НАУКОВІ ГОРИЗОНТИ

УДК 63

Редакція, видавець:
Поліський національний університет
Рік заснування: 1998
Періодичність випуску: щомісячно

Рекомендовано до друку та поширення через мережу Інтернет Вченою радою Поліського національного університету (протокол № 2 від 24 вересня 2025 року)

Рішення національної ради України з питань телебачення і радіомовлення № 1533.
Ідентифікатор медіа – R30-01593

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Журнал представлено у міжнародних наукометричних базах даних, репозитаріях та пошукових системах: Інституційний репозитарій Поліського національного університету, AGRICOLA, CAB Abstracts and Global Health (CABI), Реєстр наукових видань України, Національна бібліотека України імені В. І. Вернадського, Crossref, ERIH PLUS, International System for Agricultural Science and Technology (AGRIS), Dimension, Polska Bibliografia Naukowa, Google Scholar, Ulrichsweb Global Serials Directory, UCSB Library, EBSCO, Scopus, University of Oslo Library, University of Hull Library, SOLO – Search Oxford Libraries Online, European University Institute, Leipzig University Library, Cambridge University Library, OUCI (Open Ukrainian Citation Index), Worldcat, CORE, COPE, Litmaps

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SCIENTIFIC HORIZONS

UDC 63

Editorial and Publisher:
Polissia National University

Year of foundation: 1998
Frequency of issue: monthly

Recommended for printing and distribution via the Internet by the Academic Council of Polissia National University (Minutes No. 2 of September 24, 2025)

Decision of the National Council of Television and Radio Broadcasting of Ukraine No. 1533.
Media identifier – R30-01593

The scientific journal is included in category A of the List of scientific professional publications of Ukraine, in which the results of dissertations for the degree of doctor and candidate of veterinary, economic, agricultural, and technical sciences can be published in the following specialties: 051 – Economy; 071 – Accounting and Taxation; 072 – Finance, Banking and Insurance; 073 – Management; 075 – Marketing; 076 – Entrepreneurship, Trade and Exchange Activities; 101 – Ecology; 133 – Sectoral Engineering; 201 – Agronomy; 202 – Plant Protection and Quarantine; 203 – Horticulture and Viticulture; 204 – Technology of Production and Processing of Livestock Products; 205 – Forestry; 206 – Park and Gardening Management; 208 – Agricultural Engineering; 211 – Veterinary Medicine
(Order of the Ministry of Education and Science of Ukraine No. 1166 of December 23, 2022)

The journal is presented international scientometric databases, repositories and scientific systems: Institutional Repository of Polissia National University, AGRICOLA, CAB Abstracts and Global Health (CABI), Register of Scientific Publications of Ukraine, Vernadsky National Library of Ukraine, Crossref, ERIH PLUS, International System for Agricultural Science and Technology (AGRIS), Dimension, Polska Bibliografia Naukowa, Google Scholar, Ulrichsweb Global Serials Directory, UCSB Library, EBSCO, Scopus, University of Oslo Library, University of Hull Library, SOLO – Search Oxford Libraries Online, European University Institute, Leipzig University Library, Cambridge University Library, OUCI (Open Ukrainian Citation Index), Worldcat, CORE, COPE, Litmaps

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НАУКОВІ ГОРИЗОНТИ

Том 28, № 10
2025

НАУКОВИЙ ЖУРНАЛ
Засновано 12 березня 1998 р.
Періодичність випуску: дванадцять разів на рік

Редакційна колегія

SCIENTIFIC HORIZONS

Vol. 28, No. 10 2025

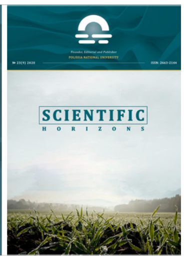
SCIENTIFIC JOURNAL
Year of establishment: Since March 1998.
Publication frequency: Twelve times a year

Editorial Board

ЗМІСТ

CONTENTS

SCIENTIFIC HORIZONS
Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 28(10), 9-20
UDC [619:579.8]:638.1 DOI: 10.48077/scihor10.2025.09



Experimental investigation of the antimicrobial activity of the preparation and its influence on the viability of honey bees (*Apis mellifera*)

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Article's History:
Received: 12.06.2025
Revised: 02.09.2025
Accepted: 24.09.2025

Abstract. The epizootic spread of bacterial infections in apiculture, intensified by the phenomenon of colony collapse disorder, necessitates the development of new and safe preventive agents. Due to legislative restrictions on the use of antibiotics, priority is given to the study of antiseptics with immunomodulatory properties. The aim of this work was a comprehensive assessment of the effectiveness of the preparation *Kombiyod*, namely the determination of its antimicrobial activity *in vitro* and the establishment of optimal safe concentrations to enhance the viability of honeybees *in vivo*. The study included the disc diffusion method using pure strains of enterobacteria and mixed microbial cultures isolated from diseased bees *in vitro*, as well as a cage experiment evaluating the viability and physiological state of bees when the preparation was added to sugar syrup (0.01-2.05%) *in vivo* under laboratory conditions. The results demonstrated the bacteriostatic efficacy of the preparation *in vitro* at concentrations of

Suggested Citation:
Zastulka, M., Romanishina, T., Lakhman, A., & Galatiuk, O. (2025). Experimental investigation of the antimicrobial activity of the preparation and its influence on the viability of honey bees (*Apis mellifera*). *Scientific Horizons*, 28(10), 9-20. doi: 10.48077/scihor10.2025.09.

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0.1-0.5%. A dose-dependent effect was observed in bees under laboratory conditions: concentrations of 0.5-2.05% caused acute toxicity with a mortality peak on the 7th day, whereas optimal concentrations of 0.05-0.1% exhibited a stimulating effect – maximum lifespan of 17-18 days, a 25% increase in viability compared to the control, and a probable immunomodulatory effect associated with iodine deficiency correction. Based on the obtained results, a 0.1% solution of the preparation in sugar syrup is recommended for oral administration and a 0.2% aqueous solution for hive sanitation in the presence of bees. The therapeutic concentration range has been established for further research. The findings may serve as a foundation for developing new prevention schemes of bee bacterioses based on iodine-containing preparations, considering the identified dose-dependent effects

Keywords: honeybees (*Apis mellifera*); povidone-iodine; antimicrobial activity; enterobacteria; microbiological studies; bee viability; immunomodulatory effect

INTRODUCTION

The decline in the population of honeybees (*Apis mellifera*) represents one of the most acute challenges in modern agricultural production, as the stability of pollination and global food security depend directly on the health of these insects. The mass losses of bee colonies, known as Colony Collapse Disorder (CCD), are of a multifactorial nature, combining biological, toxicological and microbiological factors. According to the findings of B. Mohammadian *et al.* (2024), the primary causes of this phenomenon include dysbiosis of the gut microbiota, pesticide burden and a decline in immune resistance, which together lead to the progressive weakening of colonies. Similar conclusions were drawn by G. Singh and A. Rana (2025), who emphasised that the economic losses caused by colony collapse reach hundreds of millions of dollars, with global ecological consequences.

Bacterial infections remain among the key factors contributing to brood mortality and reduced productivity in honeybees. M. Alburaki *et al.* (2024) reported that American and European foulbroods were detected in more than half of the apiaries examined across the USA, and their pathogens exhibited antibiotic resistance. Comparable results were obtained by S. Yakan *et al.* (2025) in Turkey, where the combination of bacterial infections and pesticide exposure led to increased colony mortality. Ukrainian researchers O. Galatyuk *et al.* (2020) also noted the high resistance of enterobacteria isolated from diseased bees to conventional disinfectants, which complicates the effective prevention of bacterial diseases in apiaries.

Due to legislative restrictions on the use of antibiotics in apiculture, the development of alternative antimicrobial agents has become a particularly relevant direction. According to R. Dinata *et al.* (2023), bee-derived bioactive peptides demonstrate a broad spectrum of antibacterial activity; however, their industrial application is limited by structural instability. Meanwhile, A. Truong *et al.* (2023) demonstrated that the use of probiotic *Lactobacillus* strains reduces larval mortality during *Paenibacillus larvae* infection, although the effect depends on the specific strain combination and environmental temperature. M. Damico *et al.* (2025) found that commercial probiotic formulations do not always ensure consistent outcomes, highlighting the need for compounds with prolonged antimicrobial effects.

One of the most promising approaches involves the use of iodine-containing antiseptics, which combine bactericidal and immunomodulatory properties. G. Kampf (2024) notes that povidone-iodine provides effective disinfection through the controlled release of active iodine, acting against a wide range of pathogens without inducing resistance. According to J. Meehan (2025), povidone-iodine solutions exhibit potent antimicrobial activity even at low concentrations and do not cause damage to animal cellular structures. At the same time, M. Karbownik-Lewińska *et al.* (2022) stress the importance of maintaining optimal dosages, as excessive iodine intake can affect the endocrine system through the activation of oxidative stress.

Ukrainian researchers have made a significant contribution to the study of iodine-containing preparations in veterinary medicine. D. Demyanenko *et al.* (2021) demonstrated the efficacy of the preparation *Kombiyod* in disinfecting poultry farm water systems without signs of toxicity and with the preservation of high bactericidal activity even at low concentrations. The advantages of such preparations lie in their broad-spectrum activity: they act against Gram-positive and Gram-negative bacteria, fungi, spores and viruses, without promoting pathogen habituation. As noted by I. Tlak Gajger *et al.* (2024), iodine-containing antiseptics effectively suppress *P. larvae* under laboratory conditions, indicating the feasibility of their application for hive sanitation. Given the proven effectiveness of *Kombiyod* in poultry and aquaculture, investigating its impact on the microflora and viability of honeybees represents a logical continuation of scientific inquiry in the field of safe antimicrobial technologies.

Thus, scientific interest in the study of the antiseptic properties of povidone-iodine and in determining its safe concentrations in apiculture is driven by the need to identify effective antibiotic alternatives capable not only of controlling pathogenic microflora but also of supporting the physiological state of bees. At present, there is a lack of comprehensive studies that simultaneously evaluate the antimicrobial activity of preparations *in vitro* and their effects on bee viability *in vivo*. Therefore, the aim of this study was to investigate the effects of various concentrations of *Kombiyod* on pathogenic enterobacteria *in vitro* and on the viability of honeybees *in vivo*.

MATERIALS AND METHODS

A mixed microbial association isolated from hives where bees exhibited signs of dysbiosis, along with pathogenic enterobacterial cultures of *Klebsiella pneumoniae* and *Klebsiella (Enterobacter) aerogenes*, was used for the study. The cultures were obtained from diseased colonies originating from various apiaries in the north-western region of Ukraine. Pure cultures of enterobacteria (*Klebsiella pneumoniae*, *Klebsiella (Enterobacter) aerogenes*) were identified at the Research Laboratory of the Department of Veterinary Epidemiology, Faculty of Veterinary Medicine, Polissia University, and the State Institution "Zhytomyr Regional Laboratory Centre of the Ministry of Health of Ukraine". The studied cultures are maintained at a temperature of 5-7°C at the Department of Veterinary Epidemiology, Faculty of Veterinary Medicine, Polissia University.

At the first stage of the study (*in vitro*), the effect of *Kombiyod* on pathogenic enterobacteria of bees was examined using the disc diffusion method in Petri dishes. The preparation was tested at the following concentrations: 0.01%, 0.05%, 0.1%, 0.2%, 0.3% and 0.5%. The inoculation of test cultures was carried out on Mueller-Hinton Agar (MHA). Distilled water was used for dilution. The disc diffusion test was conducted using sterile absorbent paper discs, which were impregnated with the respective concentrations of the preparation for 30 minutes. Following deep inoculation, the impregnated discs were placed on the surface of solidified MHA media containing the test cultures (Balázs *et al*., 2021). The study was performed in five Petri dishes per culture, with observations made over three consecutive days.

At the second stage of the study (*in vivo*), the effect of *Kombiyod* on mortality dynamics and lifespan of worker bees of the Ukrainian steppe breed (summer generation) was assessed under laboratory conditions. The experiment was conducted on worker bees aged 10-15 days. The influence of the preparation on bee longevity was evaluated in entomological cages by daily monitoring of the insects' physiological state and recording the number of dead bees in each cage (Fig. 1). Each cage was populated with 40 bees, with a total of 10 cages (400 bees). Bees in the control groups were fed native 50% sugar syrup simultaneously with those in the experimental groups. The cages were kept in a thermostat at a temperature of +22 to +24°C and a relative humidity of 50-70%. The experiment continued until the death of the last bee in each cage.

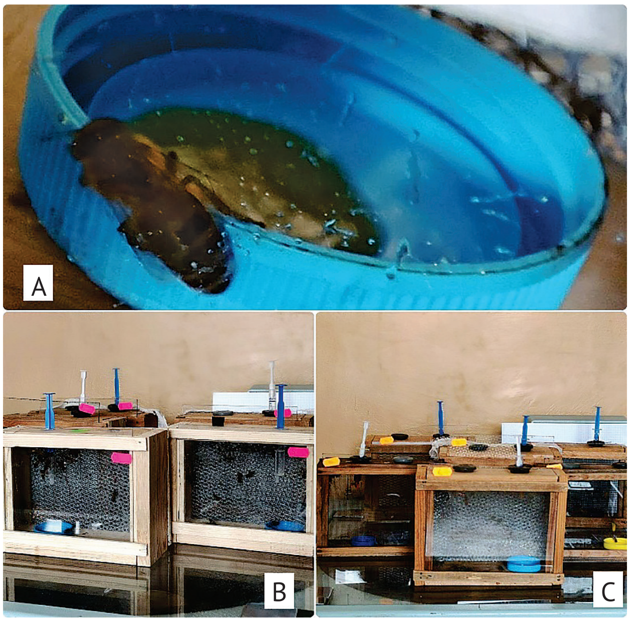

Figure 1. *Determination of the effect of preparations on the lifespan of honeybees under laboratory conditions (in entomological cages)*
Note: *A – consumption of the Kombiyod solution diluted with sugar syrup by bees per os; B, C – appearance of entomological cages populated with experimental bees*
Source: *developed by the authors*

The preliminary stage involved assessing the impact of "high" concentrations of *Kombiyod*: 2.05% (cage 3), 1.7% (cage 4), 1.35% (cage 5), and 1.0% (cage 6), each diluted with sugar syrup (1 part sugar: 1 part water). Cage 1 served as the control for testing high concentrations. During the experiment, these doses demonstrated high toxicity for bees; therefore, further observations were conducted using lower concentrations. The subsequent concentrations tested were 0.5% (cage 7), 0.1% (cage 8), 0.05% (cage 9), and 0.01% (cage 10), also diluted with sugar syrup (1 part sugar : 1 part water). Cage 2 served as the control for the assessment of low concentrations. The solutions were freshly prepared each day and administered in a volume of 4-5 cm^3 per feeding into the feeders of each cage three times daily. The experimental studies involving live honeybees (*Apis mellifera*) were conducted in accordance with the ethical principles of animal research. All procedures were carried out with minimal stress and harm to the bees, in compliance with the Law of Ukraine No. 3447-IV (2006) and international standards and recommendations, including those of the OECD (n.d.).

RESULTS AND DISCUSSION

Honeybees (*Apis mellifera*) are highly sensitive to pathogenic bacteria that can significantly affect their viability and productivity (Motta & Moran, 2024). The present *in vitro* studies indicate the antimicrobial activity of the preparation *Kombiyod* against enterobacteria and demonstrate its potential for protecting bees from bacterial infections in apiculture. The effect of *Kombiyod* on enterobacterial cultures isolated from bees, specifically *Klebsiella pneumoniae* and *Klebsiella (Enterobacter) aerogenes*, as well as on a mixed microbial association, was examined using the disc diffusion method (DDM) on Mueller-Hinton Agar (MHA). The aqueous solutions of *Kombiyod* were tested at concentrations of 0.01%, 0.05%, 0.1%, 0.2%, 0.3%, and 0.5%. Visual changes observed at different concentrations and the manifestation of the preparation's activity on the tested bacterial cultures are presented in Figures 2 and 3. As can be seen from the results displayed in Figures 2 and 3, no bactericidal effect of the preparation was detected against the tested bacterial cultures. A negative bactericidal effect was recorded when the preparation diluted with distilled water was applied at the studied concentrations, both on the first and the third day of *in vitro* observations.

