.

Other publications focus on the practical use of *Araliaceae*, in particular in landscaping. V.H. Heywood (2015) and T. Rajendran *et al.* (2020) described the cultivation of certain species in container culture, which in the conditions of Kyiv makes them promising for use in interior phytodesign.

In general, representatives of the *Araliaceae* family demonstrate significant potential for use in urban landscaping due to their decorative effect, environmental adaptability and medicinal properties. Further research in this area will facilitate the integration of these plants into the green building system, ensuring their rational use and biodiversity conservation.

The analysis of the source base has shown that the principles, approaches and methods for assessing the decorative effect of plants differ significantly between researchers from different countries. V. Kokhanovskyi *et al.* (2020) developed a transformed methodology for determining the decorative value of woody plants of the *Pinorhynchia* division and tested an integrated assessment of the decorative value of woody plants of the *Magnoliophyta* division. V.A. Vitenko *et al.* (2019) presented a methodology for a comprehensive assessment of the condition of woody plants Morus alba L., and researchers V.P. Shlapak & N.P. Shpak (2018) developed a comprehensive scale for assessing the decorative value of the species *Sorbus torminalis*.

To determine the decorative effect of plants, B. Sulistyantara & N. Mentari (2017) and P. Boycheva *et al.* (2021) used sociological survey methods, where visual criteria for plant decorativeness were determined by questioning 50 respondents (students of the course "Landscape Plants"). Indicators of the external attractiveness of plants were assessed according to four criteria: colour, shape, texture and scale, and then the overall score was calculated using the appropriate formulas. When assessing the decorativeness of 150 plant species, including representatives of the *Araliaceae* family, 60 of them scored above the average level, so, as the authors of the study emphasise, these species have the potential to be used in landscape design. The results of the assessment of 8 species of plants of the *Araliaceae* family in Kyiv indicate that they are highly decorative and can be implemented in the system of green spaces of urban and park areas.

An increase in ethnobotanical publications was identified, where the study of aspects of the use of ornamental plants, in particular in landscaping, is a priority (Natchathiram *et al.*, 2023). Given the economic value of various types of medicinal plants, researchers are studying the possibility of using them as ornamental plants, including for creating medicinal gardens. According to Y. Wang *et al.* (2020), native plant species of the

Araliaceae family are characterised by a long flowering period (beginning in the second half of the year), and the fruiting phase of some members of the family can last until the following spring, which significantly increases the potential of their decorative value. In the conditions of introduction (Kyiv), species of plants of the *Araliaceae* family bloom in the second half of the year until the first decade of October inclusive (*E. sieboldianus*).

Notably, the flowering of *K. septemlobus* plants does not occur every year, even within the natural habitat, and they bear fruit only in the most favourable years (Fujimori *et al*., 2006). In the city, the flowering of *K. septemlobus* plants was recorded twice during the study period (2018-2021). *K. septemlobus* plants form racemes 25-30 cm in diameter, which are localised at the tops of branches, but some of their fruits remain until the beginning of the next growing season. It has been established that representatives of the *Araliaceae* family have a high decorative value and are used to create gardens in southeastern Tibet (Wang *et al*., 2018).

Caprophagous birds function as seed dispersers: *Zosterops japonicus* Temminck & Schlegel disperse of *A. elata* seeds locally in central Japan (Kamei & Ohkawara, 2022). In the UK, nine species of birds feed on the fruits of *Hedera helix* L. (Morozko *et al*., 2021), of which *Turdus merula* L., *Sturnus vulgaris* L. and *Passer domesticus* L. are typical representatives of the avifauna of Ukraine. During the field surveys, individuals of *T. merula* and *P. domesticus* were observed in the experimental plots with *Araliaceae* species, which potentially feed on the fruits of these plants. Thus, monitoring of carpophagous birds feeding on the fruits of *Araliaceae* plant species is another promising area of research in the family's autecology.

Conclusions

The study of decorative qualities and the degree of decorativeness of representatives of 8 species of woody and shrubby plants of the family *Araliaceae* growing in the collection plantations of three botanical gardens in Kyiv was carried out, the dynamics of their decorativeness during the growing season was analysed. The study revealed that plants of *A. elata* species acquire the most attractive appearance in the period from April to September; plants of *E. senticosus* and *E. wardi* – from June to September; high decorativeness of plants of *E. lasiogyne*, *E. sessiliflorus*, *E. trifoliatus* and *E. sieboldianus* is observed in the period from May to September, and of *K. septemlobus* – from May to August. High decorativeness of plants of woody species of the *Araliaceae family* is noted with the passage of flowering, formation to fruit ripening.

The results obtained indicate a high degree of plant decorativeness and the prospects and feasibility of their further use not only within the collection plantings of botanical gardens but also to improve the architectural and artistic appearance of urban and park areas by using the natural aesthetics of plants. Accounting for the experience of foreign scientists, the studied species of plants of the *Araliaceae family* may be promising for the creation of medicinal gardens. Considering the biomorphological features, it is recommended to involve representatives of the *Araliaceae* family in the formation of Kyiv plantations, namely: for ordinary plantings – *K. septemlobus*; as a tapeworm – *A. elata, K. septemlobus, E. senticosus, E. sessiliflorus, E. lasiogyne, E. trifoliatus, E. wardii, E. sieboldianus*; formation of hedges – *E. sieboldianus*; decorative groups – *A. elata, K. septemlobus, E. senticosus, E. sessiliflorus, E. lasiogyne, E. trifoliatus, E. wardii, E. sieboldianus;* curtains – *A. elata, E. lasiogyne, E. trifoliatus, E. wardii*; for slope stabilisation – *E. senticosus*.

The prospect of further research is a comprehensive assessment of the decorative characteristics of woody species of the family *Araliaceae* Juss., in particular, the study of their adaptive properties to changing climatic conditions and urban environments. The assessment of the decorative qualities of these plant species should include not only the study of their ecological and biological characteristics but also the study of

the influence of agronomic conditions on their growth and decorative parameters. It is necessary to address the resistance of woody species of the family *Araliaceae* Juss. to stress factors such as air pollution, temperature and humidity changes.

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None.

Conflict of Interest

None.

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Комплексна оцінка декоративності деревних видів родини *Araliaceae* Juss. на території колекційних насаджень ботанічних садів м. Києва

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Анотація. Знання декоративних особливостей рослин у межах урбоекосистем дозволяє створювати високодекоративні насадження з тривалим декоративним ефектом, які гармонійно взаємодіють із міськими системами. Метою дослідження було встановлення ступеня декоративності дендросозоекзотів родини *Araliaceae* Juss., представлених на території колекційних насаджень ботанічних садів м. Києва. Здійснено комплексну оцінку декоративності 8 видів деревних рослин родини *Araliaceae*. Наведено результати оцінювання ступеня декоративності досліджуваних видів рослин і встановлено, що 2 види мають дуже високий ступінь декоративності (*Aralia. elata* (Miq.) Seem. та *Eleutherococcus lasiogyne* (Harms) S.Y.Hu.), 5 видів характеризуються високим ступенем декоративності (*Kalopanax septemlobus* (Thunb.) Koidz., *Eleutherococcus senticosus* (Rupr. & Maxim.) Maxim., *Eleutherococcus sessiliflorus* (Rupr. & Maxim.) S.Y.Hu, *Eleutherococcus trifoliatus* (L. f.) S.Y. Hu, *Eleutherococcus wardii* (W.W.Sm.) S.Y.Hu.). Посередню декоративність відзначено в одного виду – *Eleutherococcus sieboldianus* (Makino) Koidz. Проаналізовано динаміку сезонної декоративності дендросозоекзотів родини *Araliaceae* та виявлено, що високий ступінь декоративності спостерігається у 87,5 % досліджуваних видів рослин. Пік декоративності дендросозоекзотів припадає на літній період та триває близько 120 діб (з 3 декади травня по 2 декаду вересня), що пов'язано з біологічними особливостями та фазами онтогенезу інтродуцентів, зокрема тривалими у часі періодами квітування, формування плодів та їх дозрівання. Отримані результати є основою для оптимізації видового складу насаджень міських та паркових територій мегаполісів та підвищення їх декоративності в умовах урбанізованого середовища за врахування показників стійкості досліджуваних видів рослин до антропогенного навантаження

Ключові слова: сезонна декоративність; дендросозоекзоти; фітодизайн; інтродуценти; лікарські рослини; квітування; плодоношення; вегетація

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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 electrohydraulic 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

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Impact of stress on the body of service dogs and alleviation methods: Literature overview

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Abstract. Stress causes changes in the immune, nervous and endocrine systems, which can lead to diseases and behavioural problems in animals. The study of these changes can be used to develop effective methods of diagnosis and prevention. The study aims to investigate the effect of stress on the body of dogs at the anatomical and physiological levels; and methods of diagnosis, treatment and prevention of stress disorders in these animals. The study analysed scientific publications on the detection, diagnosis, control and treatment of service dogs under stressful conditions. The main criteria that helped to differentiate different forms of behavioural reactions in service dogs under the influence