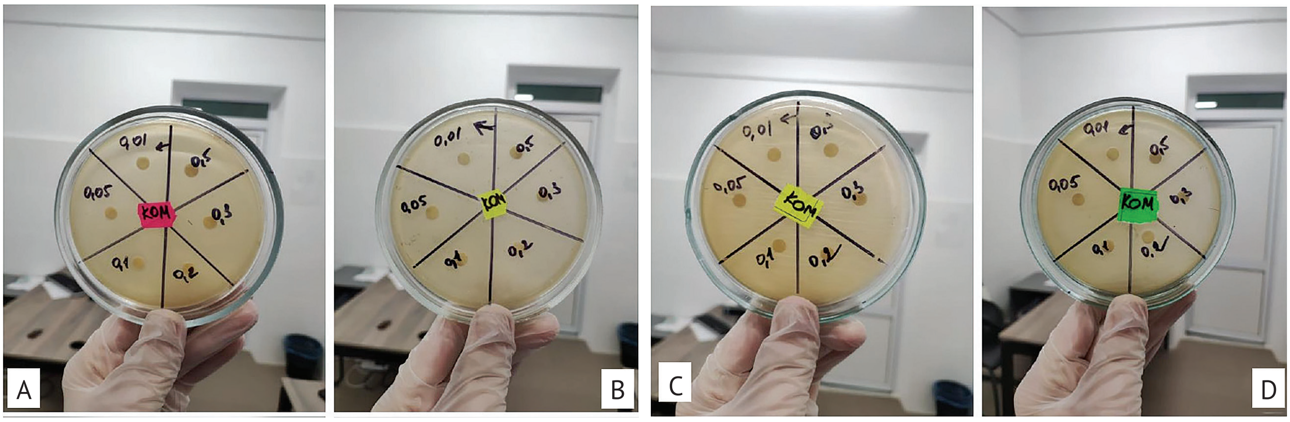

***Figure 2**. Visual changes observed during bacteriological studies of the preparation's activity on the tested bacterial cultures*

***Note:** medium – Mueller-Hinton Agar (MHA); tested concentrations: 0.01%, 0.05%, 0.1%, 0.2%, 0.3%, 0.5%; A – Klebsiella pneumoniae (1 day); B – Klebsiella (Enterobacter) aerogenes (1 day); C, D – mixed microbial association (3 days)*

***Source:** developed by the authors*

At the same time, a bacteriostatic effect of *Kombiyod* was recorded on the first day of the experiment at concentrations of 0.1%, 0.2%, 0.3%, and 0.5%, where growth inhibition of the mixed bacterial culture was observed, indicating the development of bacteriostasis in the pathogenic microorganisms (Fig. 3). These concentrations of the preparation affect pathogenic microorganisms by altering their metabolism, energy exchange, and cellular structure. Such pathogens are no longer capable of exhibiting a high degree of pathogenicity within the host organism; however, they may persist latently and be excreted into the external environment. In this state, the infected organism becomes a bacterial carrier, and such bee colonies continue to serve as a source of infection within the apiary. Therefore, it can be assumed that the treatment of dysbiotic conditions in bees from an affected apiary, following a course of *Kombiyod*, should be continued with the administration of probiotics until complete recovery is achieved.

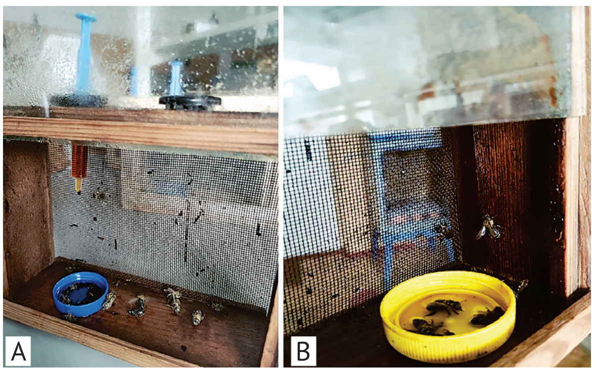

***Figure 3**. Visual changes observed during bacteriological studies of Kombiyod activity against the mixed bacterial culture on Mueller-Hinton Agar (MHA) on the first day of the experiment*

***Note:** concentrations – 0.01%, 0.05%, 0.1%, 0.2%, 0.3%, 0.5%*

***Source:** developed by the authors*

Thus, *Kombiyod* at concentrations of 0.1%, 0.2%, 0.3%, and 0.5% exhibits a bacteriostatic effect against the mixed bacterial culture isolated from hives *in vitro*, where bees showed clinical signs of dysbiosis. Therefore, the preparation represents an environmentally safe therapeutic agent of potential interest for apiculture. The active substance of the preparation is povidone-iodine (polyvinylpyrrolidone-iodine complex) – an iodine-containing polymer compound characterised by pronounced bactericidal properties combined with lower toxicity compared to preparations containing free iodine (Boisson *et al*., 2019: Makhayeva *et al*., 2023). This effect is due to the gradual release of free iodine, which binds to proteins and penetrates through cellular membranes (Eggers, 2019). In the present *in vitro* experiment, at low concentrations (0.01-0.05%), the bacterial test cultures multiplied faster than free iodine was released during the dissociation of povidone-iodine, which explains the absence of both bactericidal and bacteriostatic effects.

At the same time, *Kombiyod* at concentrations of 0.1%, 0.2%, 0.3%, and 0.5% exhibited a bacteriostatic effect against the mixed bacterial culture isolated from hives *in vitro*, where bees presented clinical manifestations of dysbiosis, confirming its potential as an environmentally safe therapeutic preparation. Subsequently, the effect of higher concentrations (1.0%, 1.35%, 1.7%, and 2.05%) of *Kombiyod* on the lifespan dynamics of worker bees of the summer generation was studied in cage experiments under laboratory conditions. The results of the influence of high concentrations of the preparation on caged bees are presented in Table 1. According to the data in Table 1, bees in the control group, which received native sugar syrup, showed mortality as follows: on day 1 – 2 bees (5%), on day 6 – 4 bees (10%), and on day 12 – 7 bees (17.5%). In the subsequent days of the experiment, bees in the control group continued to die daily, with all individuals perishing between the 13^th^ and 17^th^ days of the experiment. Therefore, bees in the first control group survived for a total of 17 days.

Table 1. *Dynamics of bee mortality in cages at different concentrations of Kombiyod in sugar syrup*

Day of experiment	Number of dead bees									
	Control group (1)		Group 3 2.05% *Kombiyod* in sugar syrup		Group 4 1.7% *Kombiyod* in sugar syrup		Group 5 1.35% *Kombiyod* in sugar syrup		Group 6 1.0% *Kombiyod* in sugar syrup	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%
1	2	5	0	0	0	0	0	0	0	0
2	0	0	5	12.5	3	7.5	0	0	2	5
3	0	0	2	5	5	12.5	1	2,5	8	20
4	0	0	0	0	0	0	0	0	3	7.5
5	0	0	5	12.5	5	12.5	4	10	9	22.5
6	4	10	0	0	1	2.5	1	2.5	8	20
7	0	0	13	32.5	9	22.5	3	7.5	3	7.5
8	0	0	5	12.5	3	7.5	1	2.5	0	0
9	0	0	2	5	4	10	4	10	2	5
10	0	0	2	5	6	15	5	12.5	5	12.5
11	0	0	6	15	1	2.5	0	0		
12	7	17.5			3	7.5	6	15		
13	2	5					15	37.5		
14	8	20								
15	11	27.5								
16	4	10								
17	2	5								
Total	**40**	**100**	**40**	**100**	**40**	**100**	**40**	**100**	**40**	**100**

Note: *concentrations – 1.0%, 1.35%, 1.7%, 2.05%*
Source: *developed by the authors*

Studies of bee mortality dynamics at high concentrations of the preparation *Kombiyod* demonstrated that insect mortality was higher compared with the first control group. At concentrations of 2.05% (Fig. 4A) and 1.7%, the maximum lifespan of bees was 11-12 days, accompanied by diarrhoea and subsequent death of the individuals. The highest mortality rate was recorded on the 7^th^ day of the experiment. It is likely that the gradual accumulation of the preparation in the bodies of experimental bees reached critical levels for most individuals during this period. A reduction in concentration to 1.35% did not alter the overall trend in mortality dynamics (Fig. 4B). When *Kombiyod* was administered at a concentration of 1%, a reduction in bee lifespan and a high mortality rate within 3-5 days were observed. This concentration is likely toxic to the experimental insects (cage 6). During observation of the physiological condition of bees in this cage, clustering behaviour was noted, with bees forming a tight cluster on the wall of the cage starting from the third day of the experiment, indicating hyperthermia – a sign of intoxication. In some individuals from this cage, diarrhoea was also observed, visible on the mesh surface of the cage, further confirming the presence of intoxication (Fig. 5A). In contrast, no signs of hyperthermia or diarrhoea were observed in bees from the control cage; the bees remained active and consumed all the syrup provided (Fig. 5B).

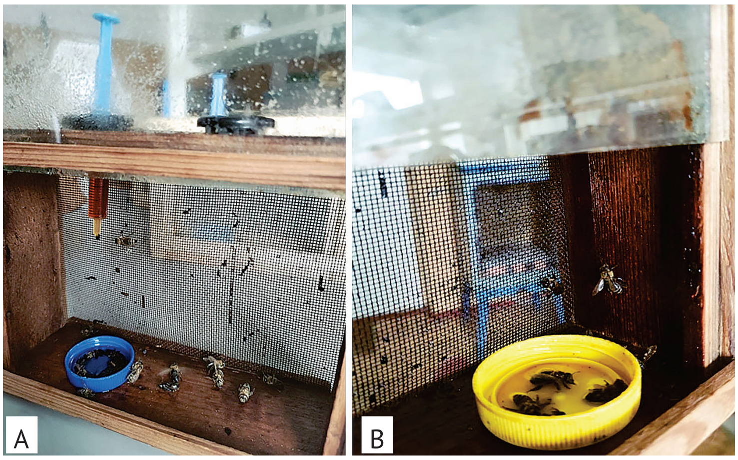

Figure 4. *Physiological condition of experimental insects from cages 3 and 5*
Note: *A – Appearance of bees fed with 2.05% Kombiyod solution diluted with sugar syrup (cage 3, day 7 of the experiment); B – Appearance of experimental bees fed with 1.35% Kombiyod solution diluted with sugar syrup (cage 5, day 7 of the experiment)*
Source: *developed by the authors*

Figure 5. *Physiological condition of insects from the experimental and control groups*
Note: *A – Clustering of experimental bees following administration of a 1% Kombiyod solution diluted with sugar syrup (cage 6, day 3 of the experiment); B – Appearance of bees from the control group (day 3 of the experiment)*
Source: *developed by the authors*

Thus, the consumption of sugar syrup containing *Kombiyod* at concentrations ranging from 1% to 2.05% proved to be acutely toxic, causing symptoms of toxicosis and bee mortality by days 10-12. The subsequent stage of experimental research focused on analysing the effects of lower *Kombiyod* concentrations (0.01%, 0.05%, 0.1%, and 0.5%) on the lifespan of summer-generation worker bees under laboratory cage conditions. It was established that the use of low-concentration *Kombiyod* solutions resulted in an extension of bee lifespan compared with administration of the preparation at higher concentrations. Moreover, the viability of worker bees exposed to low concentrations of *Kombiyod* was longer (at 0.1% and 0.05%) or comparable (at 0.01%) to that of insects from the second control group (Table 2). The physiological state of bees in entomological cages 8 and 9 was characterised by pronounced activity: constant buzzing, absence of anorexia and thirst, rapid movement of bees along the cage walls, and the absence of diarrhoea or depression (Fig. 6).

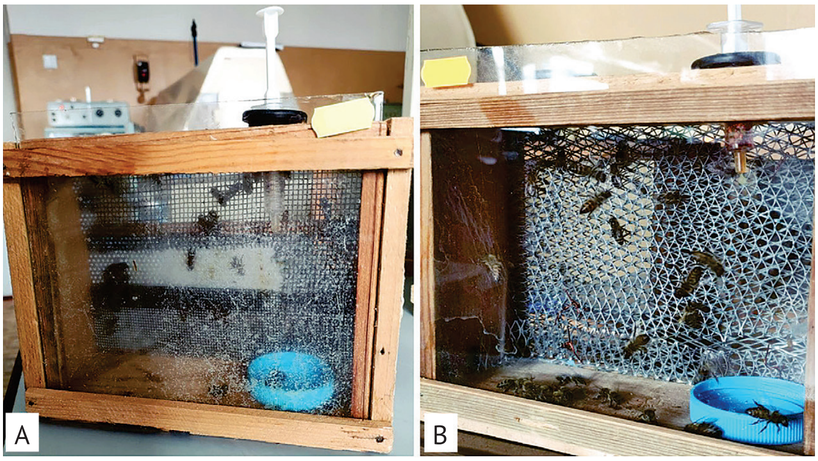

***Figure 6**. Physiological condition of insects from experimental cages 8 and 9*
***Note:** A – Appearance of experimental bees fed with 0.1% Kombiyod solution diluted with sugar syrup (cage 8, day 10 of the experiment); B – Appearance of experimental bees fed with 0.05% Kombiyod solution diluted with sugar syrup (cage 9, day 10 of the experiment)*
***Source:** developed by the authors*

***Table 2**. Dynamics of bee mortality in cages with Kombiyod diluted in sugar syrup (0.01%, 0.05%, 0.1%, 0.5%) under laboratory conditions*

Day of experiment	Number of dead bees									
	Control group (2) *n*		Group 7 0.5% *Kombiyod* in sugar syrup		Group 8 0.1% *Kombiyod* in sugar syrup		Group 9 0.05% *Kombiyod* in sugar syrup		Group 10 0.01% *Kombiyod* in sugar syrup	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%
1	0	0	0	0	0	0	0	0	0	0
2	0	0	2	5	2	5	0	0	0	0
3	1	2.5	5	12.5	4	10	2	5	1	2,5
4	1	2.5	1	2.5	1	2.5	0	0	0	0
5	0	0	3	7.5	2	5	0	0	0	0
6	0	0	4	10	2	5	2	5	2	5
7	3	7.5	9	22.5	2	5	1	2.5	1	2.5
8	6	15	8	20	2	5	1	2.5	8	20
9	5	12.5	8	20	2	5	1	2.5	4	10
10	10	25			2	5	1	2.5	7	17.5
11	8	20			7	17.5	4	10	10	25
12	3	7.5			3	7.5	11	27.5	7	17.5
13	3	7.5			2	5	4	10		
14					2	5	6	15		
15					2	5	4	10		
16					2	5	2	5		
17					3	7.5	1	2.5		
18					2	5				
Total	**40**	**100**	**40**	**100**	**40**	**100**	**40**	**100**	**40**	**100**

***Source:** developed by the authors*

Changes in the trends of bee mortality dynamics and lifespan may be associated with the kinetics of iodine release from the complex compound polyvinylpyrrolidone-iodine (Meehan, 2025). From a chemical perspective, the release dynamics of iodine in a 0.1% solution of the preparation reach an equilibrium state, meaning that a stable ratio between chemically bound and free iodine is maintained. Disruption of this equilibrium occurs depending on the depletion of one of the compound's components. The release of iodine therefore proceeds gradually, as the available free iodine is consumed (Turganbay *et al.*, 2025). Consequently, no abrupt imbalance in concentration occurs, which creates favourable conditions for the preparation's physiological effect on the organism of experimental bees under laboratory conditions.

The optimal disinfectant concentration providing the longest lifespan and best physiological condition of bees was determined to be 0.1%, as confirmed by the obtained experimental data (Fig. 6A). Thus, the most "favourable" concentrations for the insects were 0.1% and 0.05%, at which the preparation exhibited a stimulating effect, improving the viability of experimental bees under laboratory conditions. The lifespan of bees in these cages was maximal, lasting 17-18 days. Further reduction of the solution concentration led to mortality and lifespan indicators approaching those of the control group, suggesting a weak physiological impact of the preparation on the experimental insects. Conversely, the use of higher concentrations ranging from 0.5% to 2.05% resulted in rapid death due to the toxic effects of the preparation. A relatively high concentration of 0.5% at this stage of the experiment demonstrated a clear tendency towards toxicity: bees in group seven survived for only nine days – four days less than the bees in the control group (Fig. 7).

***Figure 7**. Physiological condition of insects from experimental cages 7 and 10*
***Note:** A – Appearance of experimental bees fed with 0.5% Kombiyod solution diluted with sugar syrup (cage 7, day 7 of the experiment); B – Appearance of experimental bees fed with 0.01% Kombiyod solution diluted with sugar syrup (cage 10, day 8 of the experiment)*
***Source:** developed by the authors*

The active substance of *Kombiyod* is povidone-iodine (polyvinylpyrrolidone-iodine complex), an iodine-containing polymer compound possessing bactericidal properties while exhibiting lower toxicity compared with free iodine formulations. This is attributed to the controlled release of free iodine, which binds to proteins and penetrates cellular membranes. The molecular structure of the polymer forms steric barriers that restrict substance transport through biological membranes, thereby reducing systemic toxicity (Verwold *et al*., 2021). The toxicity of povidone-iodine is likely associated with several mechanisms of action: poisoning by free iodine, leading to inactivation or degradation of structural and enzymatic proteins, disruption of protein and nucleic acid synthesis, impairment of excretory system function, induction of epithelial cell apoptosis, and disturbances in the intestinal microbiota balance of bees (Lepelletier *et al*., 2020). On a molecular level, toxicity involves oxidation of sulfhydryl groups in enzymes and structural proteins by free iodine, resulting in loss of their functional activity (Shi *et al*., 2024). The inhibition of macromolecular synthesis is related to oxidative stress induction and nucleic acid damage (Karbownik-Lewińska *et al*., 2022). Epithelial toxicity manifests through activation of the caspase cascade (Wang *et al*., 2022), while microbiome disturbances arise due to the non-selective antiseptic action of the compound (Chen *et al*., 2024). The bactericidal activity of *Kombiyod* ensures the prevention of bacterial, helminthic, viral, and protozoal infections. In addition, its application contributes to the correction of iodine deficiency in bees, an important factor for maintaining metabolic homeostasis (Morthorst *et al*., 2023). The obtained results suggest that the preparation also exhibits immunomodulatory properties, likely realised through two interrelated mechanisms: enhancement of bacterial toxin neutralisation followed by the induction of anatoxin formation (Yu *et al*., 2022).