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of stressors were recorded by the methods of comparison, synthesis and analysis. Physiological criteria that should be used in the diagnosis of stress were established and methods for diagnosing stressful conditions in service dogs were described. Service dogs are more stress-resistant than other animals, but they are also exposed to negative environmental factors. This leads to physiological changes in the body of animals, which affects their performance and behavioural reactions. The physiological and behavioural markers of acute and chronic stress in dogs were determined. Changes in the immune system of dogs and the importance of cortisol as a stress-correlated marker were analysed. The study determined that the content of cortisol in blood plasma, saliva, and hair correlates with stress indicators in animals, but may also depend on many other factors. This indicates that this indicator alone cannot be relied upon to diagnose stress in animals. The results of the study can be used in the development of diagnostic criteria and methods for monitoring and correcting changes in the bodies of animals caused by stressful phenomena

Keywords: acute stress; chronic stress; diagnosis; behavioural changes; cortisol; post-traumatic stress disorder

Introduction

Stress is a common occurrence in everyday life, as all beings have to adapt to environmental instability to ensure survival and reproduction. At the same time, animals of different species, including dogs, are easily exposed to stressors, which affect their health, behaviour and functions. For service dogs that regularly perform complex tasks in stressful conditions, such as searching for explosives, participating in search and rescue operations, or ensuring security at mass events, this impact can be particularly pronounced. Constant exposure to stress can cause not only temporary disorders in the body but also chronic changes that reduce their performance and jeopardise the performance of their professional duties. Physiologically, stress in dogs is manifested by increased cortisol levels, changes in the cardiovascular system, and disorders of the immune system and metabolism. Behavioural signs of stress, such as aggression, anxiety or non-cooperation, are also serious indicators that require immediate intervention. Failure to identify and correct a stressful condition in time can lead to the development of somatic diseases, a decrease in the quality of life of the animal and even the premature end of its career.

M. Salonen *et al*. (2020) determined that the prevalence of fear and anxiety in dogs averages between 26% and 50%, which corresponds to millions of animals potentially suffering from behavioural problems caused by fear and anxiety. Research conducted by Green Element (USA) in 2022 shows that in the last two years alone, anxiety levels in dogs during the COVID-19 pandemic have increased from 40% to over 70% (Weng & Ogata, 2023). The fear of strangers and separation behaviour is particularly acute. However, under martial law, the risks of stress in animals are much higher and are often associated with loud noises, lack of food, owners and life safety. At the same time, service dogs that are actively involved in search and clearance operations are also exposed to stress, which hinders their effective use. High levels of noise from cars, explosions, shooting, shock waves; constantly changing terrain; high levels of dust and smoke; noisy machinery and movement are stressful factors for animals. J. Herbel *et al.* (2020) noted that transport is also a stressful factor for dogs.

In addition, animals that have been exposed to extreme situations, including those caused by loud explosions or gunfire, may eventually develop post-traumatic stress disorder (PTSD), which affects the behaviour of a service dog with various manifestations. As noted by S. Nichiporuk *et*

al. (2023), the issue of PTSD in dogs was not sufficiently covered, as it is inappropriate to transfer the signs of human PTSD to animals. However, since dogs have a much larger hearing range, loud sounds of uncertain aetiology are usually the cause of PTSD in dogs. This was confirmed by A.S. Mann *et al.* (2024), who found that 44.4% of dogs had fear associated with fireworks, thunder, gunshots, and vehicle noise. Animals may respond to these with behavioural signs of fear or anxiety, including depression or agitation, withdrawal or aggression, chaotic movements, or freezing. Even animals that are accustomed to gunshots may react inappropriately.

Service dogs often work for many hours in difficult conditions, in the presence of other animals, with different people who may also have different stress tolerances. Thanks to their sense of smell, dogs can easily detect the smell of cortisol, adrenaline and norepinephrine in humans in a calm state and a stressful situation. C. Wilson *et al.* (2022) pointed out that during the development of stress, physiological processes occur in the body that cause the release of volatile organic compounds in breath or sweat. Service dogs can distinguish these compounds with high accuracy. The ability to recognise different compounds is used for the service characteristics of service dogs and helps the interaction between a person and a service dog, which is used for emotional support and treatment of post-traumatic stress disorder (PTSD).

K.E. Rodriguez *et al.* (2018) highlighted that the engagement of military personnel returning from combat zones with guide dogs has a positive impact on recovery and significantly reduced the severity of post-traumatic stress disorder symptoms, as well as reduced anxiety, anger, and sleep disturbances. These findings were confirmed in a study by S.C. Leighton *et al.* (2024) indicating that military personnel and veterans with post-traumatic stress disorder have better psychosocial outcomes when using specially trained service dogs compared to conventional treatment. Therefore, as noted by H. Yatsenko (2022), since 2019, the SES units in Ukraine have been implementing canine therapy, allowing employees to recover from the events experienced through interaction with specially trained service dogs.

At the same time, such interaction requires constant control of the service dog. E. De la Fuente-Moreno *et al.* (2023) noted that service dogs used as guides for blind people have higher levels of cortisol in their blood and saliva, which is associated with their cognitive and emotional processes. Elevated levels of cortisol have also been observed in service dogs used by the military.

Notably, service dogs often hide their stress, so the signs can be unnoticed, however, changes at the biological level still occur. L. Lazarowski *et al.* (2020) determined that a prominent example is the behaviour of service dogs, which, being trained and hardy, suddenly change their behaviour towards their owners after service in dangerous conditions for a long time.

In view of this, it is necessary to determine the physiology of stress in service dogs, analyse the changes they cause in the body of these animals and understand the approaches to diagnosing and timely correction of pathological conditions of the animal's body in the event of stress.

The study aims to summarise the existing literature on the impact of stress on the body of service dogs, ways to diagnose stressful conditions and prevent their development in these animals.

The research material included scientific data on the impact of stress on the body of service dogs and methods of its diagnosis in experimental conditions and veterinary clinics. PubMed and Elsevier databases and specialised scientific journals were used as information sources. The comparison method, analysis and synthesis, and the descriptive method were used. The method of comparison was used to compare different approaches to the diagnosis and treatment of stressful conditions in dogs described in scientific sources. This method identified commonalities and differences between the methods used in experimental conditions and practical veterinary medicine. The method of analysis consisted of a

detailed study of each data source, including the identification of physiological, behavioural and biochemical markers of stress. This determined the mechanisms of stress on the body of service dogs, as well as assess the effectiveness of existing approaches to their diagnosis and correction.

Results

Behavioural manifestations of fear and anxiety in service dogs

Service dogs are specially trained animals that can perform specific tasks to ensure the safety of people. The behavioural, physiological and structural characteristics of the animals selected for such work are of great importance. In particular, the developed sense of smell, stress resistance, the animal's ability to learn, and the level of basic excitability of the animal.

L. Lazarowski *et al.* (2020) distinguish between negative arousal (stress) and positive arousal (e.g. excitement) in service dogs. A high level of arousal in an animal can interfere with performance. Initially, arousal can improve task performance up to a certain point, after which the inhibition stage begins. This effect depends on the animal's baseline level of excitability. In addition, increased arousal in service dogs can impair learning, memory and decision-making, and lead to the activation of physiological reactions such as increased respiration and heart rate, which reduces olfactory abilities, as dogs cannot smell and breathe at the same time (Bray *et al*., 2015).

As noted by L. Townsend & N.R. Gee (2021), dogs can experience triggered stress accumulation when an animal is exposed to multiple stressors at the same time. Triggered accumulation can occur over a short or long period, depending on the intensity and duration of the stressor. This can cause unpredictable behaviour or a refusal to cooperate.

If a dog is repeatedly exposed to unavoidable stressors, intense fear, anxiety, or phobia can occur. A fear response is an animal's behaviour in response to a real perceived danger. Anxiety is an emotional state that occurs if animals are exposed to threatening situations, such as a new environment. According to E.J. Blackwell *et al.* (2013), the term "phobia" is generally used when the behavioural response is extreme, long-lasting, and involves a marked, persistent, and excessive fear of certain stimuli. However, the differentiation of these types of reactions in animals is unclear.

The causes of fear and anxiety in dogs are multifactorial and may include inherited genetic influences, environmental influences, and experiences during certain work situations. N.J. Rooney *et al.* (2016) determined that fear-related behaviour negatively affects the animal's performance or results in a significant number of service dogs failing training and becoming unfit for duty. Prolonged exposure to stressors can lead to the development of fear and general anxiety in dogs, which negatively affects their performance.

Fear in an animal can be interpreted as one of the forms of fulfilling self-preservation. Researchers C. Mariti *et al.* (2012) demonstrated that a behavioural response is often the most effective way to resolve a stressful situation, allowing the body to restore homeostasis. There are three main ways to resolve a stressful situation: active attack, passive defence, and escape.

The literature describes attempts to characterise the "coping styles" in dogs based on physiological and behavioural reactions. In particular, E.J. Blackwell *et al.* (2013) highlighted a "reactive" style of animal response to stress or a more "proactive" style. Z. Horváth *et al.* (2007) identified 3 categories of behavioural responses in service dogs. The usual behavioural response of dogs to severe stressors is defensive aggression, hiding, and avoidance of contact with people. Another group of animals, on the contrary, seek contact with people or other animals and are characterised by behaviour that attracts attention (e.g. jumping, pawing at people). The third group of behavioural reactions is excessive dog activity, increased respiratory rate, salivation, pupil dilation, vocalisation, lowered posture, flattened ears and a pinned tail, and anorexia. There are also three categories of unhealthy behaviour caused by

stress in dogs: stereotypical animal actions (e.g. excessive licking, side sucking, circling or spinning); excessive movement (tail chasing, fence running, excessive barking, polydipsia and polyphagia) and so-called "hallucinogenic" behaviour (e.g. staring and "chasing flies").