Modern research into infectious diseases of honeybees demonstrates an integration of microbiological, toxicological, and immunological approaches to assessing colony health. G. Peña-Chora *et al.* (2023) emphasise that American and European foulbroods remain the most widespread bacterial infections globally, while the absence of safe antimicrobial agents limits the possibilities for effective prevention. These conclusions confirm the relevance of exploring antiseptic preparations, particularly those based on iodine-containing compounds. B.A. Daisley *et al.* (2023) demonstrated that the development of bacterial infections in bees is closely associated with intestinal dysbiosis, which reduces the colonisation resistance of the organism. S.M. Killam *et al.* (2024) argue that maintaining a stable microbiota is key to sustaining colony health and therefore propose microbial therapeutics as alternatives to antibiotics. The obtained antimicrobial test results confirm the potential for using preparations with selective bacteriostatic effects that inhibit pathogenic microorganisms without destroying the natural microflora. A similar perspective is expressed by A. Smriti Rana *et al.* (2024), who highlight the importance of combining probiotics with antiseptic agents to achieve long-term remission in cases of bee dysbiosis.

N.S. DesJardins *et al.* (2023) reported that sublethal doses of pesticides can cause cognitive impairments in bees, including reduced learning and orientation abilities. The absence of such effects in laboratory observations when using low concentrations of the iodine-containing preparation indicates its relative safety. R. Hussain *et al.* (2023) proposed silver and zinc nanoparticles as antibiotic alternatives but noted the risk of metal accumulation and toxicity with prolonged exposure. Z.S. Lamas *et al.* (2024) stressed that mass colony losses result not only from infections but also from the combined influence of environmental stressors. A. Brhich *et al.* (2025) similarly noted the synergistic interaction between pesticides and bacterial agents, which increases the risk of colony collapse. In this context, the toxic effect of high concentrations of iodine-containing compounds may be regarded as a model for studying the combined impact of chemical stress on bee physiology. Meanwhile, S. Nekoei *et al.* (2023), in a systematic review, questioned the efficacy of chemical disinfectants and recommended focusing on biological approaches. However, the present experimental data demonstrate that, within the therapeutic concentration range, the antiseptic can be both safe and effective.

Several researchers adopt contrasting positions. L. Silva Morais *et al.* (2023) consider genetic selection of resistant bee lines the primary means of preventing diseases, while M.A. Aziz and S. Alam (2024) suggest prioritising the enhancement of natural resistance rather than relying on chemical agents. Although these approaches possess undeniable scientific value, they do not provide a rapid reduction in pathogenic load under practical apiary conditions. Experimental data on the dose-dependent activity of the iodine-containing preparation confirm the feasibility of a combined approach that integrates antiseptic action with the maintenance of physiological balance in the bee organism. M. Zhyla *et al.* (2024) reported that *Kombiyod* in low doses improves morphofunctional parameters in poultry, indicating a potentially universal mechanism of polymeric iodine action. These findings support the hypothesis that the preparation may exert immunomodulatory properties and enhance resistance to bacterial infections across various animal species.

The synthesis of literature data allows the conclusion that polymeric iodine-based antiseptics can combine bactericidal, anti-inflammatory, and immunocorrective properties. The demonstrated effectiveness of *Kombiyod* at low concentrations confirms its potential for preventive use in apiculture as a safe alternative to antibiotics in the control of bacterial infections.

CONCLUSIONS

Bacteriostatic effects were established when *Kombiyod*, diluted with distilled water, was applied *in vitro* at concentrations of 0.1%, 0.2%, 0.3%, and 0.5% against a mixed bacterial culture isolated from hives where bees exhibited clinical signs of dysbiosis. High concentrations of *Kombiyod* ranging from 0.5% to 2.05%, when administered to bees with sugar syrup, caused acute toxicosis, with the highest mortality rate observed on the seventh day. The lifespan of bees in these groups was 11-12 days. Such concentrations of *Kombiyod* are classified as toxic and unsuitable for use in the presence of bees. It was determined that the most acceptable concentrations for bees are 0.05% and 0.1%. The administration of the preparation in these doses with sugar syrup exhibited a stimulating effect, resulting in the maximum mean lifespan of 17-18 days – 4-5 days (approximately 25%) longer than that of the control group – demonstrating a significant improvement in bee viability. For the prevention and treatment of infectious diseases in bees, it is recommended to administer a 0.1% solution of *Kombiyod* in 50% sugar syrup, or to apply a 0.2% aqueous solution for spraying bees and combs as stimulating doses of the preparation. Further experimental studies are planned to assess the therapeutic efficacy of 0.1% and 0.2% *Kombiyod* solutions in apiaries affected by infectious bee diseases.

ACKNOWLEDGEMENTS

The authors express their sincere gratitude to A.V. Berezovskyi, Chairman of the Supervisory Board of LLC “BrovaFarma”, for valuable consultations and for providing the preparation *Kombiyod* for experimental testing.

FUNDING

None declared.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Експериментальні дослідження антимікробної активності препарату та його впливу на життєздатність медоносних бджіл

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Анотація. Епізоотія бактеріальних інфекцій у бджільництві, посилена явищем колапсу бджолиних сімей, вимагає розробки нових та безпечних профілактичних засобів. Через законодавчі обмеження застосування антибіотиків пріоритетним напрямком є дослідження антисептиків з імуномодулюючими властивостями. Метою роботи стала комплексна оцінка ефективності препарату «Комбійод», а саме – визначення антимікробної активності *in vitro* та встановлення оптимальних безпечних концентрацій для підвищення життєздатності бджіл *in* vivo. Дослідження включало диско-дифузійний метод з використанням чистих штамів ентеробактерій та змішаної культури мікрофлори від хворих бджіл *in vitro*, а також садковий експеримент з оцінки життєздатності та фізіологічного стану бджіл при додаванні препарату до цукрового сиропу (0,01-2,05 %) *in vivo* у лабораторних умовах. Встановлено бактеріостатичну ефективність препарату *in vitro* при концентраціях 0,1-0,5 %. Виявлено дозозалежний ефект у бджіл в умовах лабораторії: концентрації 0,5-2,0 5 % викликають гостру токсичність з піком смертності на 7 добу, тоді як оптимальні концентрації 0,05-0,1 % демонструють стимулюючу дію – максимальну тривалість життя 17-18 діб, підвищення життєздатності на 25 % відносно контролю та ймовірний імуномодулюючий ефект із корекцією йодного дефіциту. На підставі отриманих результатів рекомендовано 0,1 % розчин засобу в цукровому сиропі для перорального застосування та 0,2 % водний розчин для санації гнізда в присутності бджіл. Встановлено терапевтичний діапазон концентрацій для подальших досліджень. Отримані результати можуть бути основою для розробки нових схем профілактики бактеріозів бджіл на основі йодовмісних препаратів з урахуванням виявленої дозозалежності їхньої дії

Ключові слова: медоносні бджоли (Apis mellifera); повідон-йод; антимікробна активність; ентеробактерії; мікробіологічні дослідження; життєздатність бджіл; імуномодулючий ефект

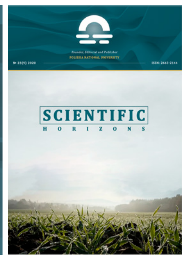
SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 28(10), 21-31

UDC 639.3

DOI: 10.48077/scihor10.2025.21



Current trends and prospects for the development of feed resources in aquaculture

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Article's History:
Received: 19.04.2025
Revised: 22.08.2025
Accepted: 24.09.2025

Abstract. The purpose of the study was to identify trends in changes in the production efficiency of the main groups of fish in aquaculture of Ukraine during 2022-2024 considering the influence of technological, environmental, and economic factors on the efficiency of feeding and the development of the feed base. The methodology was based on systematic, statistical and comparative analysis of data from twelve fish farming enterprises representing different levels of intensification – from pond farms to enterprises with closed water supply systems (CWSS). The analysis covered a five-year period (2020-2024) using correlation and regression analysis methods to assess feed conversion rate (FCR), cost-effectiveness, and the impact of environmental factors on productivity. As a result of the study, significant fluctuations in feed consumption volumes and interspecific differences in FCR values were established. It was revealed that the minimum feed costs occurred in 2022 (23,327.3 tonnes), and the maximum – in 2020 (34,243.3 tonnes), which is conditioned by economic and military instability. Carp species demonstrated the highest feed conversion efficiency, with FCR for broodstock and commercial fish falling to 1.2 and 1.3, respectively, in 2024. Catfish have consistently high FCR values, indicating low feeding efficiency for this group. Sturgeon showed a sharp deterioration in feed efficiency in 2023-2024 due to technological failures and the feed base degradation. Salmon showed extreme fluctuations with a record high FCR of 3.5 in 2023 and a sharp improvement to 1.0 in 2024, indicating a technological adaptation of production. It was generalised that a high FCR in a broodstock is not only a current economic loss, but also an indicator of future decline in offspring productivity, so feeding optimisation should be based on the use of functional feeds and precise control technologies. The practical significance of the study lies in the possibility of using the results obtained to develop strategies

Suggested Citation:
Lavryniuk, O., & Matkovska, S. (2025).Current trends and prospects for the development of feed resources in aquaculture. *Scientific Horizons*, 28(10), 21-31. doi: 10.48077/scihor10.2025.21.

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for rational management of feed costs in fisheries enterprises of Ukraine, which will contribute to increasing the profitability and environmental sustainability of aquaculture production

Keywords: feed conversion rate (FCR); fish farms; fish feeding; broodstock and replacement stock; commercial fish

INTRODUCTION

The dev

According to review by C. Ai *et al.* (2025), in world practice, research in the field of fish nutrition is aimed at optimising the composition of feed, improving the protein-energy ratio, and reducing the loss of nutrients during feeding. The researchers emphasised that the key priorities were to increase the efficiency of feed use (reducing the FCR indicator) and minimise the impact on the environment. A similar opinion was expressed by C. Boyd and A. McNevin (2023), who emphasised that it is systems with high FCR that are the main source of excessive resource consumption and eutrophication of water bodies. According to the researchers, effective management of feed costs is not only an economic, but also an ecological category that determines the sustainability of aquaculture production.

The issue of finding alternative protein sources remains central to current research. V. Serra *et al.* (2024) analysed the possibilities of replacing fish meal with plant and microbiological proteins, emphasising that the use of local raw materials can reduce dependence on imports and increase economic profitability. A significant contribution to the development of this area was made by R. Fantatto *et al.* (2024), who proved that insect protein has a high digestibility potential and has a positive effect on fish growth, reducing the feed conversion rate by 12-18%. Additionally, N. Yadav *et al.* (2025) emphasised that the integration of insect protein into mixed feeds is not only an environmentally sustainable solution, but also allows creating high-performance functional feeds. B. Glencross *et al.* (2024) reviewed the evolution of sustainability indicators in the marine ingredients sector, highlighting the need to move to "closed cycles" in feed production and reduce the carbon footprint through processing by-products of the fishing industry. L. Li *et al.* (2025) proved that the use of fermented food industry waste as a substrate for bioconversion into protein feed mass provides a double effect – reducing the cost of mixed feed and reducing the amount of waste. Another promising area for optimising the feed base is the selective improvement of feed efficiency. A. Kause *et al.* (2022) demonstrated that genetic selection based on FCR in rainbow trout reduced feed consumption by 15% without compromising growth rates. Analysis of morphophysiological factors of Micropterus salmoides by X. Shi *et al.* (2024) found a direct link between genetic growth traits and nutrient uptake efficiency, opening up new perspectives in breeding work with highly productive aquaculture species.

Among Ukrainian researchers, the problem of feed efficiency was actively covered by R. Umanets *et al.* (2023), who summarised the results of global studies on the use of non-conventional protein sources in feeding African sharptooth catfish (*Clarias gariepinus*). The researchers noted that replacing deficient fish meal with vegetable proteins is an effective way to reduce the cost, but requires careful balancing of the amino acid composition so as not to worsen the biological value of the feed. The practical aspect of rational use of feed was also revealed by N. Myskovets (2020), who noted that the fishing industry in Ukraine faces the problem of import dependence in the production of mixed feed and needs to develop a national raw material base. An important addition to the scientific context was the results of the study by M. Klimenko *et al.* (2025), which proved the significant influence of the temperature regime on nitrification processes and the state of the aquatic environment in aquaponic systems. This factor indirectly determines the effectiveness of feeding, because changes in temperature affect fish metabolism and nutrient bioavailability. In Ukrainian conditions with pronounced seasonal variability, this aspect is of particular importance for the development of adaptive feeding strategies.

Generalisation of contemporary scientific approaches shows that the development of the aquaculture feed base is moving towards resource efficiency, biotechnological innovations, and replacement of conventional protein components with alternative sources that can provide a stable increase and decrease in the FCR coefficient. However, the task of developing an economically sustainable feed production system based on local resources and the biological characteristics of cultivated species and regional climatic conditions remains relevant for Ukraine. The purpose of the study was to analyse the dynamics of production indicators of the main groups of fish in aquaculture of Ukraine for 2022-2024, considering factors that determine interspecific differences in feeding efficiency and prospects for optimising the feed base.

MATERIALS AND METHODS

The study was conducted on a combined scientific and practical basis using the methods of system, statistical and comparative analysis. The empirical basis was the data of twelve fisheries enterprises of Ukraine operating in different climatic zones – Poltava, Chernihiv, Sumy, Lviv, and Kyiv oblasts. The sample included both conventional pond farms that use semi-intensive cultivation technologies, and high-tech enterprises using closed water supply systems (CWSS). This approach provided representative coverage of different levels of aquaculture intensification and allowed investigating the effect of the type of production on feeding efficiency.

The chronological limits of the study covered 2020-2024, which allowed tracing the five-year dynamics of changes in feed use, feed conversion rate (FCR), and production structure of the main fish groups. The main source of primary data was technological logs and accounting documents of farms, which contained information on feed consumption, average weight of livestock, growth and volume of production. Secondary data was obtained from official statistical materials of the State agency of Ukraine for the development of land reclamation, fisheries and food programme (forms No. 1-Fish, No. 2-Aqua, reporting bulletins for 2020-2024) (n.d.), and from industry analytical reports (Report on research work…, 2022).

The objects under study were classified into three main categories: juveniles – fish in their first year of life with an average weight of up to 0.1 kg; broodstock and replacement stock – breeding individuals used for reproduction; commercial fish – fish weighing more than 0.5 kg, grown to marketable size. This systematisation corresponds to the classical principles of fish farming and breeding provided by I. Sherman *et al.* (1999). The following indicators were determined for each category:

1. Absolute weight gain of fish (Δw, kg);
2. Feed consumption per unit of production (t/t);
3. Share of expenses by category (%);
4. Feed conversion rate (FCR) calculated using the equation:

$$FCR = \frac{Wf}{Wg}, \quad (1)$$

where *Wf* – weight of feed consumed, kg; *Wg*w – fish weight gain, kg.

A lower FCR value indicates a higher feed efficiency. The analytical part of the study was performed using specialised software Statistica 13.5 and Microsoft Excel 365. Correlation (R-Pearson) and regression analysis methods were used to identify statistically significant dependencies. The reliability of interannual differences was checked using the Student's t-test at the significance level $p < 0.05$. Additionally, comparative modelling of the economic efficiency of various feed strategies was carried out by estimating the ratio between FCR and the cost of grown products. Environmental and technological factors that may affect feeding efficiency were considered to ensure a comprehensive assessment. These factors included water temperature, dissolved oxygen concentration, ammonium nitrogen, nitrites, phosphates, and pH of the medium. Hydrochemical parameters were determined in accordance with the current state standards for aquaculture (Law of Ukraine No. 400, 2010).

The methodological basis of the study was an integrated approach that combines quantitative analysis of feed efficiency dynamics with a critical assessment of industry trends. In the course of the study, methods of descriptive statistics, dynamic analysis for tracking interannual changes and comparative analysis for interspecific assessment of feed efficiency were used. Correlation and regression models allowed establishing relationships between FCR, fish weight growth, and feed costs for different groups of aquaculture facilities. Ethical aspects of the study were considered in accordance with the provisions and recommendations of the Food and Agriculture Organisation of the United Nations (2025). All data were collected without interfering with the physiological state of fish, in compliance with the principles of bioethics and confidentiality of economic information.

RESULTS AND DISCUSSION

Analysis of the dynamics of feed consumption in the fisheries sector during 2020-2024 revealed significant fluctuations in the total volume, which indicates instability of production processes (Table 1).

Table 1*. Analysis of feed use in fish farms of Ukraine by fish categories, tonnes*

Years	Total	fish categories		
		juveniles	broodstock	commercial fish
2020	34,243.3	7,941.6	738.9	25,562.7
2021	28,454.5	6,336.5	1,263.4	20,854.5
2022	23,327.3	5,335.1	717.0	17,275.1
2023	28,770.9	10,007.6	593.2	18,265.9
2024	29,493.4	8,062.2	743.8	20,687.4

Note: *the initial statistics were based on official data from the State agency of Ukraine for the development of land reclamation, fisheries and food programme (n.d.) and generalised materials of the report (Report on research work…, 2022), which ensured the reliability of the initial analysis parameters*
Source: *compiled by the authors*

Fluctuations in total feed costs were significant: the minimum value was recorded in 2022 (23,327.3 tonnes), probably due to the devastating impact of military operations and economic instability, while the maximum was in 2020 (34,243.3 tonnes). This dynamic is conditioned by a number of factors, in particular, changes in production volumes, technologies, availability and prices for feed, and external economic and environmental conditions. Spending on juvenile fish showed high volatility with a sharp increase in 2023 (by 87.58%), which may indicate adjustments in the strategy for raising fish. However, the cost of broodstock, although insignificant, also had noticeable relative changes, probably related to the intensity of breeding or breeding. The largest share of total costs (from 63.49% to 74.65%) was spent on commercial fish, which underlines the critical importance of optimising the feed base and managing these costs to improve overall production efficiency (Fig. 1).

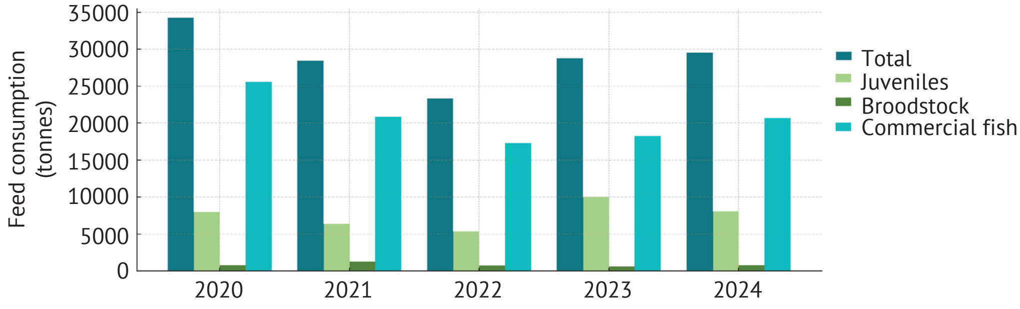


***Figure 1**. Analysis of feed use in fish farms in Ukraine*

***Source:** compiled by the authors*

The results of the analysis indicate the need for constant monitoring and study of factors that affect feed costs. The purpose of such monitoring is to develop effective strategies for improving production processes. This includes: the introduction of advanced feeding methods, the use of high-quality and cost-effective feed, and rapid adaptation to changing market conditions and strict environmental requirements. The findings confirm the critical importance of feed rationalisation and cost management for increasing overall efficiency. It should be remembered that feed costs are one of the most significant components in the cost of grown fish, directly affecting the profitability of fish farms. The broodstock showed a slight temporary drop in weight in 2023, followed by recovery, while feed costs were stable. However, the FCR worsened significantly in 2023, indicating a temporary decline in feed efficiency, although the indicator improved slightly in 2024. The juvenile category, on the contrary, showed high stability: a slight decrease in weight and an increase in spending in 2023 was replaced by an increase in weight and a decrease in spending in 2024. Its FCR remained low throughout the entire period, confirming the high efficiency of feed assimilation by juvenile fish. The commercial fish category was marked by a significant increase in weight throughout the study, especially intensive in 2023-2024, which, quite logically, was accompanied by an increase in feed costs. The FCR was relatively stable at a moderate level, although its slight increase in 2024 may indicate a slight decrease in feeding efficiency in the final stages of cultivation.

Feed conversion rate (FCR) is a key indicator that shows how many kilogrammes is required to spend to get 1 kilogramme of fish weight gain. A lower FCR means higher economic efficiency (Table 2).

***Table 2**. Feed conversion rate indicators*

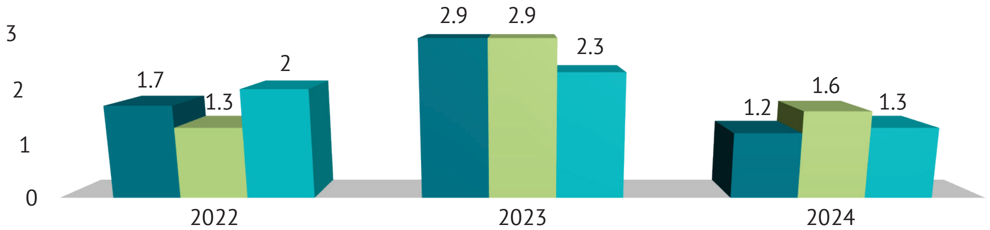
Category	FCR dynamics (2022-2024)	FCR level efficiency	Category
Juveniles	Stable	The most effective group	Juveniles
Commercial fish	Relatively stable	The efficiency is satisfactory	Commercial fish
Broodstock	Increased	Least effective	Broodstock

***Source:** compiled by the authors*

The best efficiency of feed use during 2022-2024 was demonstrated by the juvenile category due to the consistently low FCR value. The broodstock is of the greatest concern, where a significant increase in FCR in 2023 indicates the need to review the feed composition or feeding regime for this group to increase profitability. The analysis clearly shows the need for constant and detailed monitoring of all factors affecting feed costs, and the development of targeted strategies for optimising production processes. This optimisation should include the introduction of advanced and efficient feeding technologies, the use of high-quality and cost-effective feed products, and flexible adaptation to changing market realities and strict environmental standards. It is worth noting that feed costs make up the most significant part of the cost of farmed fish, which makes them a key lever of influence on the economic efficiency of any fisheries.

A high feed conversion rate (FCR) in broodstock is a wake-up call, as it means that the fish is receiving an unbalanced diet or has problems effectively absorbing key nutrients. This directly leads to a deterioration in the quality of sexual products. In particular, a lack of vital nutrients, such as omega-3 fatty acids and vitamins E and C, causes the accumulation of insufficient reserves in caviar. As a result, the fertilisation rate of eggs decreases sharply, its overall quality decreases, and the yield of viable larvae decreases significantly. In addition, nutrient deficiencies negatively affect the subsequent stages of development, causing a decrease in the survival rate of embryos and larvae. Caviar that does not have sufficient energy reserves does not go well through critical stages of development. This leads to high mortality at the embryonic stage, frequent deformities in larvae (e.g. curvature of the spine) and low resistance to disease at an early age. Thus, inefficient feeding of the broodstock actually creates weak, vulnerable, and unviable offspring. Even those larvae that survive show slower growth of juveniles and worse health indicators compared to those from parents who had sufficient nutrition. This slow initial growth directly extends the time frame for fish to reach marketable weight, which, in turn, reduces the economic efficiency of the farm in the long term. Therefore, high FCR in broodstock is far more than just feed wastage; it is an investment in low productivity and future losses due to the weakness of the next generation of fish.

Analysis of quantitative data on carp fish production for 2022-2024 revealed heterogeneous dynamics of key production parameters. In particular, significant annual fluctuations in the total weight of broodstock and replacement stock were observed. This instability can be caused both by adjusting the strategy for establishing the breeding core of the farm, and by the influence of various external factors. At the same time, the feed conversion rate (FCR) indicators for different age groups of carp fish also show high dynamism (variability) (Fig. 2).



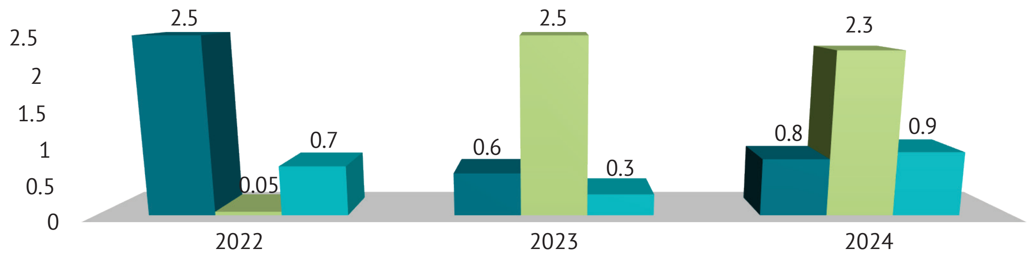
	2022	2023	2024
Broodstock and replacement stock	1.7	2.9	1.2
Juveniles	1.3	2.9	1.6
Commercial fish	2	2.3	1.3

***Figure 2**. Feed conversion rate of carp species*

***Source:** compiled by the authors*

In 2024, there was a statistically significant improvement in the feed conversion rate (FCR) for two key groups: broodstock (decrease to 1.2) and commercial fish (decrease to 1.3) compared to previous years. This clearly indicates an increase in the efficiency of using feed resources in these categories. Simultaneously, the FCR for juvenile fish, although it showed positive dynamics in 2024 (1.6) compared to the problematic year 2023 (2.9), it remained higher than in 2022 (1.3). This fact indicates the presence of potential reserves for further optimisation of both diets and holding conditions in this age group. The sharp increase in the absolute weight of juveniles and commercial fish in 2024 is probably a direct consequence of the increase in breeding stock and the overall improvement in reproduction rates. However, a more in-depth statistical analysis is needed to establish accurate causal relationships between these parameters and to accurately predict future production dynamics. Such an analysis must necessarily consider potential correlations between the studied indicators, and the external influence of environmental and technological factors. Thus, the data obtained indicate the development of positive trends in the production of carp fish in 2024. These trends are expressed in an increase in total production volumes and simultaneously an increase in the efficiency of feed use for the most important production groups. Further scientific research should focus on identifying specific factors that determine the observed dynamics, and on developing evidence-based recommendations to ensure the sustainable development of the entire industry.

Analysis of quantitative indicators of catfish production for the period 2022-2024 revealed significant instability of key production parameters (Fig. 3). The weight of broodstock and replacement stock shows unstable dynamics: after growth in 2023, there was a decrease in 2024 to the level of 2022. Feed costs for this group also vary greatly and do not always directly correlate with changes in weight. This may indicate an adjustment in the intensity of feeding or changes in the composition of diet. The feed conversion rate (FCR) for broodstock was the best (lowest) in 2023 (0.6), which indicates a relatively high efficiency in the use of feed resources during this period.



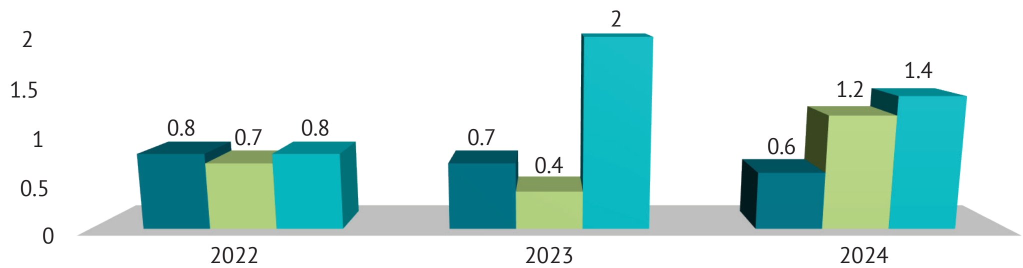
	2022	2023	2024
Broodstock and replacement stock	2.5	0.6	0.8
Juveniles	0.05	2.5	2.3
Commercial fish	0.7	0.3	0.9

***Figure 3**. Feed conversion ratio of catfish species*

***Source:** compiled by the authors*

The production of juvenile catfish is characterised by significant unevenness (interannual fluctuations) both in terms of total weight and in the corresponding feed costs. The feed conversion rate (FCR) for this age group remained relatively high throughout the analysed period, reaching peak values in 2023 (2.5) and 2024 (2.3). Such high FCR values clearly indicate a lower economic efficiency of using feed resources to increase the weight of juvenile fish compared to other categories. This signals the need for an urgent review of the diet and/or rearing conditions to increase digestibility. Commercial fish production showed a steady positive trend towards weight growth in 2023 and 2024 compared to 2022. Logically, feed costs for this growing group also increased, particularly significantly in 2024. The best feeding efficiency score (lowest FCR) was achieved in 2023 (0.3), which is an exceptionally high result. However, in 2024, the FCR increased again to 0.9, approaching the indicator of 2022 (0.7). This increase in FCR indicates a deterioration in efficiency in the final stages of fattening and indicates a potential problem that requires attention. Overall, the dynamics of catfish production during 2022-2024 highlights the high volatility of key operational indicators. Chronically high FCR values for juveniles and worsening FCR values for commercial fish in 2024 outline critical areas for optimising both feeding technologies and overall holding conditions.

Analysis of production indicators of sturgeon fish for the period 2022-2024 revealed complex, ambiguous dynamics in different categories of livestock. The weight of broodstock and replacement stock experienced a statistically significant decrease in 2023 compared to 2022, followed by a partial recovery in 2024. Feed costs correlated with weight changes, showing declines in 2023 and 2024. The feed conversion rate (FCR) for this group remained relatively stable in the narrow range of 0.6–0.8. This indicates a stable efficiency in the use of feed resources, despite fluctuations in total biomass. The production of juvenile sturgeon is characterised by high variability. In 2023, the lowest FCR was recorded (0.4), which may indicate a high growth rate under optimal conditions. However, in 2024, the volume of juvenile fish continued to decline, and the FCR increased sharply to 1.2. This threefold deterioration in efficiency is a direct indicator of destabilisation of technological holding conditions or degradation of the quality/composition of the diet for this sensitive age group (Fig. 4).



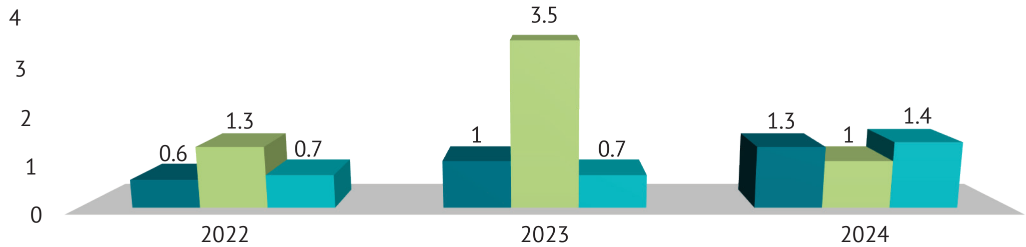
	2022	2023	2024
Broodstock and replacement stock	0.8	0.7	0.6
Juveniles	0.7	0.4	1.2
Commercial fish	0.8	2	1.4

***Figure 4**. Feed conversion ratio of sturgeon species*

***Source:** compiled by the authors*

Production of commercial sturgeon fish showed stabilisation by weight during 2023-2024, but the recorded volumes were significantly lower than in 2022. There was an increase in absolute feed costs for commercial fish both in 2023 and in 2024. This situation has led to a critical increase in the feed conversion rate (FCR). In particular, the FCR indicator in 2023 was 2.0, and in 2024 – 1.4. Both values significantly exceed the 2022 FCR (0.8), which clearly indicates a significant decrease in the efficiency of using feed resources to obtain final marketable products. The decline in the weight of the breeding stock of sturgeon in 2023 is highly likely due to the combined impact of military and economic factors, since sturgeon are sensitive to any failures in intensive aquaculture. Direct military impact included the physical loss of livestock as a result of the destruction of aquaferms and environmental disasters, such as the explosion of the Kakhovka HPP. The indirect economic impact was reflected in the deterioration of the quality of the feed base due to rising prices and logistical problems, which led to the use of less nutritious diets and, as a result, to the loss or slowing of weight gain. In addition, technological failures caused by power outages caused stress in fish in CWSS systems, which also negatively affected their overall condition and biomass.