Changes in behavioural responses to chronic stress over a long period are reflected in increased movement, yawning, pawing, and body tremors, as well as increased coprophagia, low posture and vocalisation (Bodnariu, 2008). Service dogs exhibit a wide range of behavioural and physiological responses to stress, which can significantly affect performance, with excitability, adaptability to stressors and inherited behavioural traits being central.

The effect of stress on the functioning of various animal body systems

Following A. Aleme & A. Negassie (2014), stressor activates the sympathoadrenal system, which is associated with the fight-or-flight response and is characterised by the release of adrenaline and norepinephrine. These, in turn, cause the release of glucose, an increase in heart rate and blood pressure, and an increase in respiratory rate in the animal. These processes mobilise the body and increase the capacity of the animal to effectively fight or escape, i.e. survive the threat.

If the stress is short-term, the manifestation of the stress response does not cause homeostasis disorders after the stressor ceases. According to T. Kooriyama & N. Ogata (2021), markers of the sympathoadrenal system reflect a short-term response to stressors, when catecholamine secretion peaks after 1 minute and then remains elevated for about 3 minutes. With prolonged exposure to a stressor, another mechanism of the stress response is activated – the hypothalamic-pituitary-adrenal axis, the end product of which is glucocorticoids secreted by the adrenal glands under the influence of adrenocorticotropic hormone (ACTH).

D. Salgirli *et al.* (2023) noted the adaptive nature of acute stress in dogs. Species-specific defence reactions activate to help the animal cope with stress. The bodily response to endogenous or exogenous stressors is mandatory, which is manifested by a stress response, i.e. an adaptive response aimed at restoring homeostasis and vital activity of the animal's body. T. Kooriyama & N. Ogata (2021) noted that since stress responses are activated by the sympathoadrenal and hypothalamic-pituitary-adrenal axes, the immune system is activated at the same time. C. Siracusa *et al.* (2008) also highlighted that stress affects the immune system, which, after short-term exposure to a stressor, is stimulated for 30 minutes, and in the case of prolonged stress, it is suppressed, and its effectiveness is reduced by 40-70%.

As noted by B. Kumar *et al.* (2012), hormonal changes in response to stress, including increased plasma concentrations of adrenaline, cortisol, growth hormone and prolactin, have immunomodulatory effects. At the same time, cortisol can inhibit the functions of macrophages, neutrophils, basophils and eosinophils. Glucocorticoids and adrenocorticotropic hormone affect the proliferation of B and T cells and the production of cytokines and antibodies.

B.M.G. Gormally *et al.* (2020) highlighted that the changes that occur at the cellular level are characterised by changes in heat shock proteins (Hsp), DNA damage and changes in telomere length. In particular, the heat shock proteins Hsp70 and Hsp90 are significantly reduced within 30 min-2 h after exposure to acute stressors, as well as under the influence of long-term stressors. In addition, under the influence of short-term or long-term exposure to adrenaline, cortisol, and repeated exposure to stressors, DNA damage occurs in different animal species. The authors also proved that stressors lead to a significant reduction in telomere length, which affects the life span of the animal, but these data still need further study, especially their correlation with the effect and intensity of different types of stressors.

N.A. Dreschel (2010) noted that the link between stress and susceptibility to disease in pets demonstrates that dogs with manifestations of

fear and anxiety have a shorter life expectancy and a higher frequency and severity of diseases. The suppression of the animal's immune system contributes to the development of opportunistic pathogens. This includes microorganisms that cause respiratory infectious diseases and infections caused by Salmonella sp. In response, glucocorticoids or catecholamines are released, which reduce the protective capacity of cellular immune mechanisms. In addition, they reduce the accumulation of neutrophils at the site of local inflammation, which leads to complications of bacterial infections. This suggests that some disorders are most likely triggered by the development of chronic stress in animals.

Diagnostic criteria for stressful conditions in dogs

I.A. Kartashova *et al.* (2021) stated that the choice of physiological markers for the development of stress in animals should address not only physiological parameters, but also the characteristics of the animal, its lifestyle, age, concomitant diseases, physical activity, anamnesis, and even the owner's temperament. B.M.G. Gormally *et al.* (2020) combined the indicators that characterise the development of stress in vertebrates into seven large groups, such as changes in glucocorticoids and the excretion of their metabolites in saliva, faeces, and urine; the influence of the parasympathetic nervous system (changes in heart rate, heart rate variability, and respiratory rate); impact on the immune system(comparison of the ratio of leukocyte types, in particular, heterophils/neutrophils and lymphocytes, assessment of inflammation and bacterial killing test); metabolic disorders (energy mobilisation, metabolic rate, heat regulation); cellular (membrane) disorders; delayed tissue development and behavioural changes (stereotypical behaviour in animals). Blood chemistry and leukogram indicators can also be used to characterise stress, along with physiological indicators such as heart rate and heart rate variability.

According to N.L.B. Corder-Ramos *et al.* (2019), dogs exposed to acute stress develop a general leukocytosis, the leukogram is characterised by neutrophilia, monocytosis, lymphocytopenia and eosinopenia (so-called stress leukograms). B.M.G. Gormally *et al.* (2020) noted that a change in the ratio of heterophils/neutrophils to lymphocytes is recorded in the blood of animals 1-4 hours after exposure to a stressor.

Potential immunological markers in stress responses include leukocyte responses to antigens, salivary IgA, neutrophil/lymphocyte ratio, CD4/CD8 ratio, and plasma cytokines. L.M. Glenk (2017) highlighted a decrease in secretory immunoglobulin A (IgA) under stress in dogs. In practice, serum catecholamines and glucocorticoids are the most used measurements, as they correlate with stress levels. However, while adrenaline and norepinephrine quickly disappear from the blood after the stressor stops, cortisol remains in the blood for 2-6 days. If the body is stressed for a long time, cortisol becomes constant, which leads to the development of chronic stress in animals.

Cortisol is a glucocorticoid hormone produced by the adrenal cortex under the influence of adrenocorticotropic hormone. It regulates most physiological processes in animals and plays an important role in the body's response to stress. Cortisol secretion during acute stress helps mobilize the metabolic energy needed to combat short-term stressors and restore homeostasis. At the same time, prolonged cortisol elevation caused by chronic stress contributes to maladaptive changes in the body and the development of various pathological conditions. B. Beerda *et al.* (1996) determined that this leads to immune suppression, growth retardation and developmental delays in animals.

E. Chmelíková *et al.* (2020) determined that cortisol levels in dogs vary according to the circadian rhythm, with the highest peak occurring in the morning after waking up and the lowest at bedtime. In addition to cortisol, scientists have proposed using other markers to assess acute stress in dogs, including chromogranin A (CgA), which is released along with catecholamines during acute stress but is more stable. For service

dogs, a blood cortisol test can provide valuable insight into physiological health and behaviour, as well as determine of how they adapt to their environment and tasks.

Physiological and biochemical markers, such as cortisol, glucocorticoids, immunoglobulins and other blood parameters, can be used for an efficient assessment of the stressful state of service dogs, contributing to the determination of their adaptation to stressors and maintaining their functional capacity.

Non-invasive methods for studying stress indicators in animals

Predictable and immediate stress reactions caused by the blood collection procedure in animals can increase plasma hormone levels, which makes interpretation of the results difficult. Therefore, as reported by B. Beerda *et al.* (1996), non-invasive sampling methods such as saliva, urine, or hair samples can be used. Hair cortisol determination is a promising method for detecting GH axis activity over a longer period. The cortisol content in hair varies depending on the time of year and the animal's lifestyle. However, E. van Houtert *et al.* (2023), studying Labrador retriever service dogs, found no difference in hair cortisol between service dogs and companion dogs.

According to L. Mesarcova *et al.* (2017), cortisol reaches the hair through diffusion from the blood during the period of hair shaft growth. In addition, sebum secreted by the sebaceous glands also contains cortisol, which can penetrate the hair. Intrafollicular synthesis of cortisol is also possible. As noted by N.L.B. Corder-Ramos *et al.* (2019), canine hair follicle cells in vitro can metabolise progesterone to cortisol. The evaluation and interpretation of hair cortisol concentration results should be approached with caution, as its content can potentially be influenced by several factors, such as coat colour, dog age, lifestyle and maintenance, health status, and seasonality. Salivary cortisol measurement is also a practical test for assessing stress in dogs. E. De la Fuente-Moreno *et al.* (2023) noted that cortisol enters saliva as a result of passive diffusion through acinar cells.