Analysis of key production indicators in salmon farming for 2022-2024 revealed a high degree of instability and significant fluctuations in all categories, which indicates serious problems in operational processes. The weight of broodstock and replacement stock showed an alarming downward trend in 2023, with a slight, only partial, stabilisation in 2024. In parallel, feed costs for the maintenance of this group were constantly growing. The result was a doubling of the feed conversion rate (FCR): it increased from 0.6 in 2022 to 1.3 in 2024. This indicates a significant drop in the efficiency of using feed resources for the breeding core. The juvenile salmon segment shows extreme changes from year to year, which is the most critical indicator of instability. In 2023, there was a sharp decrease in the weight of juveniles with a simultaneous increase in feed consumption, which led to a critically high FCR (3.5). However, in 2024, the situation changed dramatically: the weight of juveniles increased sharply while significantly reducing feed costs, which provided a record low FCR (1.0). Such a drastic change in the efficiency of cultivation requires an urgent and in-depth analysis of the reasons that led to such drastic changes in technological processes (Fig. 5).



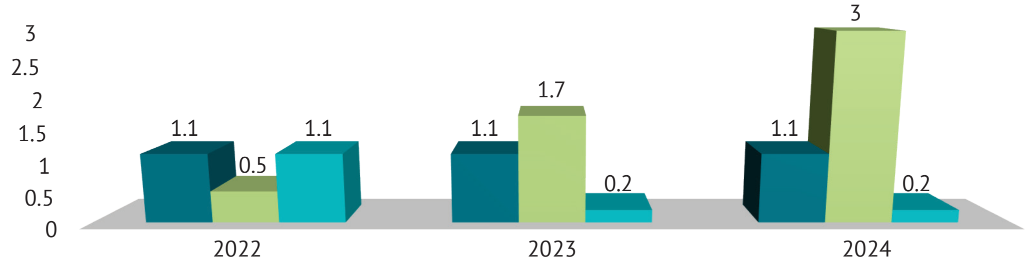
	2022	2023	2024
Broodstock and replacement stock	0.6	1	1.3
Juveniles	1.3	3.5	1
Commercial fish	0.7	0.7	1.4

***Figure 5**. Feed conversion ratio of salmon species*

***Source:** compiled by the authors*

The weight of commercial fish remained relatively stable. However, feeding efficiency significantly worsened in 2024: the feed conversion rate (FCR) doubled, from 0.7 (in 2022-2023) to 1.4, which directly indicates a decrease in the efficiency of using feed resources. The extreme increase in the weight of juvenile salmon in 2024 with a sharp drop in FCR from a critically high 3.5 to a record low of 1.0 is a clear indication of the successful solution of a serious technological or biological problem that existed in 2023 and the achievement of an optimal biological breakthrough. The most likely causes are the correction of a critical deficiency in the feed composition, the elimination of an epizootic problem (disease) that suppressed growth in the previous year, or the introduction of precise control of conditions of keeping (temperature and water quality), which allowed salmon to fully meet its genetic potential. Such a rapid recovery of efficiency, possibly enhanced by the effect of compensatory (catch-up) growth, demonstrates the high potential of the farm for rapid adaptation and effective management.

Juvenile production was characterised by high variability and critical deterioration in efficiency. In 2023, despite a sharp decline in weight, FCR increased to 1.7 (due to increased feed costs). However, in 2024, the situation worsened catastrophically: the weight of juvenile fish continued to fall, and the FCR reached the highest value (3.0), which indicates a significant decrease in the economic efficiency of growing this age group. The production of commercial fish in this group showed a strong positive trend: in 2024, a significant increase in weight was recorded, exceeding the indicators of previous years. The FCR remained extremely low (0.2) in both 2023 and 2024. This exceptionally low FCR indicates a high efficiency of using feed resources to produce marketable products, which is a significant positive trend.



	2022	2023	2024
Broodstock and replacement stock	1.1	1.1	1.1
Juveniles	0.5	1.7	3
Commercial fish	1.1	0.2	0.2

Figure 6. *Total feed conversion ratio in fish*

Source: *compiled by the authors*

The crisis, which was expressed in the growth of the FCR of juvenile fish to 3.0, required urgent and comprehensive intervention aimed at eliminating critical technological failures. Priority actions should include: audit of the feed base with replacement of low-quality batches and correction of the diet to ensure optimal protein digestibility; detailed diagnosis of the epizootic situation and urgent treatment of detected infections or infestations that inhibit growth; and stabilisation of holding conditions, which provides for increased monitoring and correction of water quality (especially oxygen levels and toxic metabolites). Moreover, it was necessary to implement strict feeding control to prevent overfeeding and feed losses, which directly lead to an increased FCR.

The results of the study show that the indicators of the feed conversion rate (FCR) in Ukrainian fishing enterprises have a significant dynamism, which depends on the type of fish, age category, holding conditions, and feed composition. The average value of FCR in the farms under study varied from 1.2 to 1.6 in high-tech closed water supply systems (CWSS) and from 1.4 to 1.8 in pond ones, which corresponds to the level of contemporary world indicators for intensive aquaculture. A similar trend was observed by Y. Li *et al.* (2025), who noted that the use of microbial cultures of *Bacillus licheniformis* and *Yarrowia lipolytica* as part of the feed provided an improved conversion of the protein component and a decrease in FCR by an average of 10-12%. Therefore, the similarity with the results of the current study is that the efficiency of feed conversion increases not only due to the composition of the feed, but also due to microbiological processes that increase the bioavailability of nutrients.

Similar conclusions were obtained by H. Shima *et al.* (2024), O. Adagha *et al.* (2024), who found that controlling the ratio of starches in mixed feeds and the time of their feeding can significantly affect the digestibility of feed and the stability of fish growth. This is consistent with the observations in this paper, where optimisation of the feeding regime allowed reducing FCR fluctuations in the commercial fish category. However, C. Boyd and A. McNevin (2023) noted that excessive restriction of feeding or changing regimens can lead to a decrease in weight gain, which was also partially confirmed in the case of broodstock, where an excessive reduction in feed rates was accompanied by an increase in FCR. Thus, the optimal level of feeding should be based on a trade-off between the growth rate and the efficiency of feed use. Confirmation of the value of technological factors was obtained by J. Thornburg (2025), who showed that automated feed feeding systems improve dosing accuracy and reduce losses by up to 15%. A similar effect was observed in high-tech CWSS farms, where the average FCR value was 0.3 lower than in pond farms. This indicates the crucial role of automation in improving feed efficiency.

An important area of research is the search for alternative protein sources to replace deficient fish meal. V. Serra *et al.* (2024) note that the introduction of plant protein or insects into feed formulations can reduce the cost of feed by 20-25%, but can cause an amino acid imbalance and an increase in FCR without careful balancing of the composition. N. Yadav *et al.* (2025) proved that the use of larval flour of *Hermetia illucens* or *Tenebrio molitor* reduces FCR to 1.0-1.2 while maintaining weight gain. These results are consistent with current data for juvenile catfish, where the lowest FCR was also observed when using functionally enriched feeds with a high protein content. A key factor affecting FCR is the genetic potential of fish. A. Kause *et al.* (2022) showed that breeding based on growth indicators can reduce FCR by 8-10% over two generations of rainbow trout. This approach may be promising for Ukrainian farms, where maintaining the stability of feed efficiency requires a combination of genetic selection and optimisation of holding conditions.

Among Ukrainian researchers, a similar pattern was noted by R. Umanets *et al.* (2023), who proved that the use of non-conventional protein sources, such as yeast products, when feeding *Clarias gariepinus* reduces FCR by 12-15%. These results are consistent with the authors' observations, where in the catfish group, feed conversion rates were the lowest among all the species under study. Special attention should be paid to B. Glencross *et al.* (2024), who emphasised the need for a comprehensive assessment of the sustainability of feed systems, considering not only biological, but also economic parameters. This is directly related to the results of this study, where cost-effectiveness modelling showed a direct link between a decrease in FCR and an increase in profitability. An important aspect of interpreting the results obtained is to consider environmental and economic factors that directly affect the stability of the aquaculture feed base. According to research by A. Horchanok *et al.* (2021), overexploitation of aquatic ecosystems and poor management of fish resources lead to degradation of hydrobiocoenoses, which reduces the natural feed capacity of reservoirs. This statement is consistent with the fluctuations in the feed conversion rate (FCR) identified in this study, because the ecological state of water bodies directly affects the digestibility of feed and the physiological activity of fish. A violation of biological balance increases the risk of eutrophication, which, in turn, reduces the concentration of dissolved oxygen, causing an increase in FCR in sensitive species such as sturgeon. Additionally, it is worth noting the meta-analysis by T.O. Magbanua and J.A. Ragaza (2022), who systematised the results of experiments on feeding tilapia with mixed feeds based on coconut meal. The researches proved that even partial replacement of conventional protein components can provide a stable reduction in FCR without reducing weight gain, provided that the amino acids are properly balanced. The results from the current study on carp confirm this pattern: in 2024, the improvement in FCR coincided with the transition of farms to functional protein mixtures containing alternative protein sources.

From an economic standpoint, I. Sinenok (2021) argued that the organisational and economic mechanisms of fishery management in Ukraine remain fragmented, which hinders the development of a sustainable feed safety policy. The researcher emphasised the need to create regional programmes to support aquaculture, taking into consideration local resources. A similar opinion was shared by N. Vdovenko *et al.* (2020), who emphasised that the efficiency of the feed system depends not only on biological indicators, but also on the financial ability of enterprises to invest in high-quality feed and automation technologies. This is directly consistent with the conclusions of the current study, where lower FCR values were observed in high-tech CWSS farms that can implement advanced feeding control systems. From an ecological standpoint, the fundamental study by O. Uvaeva *et al.* (2020) confirmed the critical role of hydrobiological conditions in maintaining feed equilibrium. The researchers emphasised that water quality – oxygen concentration, pH level, nitrite and phosphate content – is a key determinant of fish metabolism efficiency. In this study, this factor was also found to be significant: fluctuations in hydrochemical parameters correlated with changes in FCR, especially in pond farms. Thus, the generalisation of these sources confirmed the multidimensional nature of feed efficiency, which was formed under the influence of environmental, economic, and technological factors. The results demonstrate the need to integrate environmental monitoring and economic planning into the aquaculture management system.

CONCLUSIONS

The study comprehensively assessed the dynamics of production indicators of the main groups of fish in aquaculture of Ukraine in 2022-2024 and identified factors that determine the effectiveness of the feed base. It was established that the volume of feed consumption during the study period experienced significant fluctuations, which reflects the general instability of the fisheries sector under the influence of economic, military, and environmental factors. Peak costs were recorded in 2020 (34.2 thousand tonnes), while the minimum costs were recorded in 2022 (23.3 thousand tonnes). This variability was explained by the uneven resumption of production, changes in the availability of mixed feed, and different levels of farm intensification. An in-depth analysis of the feed conversion rate (FCR) revealed clear interspecific differences. The highest feed efficiency was demonstrated by carp species, where in 2024 the FCR for broodstock decreased to 1.2, and for commercial fish – to 1.3, which indicates an improvement in feeding technologies and stabilisation of holding conditions. Catfish are characterised by a chronically increased FCR (2.3-2.5), which reduces economic profitability and requires correction of diets. Sturgeon species suffered a deterioration in efficiency due to technological failures and degradation of the feed base, while salmon fish showed a sharp variation in FCR – from a critical 3.5 in 2023 to a record low of 1.0 in 2024, indicating a productive adaptation of production. It has been proven that high FCR in broodstock directly affects the quality of sexual products and the viability of offspring, creating long-term economic risks. Therefore, the key areas of optimisation should be the development of differentiated feed strategies for age groups, improvement of feed quality, automation of feeding processes, and introduction of genetic selection based on feed efficiency indicators. Prospects for further research lie in the development of mathematical models for predicting FCR and assessing the impact of climatic factors on feeding efficiency in conditions of environmental changes.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Сучасні тенденції та визначення перспектив розвитку кормової бази в аквакультурі

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Анотація. Метою дослідження було виявлення тенденцій змін виробничої ефективності основних груп риб в аквакультурі України протягом 2022-2024 рр., з урахуванням впливу технологічних, екологічних і економічних чинників на ефективність годівлі та розвиток кормової бази. Методологія роботи базувалася на системному, статистичному та порівняльному аналізі даних дванадцяти рибогосподарських підприємств, що представляють різні рівні інтенсифікації – від ставкових господарств до підприємств із замкненими системами водопостачання (УЗВ). Аналіз охопив п'ятирічний період (2020-2024 рр.) із використанням методів кореляційного та регресійного аналізу для оцінки коефіцієнта конверсії кормів (FCR), економічної ефективності та впливу середовищних факторів на продуктивність. У результаті дослідження встановлено суттєві коливання обсягів споживання кормів та міжвидові відмінності у значеннях FCR. Виявлено, що мінімальні витрати кормів припадали на 2022 р. (23,327,3 т), а максимальні – на 2020 р. (34,243,3 т), що зумовлено економічною та воєнною нестабільністю. Найвищу ефективність кормової конверсії продемонстрували коропові види, де у 2024 р. FCR для маточного стада та товарної риби знизився до 1,2 та 1,3 відповідно. Для сомових риб зафіксовано стабільно високі значення FCR, що свідчить про низьку рентабельність годівлі цієї групи. Осетрові риби проявили різке погіршення кормової ефективності у 2023-2024 рр. внаслідок технологічних збоїв і деградації кормової бази. Лососеві риби продемонстрували екстремальні коливання з рекордно високим FCR 3,5 у 2023 р. та різким поліпшенням до 1,0 у 2024 р., що засвідчує технологічну адаптацію виробництва. Узагальнено, що високий FCR у маточного стада є не лише поточною економічною втратою, а й індикатором майбутньої зниження продуктивності потомства, тому оптимізація годівлі має базуватися на використанні функціональних кормів і точних технологій керування. Практична цінність роботи полягає у можливості використання отриманих результатів для розробки стратегій раціонального управління кормовими витратами в рибогосподарських підприємствах України, що сприятиме підвищенню рентабельності та екологічної стійкості аквакультурного виробництва

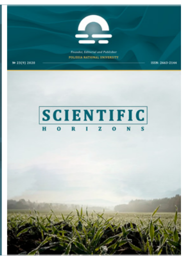
Ключові слова: коефіцієнт конверсії корму (FCR); рибні господарства; годівля риб; маточне та ремонтне поголів'я; товарна риба

SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 28(10), 32-43

UDC 338.439:004.4(477) DOI: 10.48077/scihor10.2025.32



The role of policy and economic framework conditions in shaping digitalisation in the agricultural sector in Ukraine

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Article's History:
Received: 02.05.2025
Revised: 19.08.2025
Accepted: 24.09.2025

Abstract. The purpose of the study was to examine how political and economic framework conditions influenced the development and effectiveness of digital transformation in Ukraine's agricultural sector within the Ukraine Facility Plan 2024-2027. The research applied a mixed-methods approach combining policy and regulatory analysis with a structured survey of 127 agricultural producers, local government representatives, and experts, conducted in both online and offline formats between May and July 2025. Quantitative methods were used to identify measurable trends in digital tool adoption, while qualitative content analysis helped interpret the institutional and behavioural drivers of digitalisation. It was established that digital transformation in agriculture functions as a systemic mechanism for improving transparency, investment efficiency, and integration into the European digital space. The analysis of governmental strategies and the Ukraine Facility Plan demonstrated that digitalisation is embedded in six key reforms: EU policy alignment, land market development, investment management, agrarian register modernisation, irrigation enhancement, and demining of agricultural land. The survey results revealed that 37% of agricultural producers already use satellite or drone-based monitoring, 23% rely on GIS tools, 18% employ electronic document management, 14% use digital platforms for administrative procedures, and 8% do not yet apply digital technologies. The priority ranking of reforms highlighted the dominance of EU alignment (average rank 2.0), demining (2.3), and land market reform (2.5). The integration of quantitative and qualitative findings confirmed a direct

Suggested Citation:
Dankevych, V., Ivaniuk, O., & Akhmetov, I. (2025). The role of policy and economic framework conditions in shaping digitalisation in the agricultural sector in Ukraine. *Scientific Horizons*, 28(10), 32-43. doi: 10.48077/scihor10.2025.32.

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relationship between the success of digital reforms and producers' readiness for digital innovation. The practical value of the study lies in its applicability for policymakers, agribusiness associations, and research institutions in designing targeted strategies to enhance digital infrastructure, improve digital literacy, and accelerate sustainable post-war transformation of Ukraine's agricultural sector

Keywords: digital readiness; agricultural reforms; e-governance; innovation policy; post-war recovery; EU integration; sustainable development

INTRODUCTION

The digital transformation of agriculture has become a defining component of sustainable economic growth and competitiveness across the world. In the Ukrainian context, the development of digital technologies in the agricultural sector has gained strategic importance as a mechanism for rebuilding the economy, enhancing transparency, and integrating into the European Union's policy and market frameworks. The ongoing war and post-war reconstruction have exposed the vulnerability of traditional management systems, demonstrating that the adoption of digital solutions is crucial for ensuring resilience, effective governance, and resource efficiency. According to G. Celi *et al.* (2022), the asymmetry of recovery processes in European agriculture highlights that institutional and technological readiness are the key prerequisites for sustainable development. The Ukrainian agricultural sector, being one of the pillars of national recovery, therefore requires a comprehensive digital transition supported by political and economic reforms.

The conceptual link between policy, innovation, and economic transformation has been examined by S. Abbate *et al.* (2023), who demonstrated that digital transition in the agri-food sector can only be effective under coherent governance and sustainability strategies. Their research confirms that the integration of technology into institutional mechanisms ensures systemic efficiency and environmental performance. In turn, A. Sridhar *et al.* (2023) emphasised that the implementation of digital solutions in agriculture depends on the synergy between technological advancement, financial policy, and human capital development. The authors identify data-driven management systems, precision farming, and digital advisory services as fundamental elements of a resilient agri-food ecosystem. The Ukrainian academic community also contributes significantly to understanding digital transformation in agriculture. A. Cherep and L. Sarbey (2023) argue that digitalisation acts as a catalyst for rebuilding Ukraine's economy, primarily by improving administrative transparency and reducing corruption risks in state support mechanisms. O. Borodina (2022) emphasises that the post-war transformation of Ukraine's agricultural system must adhere to the principles of social and environmental sustainability, which are best achieved through digital governance tools and open-data systems. Similar conclusions were reached by Z. Taishykov *et al.* (2024), who found that innovation management in agriculture requires strong institutional stability and a coherent investment policy to maintain the pace of technological progress.

According to Yu. Hurtovyi (2025), the modernisation of agricultural state support mechanisms, including digital monitoring and electronic application systems, improves both transparency and the efficiency of financial resource allocation. These findings align with the conclusions of B. Farace and A. Tarabella (2024), who confirmed that the implementation of digital tools in small and medium-sized enterprises fosters circular economy practices and reduces resource losses. Moreover, I. Kosmidailo and O. Makoviichuk (2025) note that adapting foreign digital platforms to Ukrainian agricultural management enhances efficiency but requires further investments in education and digital literacy. The importance of digitalisation for policy harmonisation and global competitiveness was underlined by I. Vysochyn & O. Zhuk (2025), who concluded that Ukraine's integration into the digital global space directly depends on the quality of national digital governance systems and the ability of institutions to align with EU regulatory standards. M. Wrzecińska *et al.* (2023) also observed that the effectiveness of digital transformation correlates with the availability of advisory infrastructure, financial incentives, and trust in public digital platforms.

Consequently, recent studies confirm that digitalisation in agriculture should be viewed not merely as a technological process but as a multidimensional reform encompassing political, economic, and institutional domains. The integration of digital governance instruments, sustainable financing models, and innovation ecosystems determines the effectiveness of Ukraine's agricultural modernisation and its future position within the European digital and economic landscape. The purpose of the study was to examine how political and economic framework conditions influenced the development and effectiveness of digital transformation in Ukraine's agricultural sector within the framework of the Ukraine Facility Plan 2024-2027.

MATERIALS AND METHODS

The study was designed to examine how political and economic framework conditions influenced the development of digital transformation in Ukraine's agricultural sector. A mixed-methods research design was applied, combining regulatory analysis, empirical observation, and comparative evaluation to ensure both analytical depth and empirical reliability. Quantitative methods were used to identify measurable trends in the adoption of digital tools, levels of digital readiness, and trust in state digital systems. Qualitative content analysis complemented these findings by providing interpretive insights into the contextual and institutional factors shaping the effectiveness of digital reforms. The empirical component of the study was based on a structured survey involving 127 respondents, including agricultural producers, representatives of local governments, and expert communities from various regions of Ukraine. The questionnaire addressed digital readiness indicators, access to e-support systems, and perceptions of state digitalisation policies. The questionnaire also included a ranking module, where respondents assessed the relative importance of six agricultural reforms introduced under the Ukraine Facility Plan 2024-2027. Each reform was rated on a 1-6 priority scale (1 = highest, 6 = lowest). The survey was conducted in 2025, using a combined online and offline format to ensure representativeness across regions and accessibility for respondents with limited internet connectivity. Participation in the study was entirely voluntary and anonymous. No personal identifiers were collected, and respondents were informed of the purpose of the research, the use of their responses for academic purposes only, and their right to withdraw at any time without consequence. All participants provided informed consent prior to participation. The authors adhered to the principles of the American Sociological Association's Code of Ethic (1997).

The informational base of the study consisted of open-access governmental and institutional data sources. The main policy framework analysed was the Ukraine Facility Plan 2024-2027 (Ministry of Economy of Ukraine, 2024), complemented by the Strategy of Agriculture and Rural development of Ukraine – 2030 (2024), publications from the Ministry of Agrarian Policy and Food of Ukraine (2023), and legislative acts related to the State Agrarian Register and DREAM public investment platform (Public Investment Management System, n.d.). Additional materials were obtained from the State Statistics Service of Ukraine (n.d.), OECD (n.d.) agricultural policy reviews and analytical data from KSE Agrocenter (2022). Special attention was paid to the digital components of six key reforms: EU policy alignment, land market, investment management, agrarian register development, irrigation, and demining of land. Data were processed using descriptive statistical analysis for quantitative responses and thematic coding for qualitative statements. The integration of both methods ensured a comprehensive understanding of the relationship between policy frameworks, economic mechanisms, and the practical capacity of the agricultural sector to adopt digital technologies during the post-war recovery period.

RESULTS AND DISCUSSION

The conducted research confirms that policy and economic framework conditions play a fundamental role in shaping the trajectory of digitalisation in Ukraine's agricultural sector. In the post-war context, digital transformation functions not merely as a technological upgrade but as a structural reform mechanism that enhances transparency, aligns governance with EU standards, and improves the efficiency of public resource allocation. As noted by A. Devaux *et al.* (2018), effective digital innovation in agriculture requires strong institutional support, adaptive policy instruments, and inclusive mechanisms for integrating producers into innovation systems. This corresponds to Ukraine's strategy of embedding digital solutions in the Ukraine Facility Plan as a cross-cutting component of all major reforms. The Ukraine Facility is the European Union's financial assistance programme for Ukraine. During the period of 2024-2027, 50 billion euros from the EU will be allocated to finance the state budget, stimulate investment, and provide technical support in the implementation of the program (Ministry of Economy of Ukraine, 2024)

European experience demonstrates that digital agriculture is most effective where policy design and economic instruments are closely integrated (Câmpeanu, 2022). In Ukraine, key reforms – such as the interoperability of land and property registries, the introduction of automated monitoring systems, the digitalisation of the State Agrarian Register, and the integration of geospatial land valuation – mirror EU practices aimed at building transparent and efficient agri-food governance systems. These approaches are fully aligned with the principles of the Common Agricultural Policy, which emphasises data-driven governance and sustainable resource use (Abbate *et al.,* 2023). The trust factor and inclusiveness are equally critical. As R. Tomble and H. Smuts (2023) highlight, digital transformation is most impactful when farmers are active participants in decision-making through accessible, reliable platforms. In Ukraine, such platforms include the State Agrarian Register and automated public monitoring systems, which serve not only as administrative tools but also as instruments of accountability. B. Farace and A. Tarabella (2024) note that digital technologies foster circular economy practices, which in turn strengthen sustainability outcomes in agricultural production and value chains. This corresponds with findings from N. Mamonova (2023), which emphasise that transparent and inclusive mechanisms increase resilience in rural areas during and after crises.

The economic dimension of digitalisation involves both national and international investment frameworks. According to O. Radchenko *et al.* (2023) investment in digital infrastructure enables wider technological diffusion and accelerates structural transformation. A. Sridhar *et al.* (2023) emphasise the role of public-private partnerships in scaling up digital solutions, particularly for small and medium-sized farms. In Ukraine, this is reflected in the integration of digital investment platforms, such as DREAM, into key recovery and modernisation strategies, which helps link policy priorities with concrete financial mechanisms (Kyivstar Business Hub, 2022; KSE Agrocenter, 2022). Finally, the development of human capital and advisory systems is a cornerstone of sustainable digital transformation.N. Pavlishyna and A. Kharin (2023) and Y. Doukas *et al.* (2022) stress the importance of education, extension services, and knowledge exchange in ensuring technology adoption. In this context, AKIS (Agricultural Knowledge and Innovation System) can serve as an institutional bridge between policy frameworks, economic mechanisms, and farm-level practices. Such systems enhance adaptive capacity, strengthen resilience, and enable alignment with EU Green Deal and CAP objectives (Pryshliak *et al.,* 2023). This creates a comprehensive ecosystem in which digitalisation acts as both a governance tool and a driver of economic modernisation in agriculture.

The development of digitalisation in Ukraine's agricultural sector is closely linked to the creation of a modern regulatory framework that defines the policy and economic conditions for reform implementation. One of the key steps in this direction was the adoption of the Strategy of Agriculture and Rural development of Ukraine – 2030 (2024). This document aims to shift from traditional administrative management to modern digital instruments that ensure land market transparency, more efficient interaction between stakeholders and government institutions, and alignment of national agricultural policy with EU standards. A central digital element of this strategy is the establishment of the Farm Sustainability Data Network (FSDN), which enables the collection, processing, and analysis of agricultural data from pilot regions in accordance with the acquis communautaire. This system provides continuous monitoring of the sector and supports evidence-based policy decisions on state support for producers. Digital accounting of production indicators, environmental factors, and economic parameters forms the basis for a data-driven governance model, bringing Ukraine closer to the EU's sustainable development standards.

Another milestone in the digital transformation is the automated exchange of data between the State Land Cadastre of Ukraine (n.d.) and the State Register of Real Rights to Immovable Property (n.d.). This integration improves the efficiency and transparency of land transactions, reduces bureaucratic procedures, and minimises corruption risks. An automated public land monitoring system and a GIS-based mass land valuation system have also been launched, significantly increasing the transparency and efficiency of land resource management. A key role in digitalisation is played by the State Agrarian Register (n.d.) (SAR), officially recognised as a public digital register of all stakeholders in the agricultural sector – producers, processors, water users, and others (Table 1). Registration in SAR is a prerequisite for receiving state support, and the publication of the list of beneficiaries increases transparency in the allocation of financial resources. According to official reports, by the end of 2025, at least 80% of agricultural state support will be distributed through this platform. Systemic digitalisation also extends to water resource management, including the adoption of a Long-Term Development Plan for Ukraine's Irrigation System (Ministry of Agrarian Policy and Food of Ukraine, 2023). This plan integrates digital platforms into the planning, analysis, and implementation of irrigation projects, applying a basin management approach and environmental impact assessment consistent with EU and national legislation. Equally important is mine action, which plays a critical role in restoring agriculture in de-occupied regions. The adoption of the Strategic Document on Mine Action until 2033 sets out mechanisms for coordination, operator support, donor engagement, and the use of electronic certification registries to enhance transparency and operational efficiency (Ministry of Agrarian Policy and Food of Ukraine, 2023).

***Table 1**. Directions for the recovery of the agri-food sector within the Ukraine facility and the integration of digital components*

Reforms and Investments	Content	Digital Component
Reform 1. Alignment of institutional frameworks for agriculture and rural development with EU policy	Adoption of the strategy for the development of agriculture and rural areas until 2030	An important part of the strategy is to ensure the functioning of the land market on the basis of transparency and openness, supported by digitalisation of processes, digital solutions for learning, service access, and registry interoperability.
	Creation of the farm sustainability data network (FSDN)	Creation of a digital system for data collection, processing and analysis to support digitalisation of public administration and analytics in the sector.
Reform 2. Ensuring the functioning of the land market	Automated data exchange between land cadastre and property register	Automation of data exchange between registers (interoperability) to ensure access to information in land relations.
	Launch of an automated public land monitoring system	Creation of a digital land relations monitoring system through the interaction of different registers (databases). A geoinformation system for automated land valuation as part of the digitalisation of land resource management.

Table 1. Continued

Reforms and Investments	Content	Digital Component
Reform 3. Strengthening investment program management	Entry into force of legislation on state support for agriculture in Ukraine	Digitalisation of producer information, expansion of electronic document management, and engagement of producers and processors through a single digital platform for state support distribution.
Reform 4. Improvement of the agricultural enterprise register	Entry into force of the Law on the State Agrarian Register	Use of the digital information and communication platform – the State Agrarian Register – for analysis and decision-making on state support (for public administration).
	Provision of support through the State Agrarian Register (SAR)	Prioritisation of the digital platform for providing state support to agricultural producers.
Reform 5. Long-term irrigation development for climate resilience	Adoption of a long-term irrigation system development plan	The digital component is ensured through the public investment platform.
Reform 6. Demining of land and water areas	Entry into force of the strategic document on mine action until 2033	Mine action certificate registry operates and is integrated into the DREAM investment platform

Source: *developed by the authors based on the Ministry of Agrarian Policy and Food of Ukraine (2023) and Ministry of Economy of Ukraine (2024)*

The investment component of this program foresees allocating at least €100 million for agricultural land demining, financed through the state budget and monitored using digital treasury and reporting tools. This ensures transparent fund allocation, efficient monitoring, and accelerated restoration of agricultural land for production purposes. Together, these results confirm that digitalisation is not just a technological upgrade but a core structural element of Ukraine's agricultural policy, enabling transparency, efficiency, and alignment with European standards in the post-war recovery period. Digitalisation is becoming an integral component of the policy and economic framework conditions for the development of Ukraine's agricultural sector. It ensures interoperability of state registers, transparency in resource allocation, supports data-driven decision-making, and facilitates the sector's adaptation to EU standards. These transformations not only stimulate post-war recovery but also shape a new quality of governance, enhancing the sector's international competitiveness. Digital infrastructure is emerging as the foundation for Ukraine's integration into the European economic space within the framework of the Ukraine Facility Plan 2024-2027.

Most measures for restoring the agri-food sector are based on digital solutions – building electronic interaction systems, collecting and analysing large datasets, and ensuring register interoperability. This is a key element of digital transformation for the development of e-governance in agriculture. Such measures not only enhance the efficiency of public authorities but also simplify access for businesses, citizens, and analysts to information and services by integrating registers into a unified interaction system at both the national and European levels. The 69 reforms in the Plan are supported by more than 150 quarterly implementation indicators. In addition to the reform indicators, the plan includes 16 investment indicators. To fulfill them, it is necessary to allocate funds for the implementation of individual projects – infrastructure development, demining, renewable energy, support for small and medium-sized enterprises, etc (Ministry of Economy of Ukraine, 2024).

Reform 1. Alignment of the institutional framework for agriculture and rural development with EU policy. Reform 1 is strategically significant for modernising Ukraine's agricultural sector and bringing it closer to EU standards. Its central element is the adoption of the Strategy for the Development of Agriculture and Rural Areas until 2030, which identifies digitalisation as a core transformation tool. The document envisages the wide application of digital technologies to ensure transparency and efficiency in governance, particularly through interoperability of state registers, digitisation of phytosanitary documentation, integration into international data exchange systems, and automation of permitting procedures in the land sector. In the field of land relations, the strategy emphasises the full digital registration of agricultural land and the creation of online platforms for open data access. This will allow effective monitoring of land use, the implementation of state support programs – including compensation for war damages and increased transparency of all processes. Mandatory registration of all producers in the State Agrarian Register is a fundamental element of the new digital ecosystem, ensuring transparent resource allocation and creating a solid basis for EU integration of the sector. A key instrument of this reform is the establishment of the Farm Sustainability Data Network (FSDN), which evolves from the European FADN system. It expands the scope of analysis from economic to environmental and social indicators, supporting the implementation of the EU's Common Agricultural Policy. The integration of FSDN with the State Agrarian Register will allow combining producer data with sustainability metrics, thereby enabling evidence-based policy and support programs. An additional component is the integration of FSDN with the State Land Cadastre and GIS systems. This synergy will ensure the collection and analysis of spatial, environmental, and economic data necessary for strategic planning. It will strengthen the state's analytical capacity, improve resource management efficiency, and establish a modern digital architecture for agricultural policy aligned with European sustainability standards.

Reform 2. Ensuring the functioning of the land market. Reform 2 focuses on establishing a transparent and efficient land market in Ukraine through the integration of key digital registries. Its foundation is the automated exchange of data between the State Land Cadastre and the State Register of Property Rights. This integration combines cadastral data with ownership, property rights, and encumbrance information. The result is a reliable market pricing database, reduced corruption risks, prevention of undervaluation of land, and the creation of a transparent valuation mechanism. Automated data exchange also enables electronic services for citizens and businesses, such as automatic land valuation and the issuance of property value certificates. Another important component is the automated public land monitoring system, integrated within the State Land Cadastre. It continuously collects, processes, and updates information on land resources, market transactions, ownership changes, and other indicators. Such monitoring increases market transparency, improves evidence-based decision-making, and allows for timely responses to changes in land use patterns. A key role in this reform is played by the GIS-based mass land valuation system, which is fully interoperable with cadastral software and connected to the State Service of Ukraine for Geodesy, Cartography, and Cadastre and the Unified State Register of Court Decisions. This creates a comprehensive digital platform for land valuation and management, increasing trust in the land market, improving the investment climate, and fostering sustainable development of the agricultural sector.