L.M. Glenk (2017) emphasised that salivary cortisol levels reflect plasma cortisol concentrations with a 20-30 min delay. However, it is necessary to address the different cortisol content in the saliva of dogs under acute and chronic stress. In particular, the study determined that under acute stress, cortisol increases significantly. At the same time, with prolonged exposure to the same stressors, the level of cortisol in saliva decreases, but it is not fully understood whether these are adaptive changes or habituation to the environment. J. Wojtaś *et al.* (2022) confirmed that the effect of a stressor on dogs entering a shelter correlates with time and is characterised by an increase in salivary cortisol in dogs of 2.7 ng/ml on admission, 2.1 ng/ml 24 hours later, and 1.9 ng/ml 48 hours after entry. E. Kang *et al.* (2023) suggested that alpha-amylase should be measured in saliva along with cortisol, as it was proven to correlate with cortisol levels under painful stress.

However, following E. Chmelíková *et al.* (2020), the determination of salivary cortisol as a stress marker also has certain limitations. The influence of individual variability in the level of the hormone cortisol in an animal can lead to misinterpretation of the data. Therefore, research should be supplemented with observations of animal behaviour, although symptoms of behavioural stress may not always correlate positively with cortisol production. It is advisable to supplement cortisol measurements with other stress markers in animals. R. Palme (2019) noted that the activity of the hypothalamic-pituitary-adrenal system can be monitored non-invasively by measuring faecal cortisol/corticosterone metabolites (FCM). However, physiological or biological validation of the methods used is mandatory for objective results.

Regarding the content of cortisol in urine, its concentration reflects the level of unbound and biologically active cortisol in the blood plasma. Measurement of free urinary cortisol is clinically important in the diagnosis of Cushing's

Syndrome. Not only does it measure cortisol levels as a stress marker, but it also analyses the content of ACTH, prolactin, secretory immunoglobulin A, catestatin and vasostatin in saliva, as well as salivary α-amylase activity.

In addition to the physiological parameters of stress, a visual assessment of the behaviour of dogs under stress should be considered. Veterinarians should keep in mind the factors associated with stress in service dogs not only at the diagnostic stage but also during further therapy.

Methods of overcoming stress in dogs

Normalisation of the condition of an animal after prolonged exposure to stressful factors requires time and appropriate medical care. Methods of correcting stressful conditions in dogs are based on limiting the impact of stress factors and creating a calm, quiet place for the animal with safe objects and a familiar smell. Cortisol levels in the blood decrease most rapidly during the dog's natural actions, such as chewing and biting, during free exploration of the territory and sniffing of the environment, and sleep. C. Siracusa *et al.* (2008) indicated that a dog should not be encouraged to play after a stressful event, as games and other intense physical activities exacerbate stress by stimulating the same mechanisms that are activated in the body during the stress response. G. Fallani *et al.* (2007) noted that playful interaction between the animal and its owner reduces cortisol levels in dogs. Medication therapy can help to ease a dog's stress response and help to learn new behaviours. Many medications are used to relieve anxiety symptoms, and behavioural or sensory disturbances, but not all are registered as veterinary medicines for dogs.

The drug of choice for acute stress is gabapentin. According to S. Nichiporuk *et al.* (2023), the use of gabapentin in a dose of 15-30 mg/kg for dogs every 6-8 hours, if necessary, prevents the development of a stress reaction in animals. In addition, alprozolam can be used immediately after exposure to a stressor at a dose of 0.04-0.08 mg/kg every 6-8 hours.

S.A. Kim *et al.* (2022) indicated that administration of trazodone at a dose of 9-12 mg/kg to dogs once before transport reduces signs of stress and is useful as a means of preventing anxiety in dogs. M. Brown *et al.* (2024) also noted that trazodone significantly reduces plasma cortisol concentrations through alpha-1 adrenergic activity, and therefore can be used to treat anxiety and stress in service dogs. However, the use of this drug in dogs with adrenal disease may affect diagnosis and clinical decision-making. E. Yalcin (2010) recommends using the antidepressant clomipramine in combination with gabapentin or trazodone at a dose of 0.5-2 mg/kg twice daily.

The effectiveness of clomipramine in the treatment of noise fear and anxiety in dogs was reported by K. Seksel & MJ. Lindeman (2001), who administered the drug at a dose of 1-2 mg/kg body weight and noted a calming effect. O. Williamson *et al.* (2024) proved the effectiveness of clomipramine hydrochloride at a dose of 2 mg/kg and fluoxetine hydrochloride at a dose of 1 mg/kg per day in relieving anxiety and stereotypical behaviour in dogs. A. Erickson *et al.* (2020) compared and confirmed the benefits of gabapentin, trazodone, oral dexmedetomidine and alprazolam in dogs with increased anxiety and stress.