Reform 3. Strengthening institutional and administrative structures for investment program management. Reform 3 is aimed at creating an effective system of state support for the agricultural sector through the digitalisation of management processes. A key step was the adoption of the Law of Ukraine No. 13202-1 (2025), which establishes new principles for designing state aid policies and mandates automated data collection and processing on beneficiaries. The law provides for the transition to electronic document management and the operation of a single digital platform for distributing state funds. Producers and processors will receive support exclusively through this platform, ensuring transparency, preventing abuse, and increasing the efficiency of program administration. This approach strengthens institutional mechanisms and builds trust in state instruments supporting the agricultural sector.

Reform 4. Enhancing the official public electronic register of agricultural enterprises. Reform 4 defines the digital component as a structural foundation for governance transformation in the agricultural sector. Its goal is to improve regulatory quality, ensure data accuracy, reduce corruption risks, and build an analytical base for forecasting agricultural development. A major step was the adoption of the Law of Ukraine No. 3980-IX (2024), which establishes the State Agrarian Register (DAR) as an automated electronic system and online platform for registering producers, informing them about support programs, and simplifying application procedures. SAR functions as a data hub, automatically exchanging information with other state registries – the Unified State Register (EDR), the State Land Cadastre, the State Register of Property Rights, and the Unified State Register of Animals. This minimises paperwork and consolidates data on land banks, livestock, and production activities. Such integration provides a comprehensive overview of the agricultural sector and prepares Ukraine to implement the Integrated Administration and Control System (IACS), a prerequisite for future EU financial support. The implementation of state support mechanisms through SAR has already shown tangible results. According to official reports, by the end of 2025 at least 80% of all agricultural state support will be allocated through this system. Consolidated, verified, and regularly updated data will allow for targeted and efficient support programs, enhance transparency, reduce corruption risks, and broaden access for producers to financing instruments.

Reform 5. Long-term irrigation development plan to strengthen climate resilience. Reform 5 targets climate adaptation of agriculture through the modernisation and digitalisation of irrigation systems. The focus is on enhancing climate resilience by automating water resource management during the construction or rehabilitation of irrigation infrastructure. This ensures more efficient water use, reduces costs, and increases productivity in irrigated farming. Although the digital component of this reform is relatively limited, it remains essential for integrated water governance. It provides for digitalisation of planning and water use control, and allows certain projects to be implemented through the DREAM public investment platform. This approach lays the groundwork for transparent resource management, attracting investment, and integrating irrigation solutions into Ukraine's modern digital agricultural ecosystem.

Reform 6. Demining of land and water areas. Reform 6 focuses on creating an effective system for mine action management and strengthening the safety of agricultural production. In 2024, the Cabinet of Ministers of Ukraine adopted the resolution on the approval of the National Mine Action Strategy until 2033 and the Operational Action Plan for 2024-2026 (Ministry of Economy of Ukraine, 2024). This document defines the state's key priorities in mine action and emphasises the importance of digital transformation of certification and control processes in line with Ukraine's national digitalisation strategy. Digitalisation in this sphere will enable more efficient control over operators' activities, standardise certification and record-keeping procedures, and enhance transparency in resource management. The creation of modern digital mechanisms is an important step toward strengthening the confidence of international partners and donors supporting humanitarian demining. It will also improve the planning of operations, ensure rapid information exchange between state institutions, and reduce risks to the population and agricultural producers in demined areas.

A crucial element of the reform is the creation of a "Mine Action" sectoral portfolio on the DREAM public investment platform (Ministry of Economy of Ukraine, 2024). This tool enables real-time monitoring of project implementation in mine action, consolidates data on funding, implementers, and outcomes, and strengthens the state's ability to manage resources transparently and efficiently. It provides a strategic digital instrument for coordinating humanitarian demining, supporting the safe return of agricultural land to production and fostering a favorable investment environment in liberated territories. Within the context of the study, a survey was conducted among representatives of the agricultural sector, public authorities, local governments, and experts. The main objective was to determine how public policy and economic conditions influence the adoption of digital technologies in agriculture. Special attention was paid to perceptions of reforms under the Ukraine Facility Plan 2024-2027 and the level of readiness of agricultural producers to adopt new digital solutions. The results show that most respondents view digitalisation not only as a tool to optimise production but also as a driver of transparency, market openness, and trust in state institutions. Participants noted that the integration of digital registers and automated land management systems is a key prerequisite for reducing corruption risks and improving the investment climate in agriculture. At the same time, the survey revealed a significant gap between policy goals and the practical capacity of certain regions to meet new digital requirements. Respondents emphasised the need for additional investments in digital infrastructure, modernisation of IT solutions, capacity building, and mechanisms to support small and medium-sized producers. Without adequate funding and coordination, digital reforms risk being implemented unevenly across regions.

The interaction between policy decisions and economic framework conditions plays a crucial role in shaping Ukraine's digital agricultural ecosystem. Respondents highlighted the importance of instruments such as the State Agrarian Register, automated public land monitoring systems, GIS-based land valuation tools, and digital investment platforms. These are viewed as fundamental mechanisms for transparent land governance and effective delivery of state support. The diagram 1 illustrates the current state of digitalisation in the Ukrainian agricultural sector based on survey data. The results indicate that satellite or drone monitoring is the most commonly used digital tool, applied by 37% of respondents. This reflects a growing interest in precision agriculture technologies, which enable farmers to optimise field management and increase productivity. GIS and field mapping tools are used by 23% of participants, showing that spatial data analysis is becoming an increasingly important component of modern agricultural practices (Fig. 1).

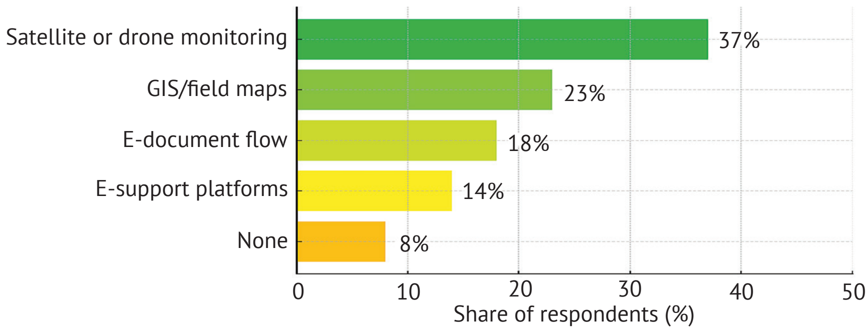

***Figure 1**. Use of digital tools in Ukrainian agriculture*

***Source:** developed by the authors*

At the same time, 18% of respondents utilise electronic document flow systems, and 14% rely on various e-support platforms, indicating steady progress toward administrative and operational digitalisation. However, 8% of respondents still do not use any digital tools, highlighting existing gaps in access to technology, infrastructure, or knowledge. These findings confirm that while the sector is undergoing digital transformation, its pace and coverage remain uneven, underscoring the need for supportive policies, capacity building, and investment in digital infrastructure. The chart illustrates the level of trust in state digital systems among agricultural stakeholders in Ukraine. The largest share of respondents (46%) indicated that they partly trust these systems, reflecting a generally positive but cautious attitude toward state digitalisation efforts. Meanwhile, 22% of participants reported that they fully trust state platforms, which demonstrates a solid foundation of confidence in existing digital services and their potential to support transparency, efficiency, and accountability (Fig. 2).

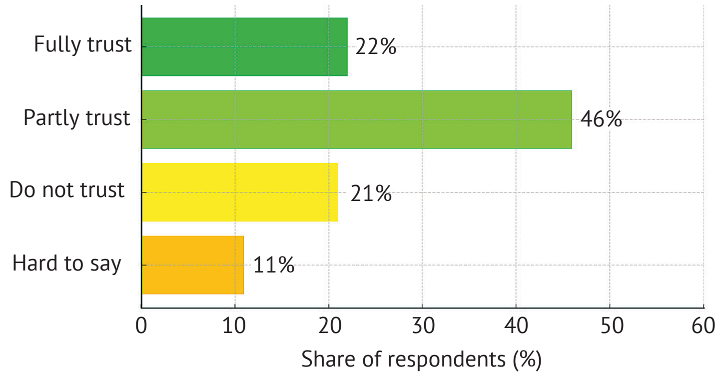

***Figure 2**. Trust in state digital systems*

***Source:** developed by the authors*

However, 21% of respondents stated that they do not trust state digital systems, and 11% found it hard to say, highlighting persistent concerns about data security, system reliability, and governance practices. These results suggest that, while digital transformation in the agricultural sector is progressing, strengthening trust in state platforms remains a critical task. This will require not only technological improvements but also greater institutional transparency, communication, and user-oriented service design. The chart presents the average priority ranking of key agricultural reforms in Ukraine, based on respondents' assessments. The two highest priorities are EU policy alignment (average rank 2.0) and demining of land and water areas (2.3), reflecting the urgent need to harmonise national agricultural policies with EU standards and to address the large-scale contamination of farmland caused by the war. The functioning of the land market ranks third (2.5), underscoring its crucial role in ensuring transparent property relations, investment attractiveness, and the efficient use of agricultural resources.

Reforms related to investment governance strengthening (3.5), irrigation development (3.8), and improvements to the State Agrarian Register (4.2) are recognised as strategically important but are perceived as less urgent than land reform, EU integration, and demining efforts. This indicates that while stakeholders acknowledge their relevance to the sector's long-term modernisation and competitiveness, they view immediate priorities through the lens of security, land access, and compliance with European regulations. Such prioritisation reflects a practical understanding of the current recovery context, where addressing critical infrastructure and regulatory gaps comes first. At the same time, these reforms play an essential enabling role in ensuring sustainable growth. Strengthening investment governance can create a more predictable and transparent environment for both domestic and international investors. Expanding irrigation infrastructure is key to adapting to climate challenges and improving productivity, particularly in southern regions. Enhancing the functionality and interoperability of the State Agrarian Register will expand access to support programs and improve data-driven decision-making. Together, these reforms form the backbone for deeper structural transformation, aligning Ukraine's agricultural sector with EU standards and ensuring long-term resilience (Fig. 3).

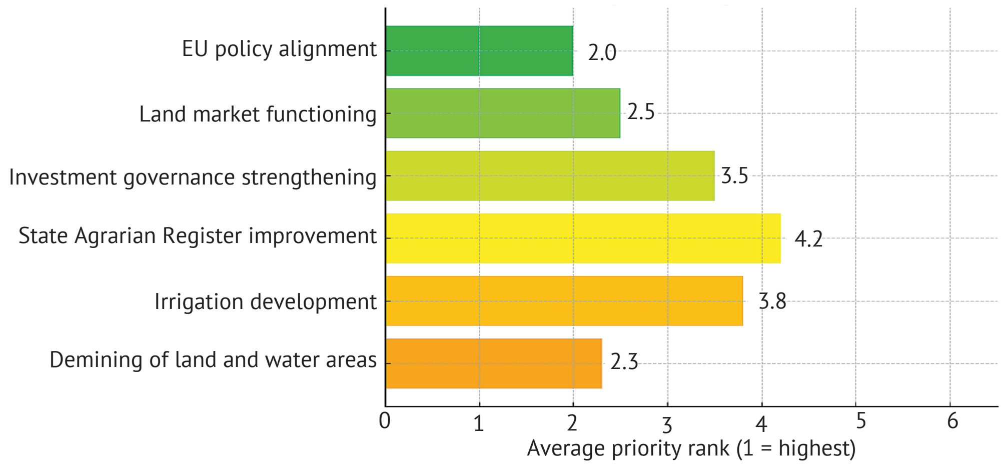

***Figure 3**. Priority ranking of reforms*

***Source:** developed by the authors*

The chart demonstrates respondents' views on the role of digitalisation in the successful implementation of agricultural reforms in Ukraine. A clear majority considers digitalisation essential: 37% of respondents view it as important, while 35% see it as critically important. This highlights a strong consensus that digital tools and platforms are key to ensuring transparency, efficiency, and accountability in reform processes, particularly in land governance, resource management, and policy implementation (Fig. 4).

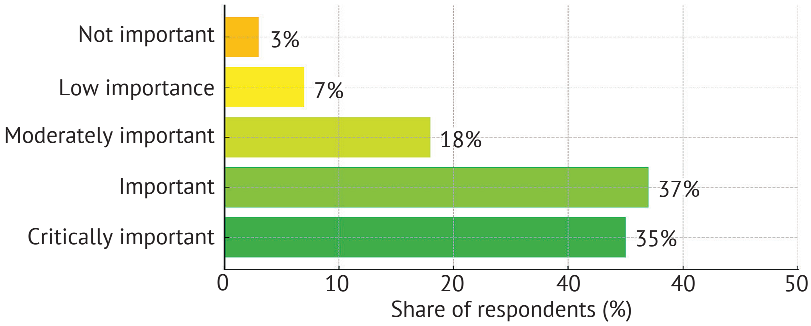

Figure 4. *Importance of digitalisation for reform implementation*

Source: *developed by the authors*

Meanwhile, 18% of respondents rated digitalisation as moderately important, and only 10% considered it of low or no importance, indicating limited skepticism toward the digital transformation agenda. These results confirm that digitalisation is widely perceived as a strategic driver of institutional change in the agricultural sector, reinforcing its role as a foundation for modernisation and integration with EU standards. The chart highlights the key priority areas for digital transformation in Ukraine's agricultural sector. The highest priority identified by respondents is land resource management (29%), reflecting the critical role of digital tools in ensuring transparent and efficient use of land, improving cadastral data systems, and supporting decision-making. The second most important area is access to state support programs (21%), which underscores the need for user-friendly digital platforms that simplify administrative procedures and improve the targeting of financial assistance (Fig. 5).

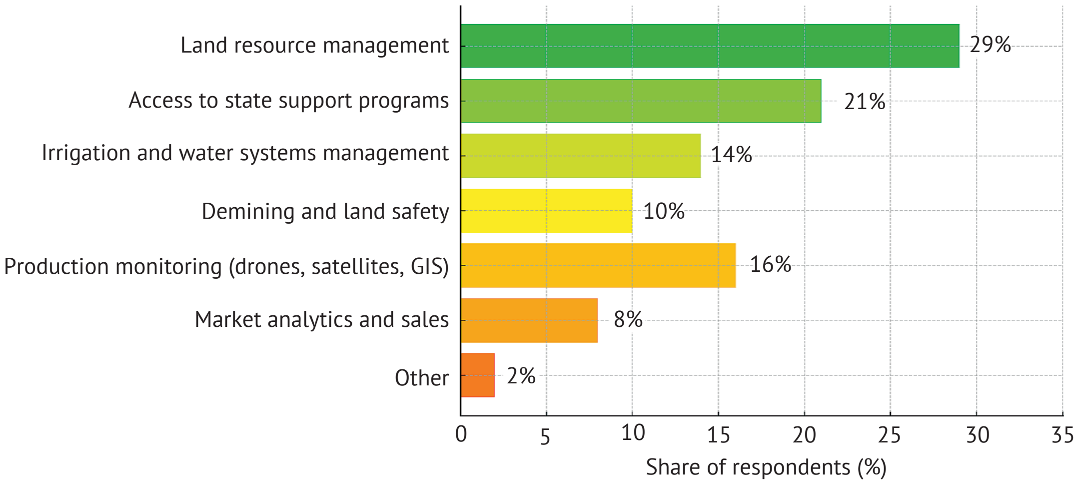

Figure 5. *Priority areas for digitalisation in agriculture*

Source: *developed by the authors*

Other notable priorities include production monitoring using drones, satellites, and GIS technologies (16%) and irrigation and water systems management (14%), which are essential for optimising resource use and climate adaptation. Meanwhile, demining and land safety (10%) and market analytics and sales (8%) were ranked lower but remain strategically significant for post-war recovery and market competitiveness. These findings confirm that stakeholders view digitalisation primarily as a tool for improving governance, efficiency, and transparency in land and resource management. Thus, the survey results confirm that the effectiveness of digital transformation in Ukraine's agricultural sector directly depends on the quality of political decisions and the economic mechanisms of their implementation. Digitalisation is viewed not merely as a technological upgrade but as a structural reform of sectoral governance. The combination of strategic decision-making, financial resources, and institutional support can form a resilient digital ecosystem, enhancing the competitiveness of Ukrainian agriculture and accelerating its integration into the European economic space.