The sedative effect of cannabinoids on animals is crucial. For instance, H.E. Flint *et al.* (2024) reported that the use of cannabidiol distillate, which does not contain tetrahydrocannabinol (CBD), reduces physiological and behavioural indicators of stress in dogs during transport. I. Corsato Alvarenga *et al.* (2023) and C.H.J. Yu & H.P.V. Rupasinghe (2021) also noted the positive effects of cannabidiol (CBD) for the treatment of reducing anxiety and aggression in dogs. M. Susol & A. Vinyarska (2024) noted the potential benefits of CBD in reducing stress, and maintaining health and immunity in animals, and its use is considered one of the main elements of an integrated approach to animal care. In addition to the drugs described above, J. Coates (2023) also used amitriptyline, buspirone, diazepam, lorazepam, paroxetine, and sertraline to treat and prevent

stress disorders in dogs. To prevent stress in dogs, products containing herbal components such as KalmVet, Anti-stress, No stress, and synthetic compounds such as Stop stress, Dolvit calm, Antistress and Stressostop can be used. There is also an anti-stress diffuser called Adaptil, which contains a synthetic pheromone that calms dogs.

Notably, the normalisation of an animal's condition under chronic stress requires time. The primary goal of treatment of animals returning from the combat zone is to eliminate the associative links in the animal's mind that bring it back to the stressful situation.

Conclusions

Human-animal interaction is becoming increasingly relevant globally. Service dogs are used in operational and investigative activities, perform security, transportation, and detection of illegal substances or explosives, and accompany people with various sensory, mental or psychological disorders. The use of service dogs for the treatment of post-traumatic stress disorder in military personnel returning from the combat zone has a positive impact on their mutual emotional health and well-being. At the same time, service dogs often react to stressors in the same way as humans. Therefore, it is necessary to study and determine the signals that indicate changes in the body of these animals.

Stress in service dogs, their fear and behavioural reactions can be specific reactions to the service environment, or cumulative reactions for an animal suffering from stress, fatigue, pain or several other factors. Signs of stress and fear are manifested in the animal's body language, posture and attitude to work tasks.

The main behavioural reactions of stress in service dogs are aggression, refusal to perform tasks, increased excitability, rapid fatigue, stereotypical behaviour, digestive system disorders, and depression. Diagnostics of stressful conditions in animals include a thorough analysis of stress factors, exclusion of concomitant diseases, analysis of catecholamines in blood, saliva, hair, immunological parameters, metabolic disorders and behavioural changes.

Methods of correction for stress in service dogs include drug therapy, elimination of stress factors, creation of comfortable conditions for the animal, and correction of negative experiences through positive training and socialisation. At the same time, it is necessary to improve the study of behavioural medicine and develop a methodological framework for determining behavioural and physiological markers of stress in service dogs during their service tasks in military operations.

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Conflict of Interest

None.

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Вплив стресу на організм службових собак та методи його корекції: огляд літератури

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Анотація. Стрес викликає зміни в імунній, нервовій та ендокринній системах, що може призводити до захворювань і проблем з поведінкою у тварин. Дослідження цих змін дозволяє розробити ефективні методи діагностики та профілактики. Метою роботи було дослідити вплив стресу на організм собак на анатомічному та фізіологічному рівнях; методів діагностики, засобів лікування та профілактики стресових розладів у цих тварин. У статті проаналізовано наукові публікації щодо виявлення, діагностики, контролю та лікування службових собак за стресових станів. Методами порівняння, синтезу та аналізу зафіксовано основні критерії, які допомагають диференціювати різні форми поведінкових реакцій у службових собак за впливу стресорів. Встановлено фізіологічні критерії, на які варто опиратися під час діагностики стресу та описано методи діагностики стресових станів у службових собак. Службові собаки є більш стресостійкими, ніж інші тварини, проте вони також піддаються впливу негативних факторів зовнішнього середовища. Це призводить до фізіологічних змін в організмі тварин, що відображається на їх роботоздатності та поведінкових реакціях. Визначено фізіологічні та поведінкові маркери гострого і хронічного стресу в собак. Проаналізовані зміни в імунній системі собак та значення кортизолу як кореляційного зі стресом маркера. Визначено, що вміст кортизолу в плазмі крові, слині, волоссі корелює із показниками стресу у тварин, проте може залежати також від багатьох інших факторів. Це вказує на те, що під час діагностики стресу у тварин не можна покладатися лише на цей показник. Результати дослідження будуть корисними при розробці діагностичних критеріїв та методів контролю і корекції змін в організмі тварин, викликаних стресовими явищами

Ключові слова: гострий стрес; хронічний стрес; діагностика; поведінкові зміни; кортизол; посттравматичний стресовий розлад

НАУКОВІ ДОПОВІДІ НАЦІОНАЛЬНОГО УНІВЕРСИТЕТУ БІОРЕСУРСІВ І ПРИРОДОКОРИСТУВАННЯ УКРАЇНИ

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