The survey of farmers and agricultural producers revealed that one of the key factors for effective digital transformation is the development of knowledge, skills, and extension services. Most respondents emphasised that even with access to digital tools, practical training, peer learning, and expert support remain essential. This indicates the need for systematic institutional development to ensure effective communication and knowledge exchange between the state, businesses, research institutions, and producers. An effective model to address this challenge could be the Agricultural Knowledge and Innovation System. This system enables collaboration among research institutions, advisory services, businesses, and farmers to foster innovation and support the implementation of digital solutions. AKIS not only provides practical knowledge to producers but also helps disseminate innovations through the integration of educational, scientific, and governance tools. Within the implementation of state agricultural policy, AKIS can serve as an institutional platform linking political objectives with economic mechanisms. It can support small and medium-sized producers, promote public–private partnerships, attract investment in digital infrastructure, and expand extension services. In this way, digitalisation becomes not only a technological shift but also a socioeconomic transformation of the sector. The use of AKIS will also support Ukraine's alignment with the EU's Common Agricultural Policy and the European Green Deal. It will help create a sustainable innovation ecosystem based on digital solutions, ensure transparent information exchange, and enable effective knowledge management. Ultimately, this will enhance the competitiveness of Ukraine's agricultural sector, strengthen its integration into the European market, and ensure sustainable development in the face of global challenges.

CONCLUSIONS

The conducted study demonstrated that the digital transformation of Ukraine's agricultural sector is not merely a technological trend but a structural component of the post-war economic recovery and European integration process. The analysis of the Ukraine Facility Plan 2024-2027 and related policy instruments confirmed that digitalisation serves as both an enabler and a driver of institutional transparency, resource efficiency, and investment accessibility. Empirical results revealed that Ukrainian agricultural producers show a growing level of digital readiness, though the pace of implementation remains uneven across regions and enterprise types. Survey findings indicate that 37% of respondents already use satellite or drone-based monitoring, 23% apply GIS systems for land management, 18% employ electronic document management, 14% rely on e-platforms for administrative procedures, while 8% still operate without digital tools. The perception of governmental digital initiatives was moderately positive: 46% of respondents expressed partial trust and 22% full trust in state digital systems, while the remainder noted the need for better data protection and user training. Among the six priority reforms identified under the Ukraine Facility Plan, the highest average rankings were assigned to EU policy alignment (2.0), land and water demining (2.3), and land market development (2.5), reflecting a focus on security, regulatory coherence, and economic resilience.

The integration of quantitative and qualitative analyses confirmed a clear correlation between the success of reforms and the adaptability of agricultural producers to new digital standards. However, infrastructural disparities, limited digital literacy, and insufficient institutional coordination continue to constrain the full-scale implementation of digital solutions. Strengthening advisory systems and expanding the Agricultural Knowledge and Innovation System (AKIS) network remain essential for achieving the long-term goals of sustainable and inclusive agricultural growth. Future research should focus on modelling regional disparities in digital adoption, assessing cost-benefit ratios of digital investments, and developing mechanisms for synchronising digital platforms across all levels of agricultural governance.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Роль політики та економічних рамкових умов у формуванні цифровізації в аграрному секторі України

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Анотація. Метою дослідження було з'ясувати, як політичні та економічні рамкові умови вплинули на розвиток і ефективність цифрової трансформації аграрного сектору України в межах програми Ukraine Facility Plan 2024-2027. У роботі застосовано змішаний методологічний підхід, що поєднує політико-нормативний аналіз із структурованим опитуванням 127 сільськогосподарських виробників, представників органів місцевого самоврядування та експертних спільнот, проведеним у онлайн та офлайн форматах у період з травня по липень 2025 року. Кількісні методи дозволили виявити вимірювані тенденції у використанні цифрових інструментів, тоді як якісний контент-аналіз допоміг інтерпретувати інституційні та поведінкові чинники цифровізації. Було встановлено, що цифрова трансформація в аграрній сфері виступає системним механізмом підвищення прозорості, інвестиційної ефективності та інтеграції до європейського цифрового простору. Аналіз державних стратегій і програми Ukraine Facility Plan показав, що цифровізація інтегрована у шість ключових реформ: узгодження політики з ЄС, розвиток ринку землі, управління інвестиціями, модернізацію аграрного реєстру, вдосконалення зрошення та розмінування сільськогосподарських земель. Результати опитування засвідчили, що 37 % агровиробників уже використовують супутниковий або дроновий моніторинг, 23 % застосовують ГІС-технології, 18 % – електронний документообіг, 14 % – цифрові платформи для адміністративних процедур, а 8 % ще не впроваджують цифрових інструментів. Рейтинг пріоритетності реформ виявив домінування євроінтеграції (середній ранг 2,0), розмінування (2,3) та реформи ринку землі (2,5). Інтеграція кількісних і якісних результатів підтвердила прямий взаємозв'язок між успіхом цифрових реформ і готовністю виробників до цифрових інновацій. Практична цінність дослідження полягає в можливості використання його результатів органами державної влади, галузевими асоціаціями та науковими установами для розроблення цільових стратегій розвитку цифрової інфраструктури, підвищення цифрової грамотності та прискорення сталого післявоєнного відновлення аграрного сектору України

Ключові слова: сила; цифрова готовність; аграрні реформи; електронне врядування; інноваційна політика; післявоєнне відновлення; євроінтеграція; сталий розвиток

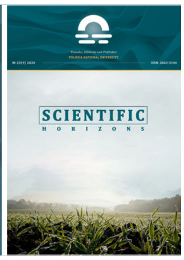
SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 28(10), 44-53

UDC 631.445:631.58

DOI: 10.48077/scihor10.2025.44



Effect of tillage methods and biological preparations on the structural state of soil

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Article's History:

Received: 06.04.2025

Revised: 05.09.2025

Accepted: 24.09.2025

Abstract. The aim of this study was to evaluate the effects of different primary tillage technologies and the application of biopreparations on the structural condition of chernozem soils in sunflower cultivation. Understanding these effects is essential for optimising soil management practices and enhancing crop productivity. To achieve this goal, the study employed a combination of field, laboratory, and statistical methods. Field methods included the establishment of a stationary experiment using a randomised block design. Laboratory analyses involved the determination of soil particle-size fractions using the dry sieving method. Statistical analysis, specifically analysis of variance, was applied to assess the significance of differences among treatments. The results demonstrated that conventional plowing produced the highest content of large aggregates (>10 mm) in the 0-30 cm soil layer (35.1%). Nevertheless, this method was associated with a relatively low proportion of agronomically valuable 5-3 mm fractions, thereby reducing structural stability against erosive processes. In contrast, chisel subsoiling and deep non-inversion tillage reduced the proportion of large clods while increasing the proportion of optimally sized aggregates by 3.6-8.3% compared to the control. These improvements contributed to a better soil water-air regime and created favorable conditions for sunflower root development. The application of microbial biopreparations (Azotobacter, Bacillus subtilis, Trichoderma, and a microbial consortium) further improved soil structure by decreasing the proportion of oversised clods and enhancing the share of agronomically valuable fractions 0.25-10 mm. The most pronounced effect was recorded during the consortium treatment, which contributed to the formation of a more homogeneous and stable lumpy-grained structure, where the number of agronomically valuable aggregates was 81.5%. The practical significance of this study lies in identifying effective tillage practices and the use of biopreparations to improve the structural condition of typical chernozem under sunflower cultivation.

Suggested Citation:

Shevchenko, M., & Dehtiarova, Z. (2025). Effect of tillage methods and biological preparations on the structural state of soil. *Scientific Horizons*, 28(10), 44-53. doi: 10.48077/scihor10.2025.44.

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The obtained results can be applied in production systems to preserve soil fertility, enhance water use efficiency, and ensure the ecological stability of agroecosystems

Keywords: tillage systems; soil structural-aggregate composition; chernozem; agrophysical propertie; sunflower; biologisation of agriculture

INTRODUCTION

Enhancing soil fertility is a key objective of modern agriculture, as it directly affects the stability and efficiency of crop production. One of the main indicators of soil fertility is its structural status, which determines water retention, aeration, and nutrient availability. In this context, studying the effects of different tillage practices and the application of biopreparations on soil structure is particularly relevant. X. Meng *et al.* (2024) emphasised that reduced-tillage technologies decrease mechanical impact on the soil and ensure a more stable structural condition, positively affecting the soil water regime and the development of crop root systems. Conventional tillage practices, such as moldboard ploughing, can lead to a reduction in soil aggregates, particularly in the upper soil layer. Specifically, W. Paye *et al.* (2024) reported a decrease in the content of 0.25-10 mm aggregates following ploughing to a depth of 25-27 cm. In contrast, the use of alternative tillage methods, such as chisel subsoiling, can positively influence soil structure preservation. For instance, C. Smith and P. Chalk (2021) observed an increase in aggregate content when applying chisel tillage to a depth of 30 cm. Among Ukrainian researchers, O. Poliakov *et al.* (2021) analysed energy efficiency and the impact on soil structure under primary tillage technologies in the southern regions of Ukraine. International studies also emphasise the importance of integrating tillage technologies with biological approaches. A. Sher *et al.* (2021) investigated the combined effects of tillage and drought stress on sunflower productivity, showing that minimal tillage supports better morphophysiological traits compared to conventional tillage under arid conditions. M. Mokgolo *et al.* (2024) reported that the application of organic fertilizers in combination with different tillage systems enhances sunflower yield, indicating a synergistic effect between agrotechnology's and organic inputs. M. Nankova and N. Nenova (2023) noted that soil compaction under minimal tillage reduces leaf area, plant height, and yield, confirming the close relationship between soil structure and crop productivity.

Recently, there has been growing interest in the use of biopreparations, particularly plant-associated microorganisms, which can mitigate the negative effects of abiotic stresses and indirectly influence soil structural condition. Soil bacteria belonging to the PGPR (plant growth-promoting rhizobacteria) group produce phytohormones and secondary metabolites that stimulate root system development, improve the water regime in the rhizosphere, and promote the formation of organo-mineral bonds. These processes, in turn, activate mechanisms that stabilise soil aggregates, directly affecting the structural condition of chernozem soils in sunflower (*Helianthus annuus* L.) cultivation. R. Sammauria *et al.* (2020) reported that the application of microbial biopreparations capable of fixing atmospheric nitrogen, mobilising phosphorus and potassium, producing phytohormones, and stimulating root system development promotes an increase in water-stable aggregates, reduces soil bulk density, and improves field water-holding capacity. P. Yadav *et al.* (2024) confirmed that the use of biopreparations enhances soil structural stability and ensures more efficient water retention, which is critical for root system development and the resilience of soil structure. M. Janmohammadi and N. Sabaghnia (2023) demonstrated that combining biopreparation application with conservation tillage technologies in sunflower crops significantly improves both soil structural properties and crop yield, highlighting the synergistic effect between biologisation and optimisation of agronomic practices.

Regarding biopreparations, recent studies in Ukrainian agricultural practice demonstrate their potential to improve soil properties. In particular, I. Nepran *et al.* (2021) analysed the effectiveness of biologically active substances on soil structure, showing that the application of humic preparations and microbial inoculants stimulates microbial development and positively affects aggregate composition. Research by Ye. Yurkevych *et al.* (2023) demonstrated that the use of the Groundfix preparation enhances crop productivity under different application methods. Additionally, C. Zhang *et al.* (2023) reported that the application of biopreparations can promote the formation of more stable soil aggregates, improving both soil structure and its water-physical properties. Despite these contributions, the combined effects of specific tillage methods (moldboard, chisel, non-inversion, and disk) together with biopreparation application on the structural condition of chernozem under sunflower cultivation in the Left-Bank Forest-Steppe of Ukraine remain insufficiently studied.

Sunflower occupies a leading position among oilseed crops both globally and in Ukraine; however, the stability of its yield largely depends on the structural condition of the soil. Optimisation of tillage systems and the application of biopreparations represent promising strategies for increasing the efficiency of sunflower production, particularly under conditions of climate change and growing demand for environmentally sustainable agriculture. Therefore, the integration of microbial biopreparations with soil-conserving tillage systems provides a promising approach for increasing agroecosystem resilience and improving the structural condition of chernozem soils in sunflower cultivation, supporting the rationale for an integrated management strategy in modern agriculture. Thus, the aim of this study was to determine the impact of selected primary tillage methods and biopreparations on the formation of the aggregate structure of typical chernozem in sunflower (*Helianthus annuus* L.) cultivation.

MATERIALS AND METHODS

The study was conducted in 2023-2024 at the Dokuchaevske experimental field of the State Biotechnological University, located in the Left-Bank Forest-Steppe zone of Ukraine. According to data from the Kharkiv National Agrarian University meteorological station, during the sunflower growing season (May-September) in 2023-2024, total precipitation amounted to 373.1 mm, and the average air temperature was 19.0 °C. The soil cover of the experimental field is represented by typical chernozem heavy loam on loess-like loam (Chernozem Haplic). This soil is characterised by good physical and mechanical, agrochemical, and some chemical properties, fairly high reserves of nutrients available to plants, high humus content, and intensive biological activity. The arable layer of the soil (0-30 cm) contains humus (according to Tyurin (DSTU 7828:2015, 2016)) – 4.9-5.1%, easily hydrolyzable nitrogen (according to Kornfield (DSTU 7863:2015, 2016)) – 81 mg/kg of soil, mobile forms of phosphorus and potassium (according to Chirikov (DSTU 4115:2002, 2003)) – 100 and 200 mg/kg of soil. Content of exchangeable cations: calcium – 37.8%, magnesium – 6.6%, sodium – 0.49%, potassium – 0.5%, hydrogen – 21 mg-equiv./kg soil. The soil reaction – pH: aqueous – 7.0, salt – 5.2-5.6. The experimental plots were arranged using a systematic method with four replicates. The size of the observation plot was 50 m^2.

Experiment A – primary tillage methods:

1. Ploughing with PLN-4-35 at 25-27 cm (control).
2. Chisel local tillage by PC-2.5 at 33-35 cm.
3. Non-moldboard tillage with PRN-31000 at 33-35 cm.
4. Disking by BDM-2.5 at 10-12 cm.

Experiment B – microbial biopreparations:

1. Control (without entry)
2. Azotobacter
3. Bacillus subtilis
4. Trichoderma
5. Microbial consortium (Azotobacter + Bacillus subtilis + Trichoderma).

The study on the effect of biopreparations was conducted under the background of moldboard plowing (PLN-4-35) to a depth of 25-27 cm. The plot area was 30 m², with an accounting area of 10 m². A total of 20 plots (five treatments with four replications) were established, covering a total area of 600 m². The experiment with biopreparations was analysed as an independent single-factor trial in the statistical analysis. The plots were arranged systematically. Effect of biopreparations on soil structure in sunflower Limagrain LG 59580 crops was studied in a randomised block design with four replications. Seed inoculation was performed using four microbial preparations: Azotobacter chroococcum (strain AC-10, Collection № IMV B-7075) – nitrogen-fixing agent; Bacillus subtilis (strain BS-26, IMV B-7324) – phosphate-mobilising bacterium; Trichoderma harzianum (strain TH-17, IMV B-7162) – fungal antagonist; a consortium of the above strains in equal proportions. The preparations were applied as liquid suspensions with a concentration of 1×10^9 CFU/mL. Sterile water with 0.5% humic substances was used as a carrier and natural adhesive. Seeds were sprayed with the suspension 24 hours before sowing at a rate of 10 mL per 1 kg of seed ($\approx 1 \times 10^8$ CFU per seed). The inoculation was performed at 20 ± 2°C and relative humidity of 60-70%. Treated seeds were air-dried and stored under ventilated conditions at ≤15°C until sowing. In the consortium treatment, the ratio of Azotobacter:Bacillus:Trichoderma was 1:1:1 in terms of viable cell count. All treatments were applied only under the ploughing background, without additional soil inoculation.

The experimental agrobackground was uniform across treatments: previous crop – winter wheat; mineral fertilisation – $N_{90}P_{60}K_{60}$ kg/ha a.i.; herbicide regime – application of "Euro-Lightning" at 1.0 l/ha in the 3-4 leaf stage. Soil structural–aggregate composition was determined using the sieving method modified by N.I. Savvinov with the definition of the main fractions of structural aggregates: lumpy (size >10 mm), agronomically valuable (10-0.25 mm) and dusty fractions (<0.25 mm) (DSTU 4744:2007, 2008). This method assesses the granulometric composition of soil aggregates by passing soil samples through a series of sieves with different mesh sizes. The material retained on each sieve was weighed, and the percentage of each fraction was calculated, allowing the classification of soil aggregates by size. The statistical assessment of the reliability of the differences in the measurement results was carried out using the least significant difference ($LSD_{0.5}$) by comparing the calculated Fisher criterion with the theoretical one.

RESULTS AND DISCUSSION

The analysis of soil structural condition revealed significant differences in aggregate distribution depending on the tillage method. In the upper 0-10 cm soil layer, the control treatment (ploughing) exhibited the highest proportion of aggregates >10 mm at 42.4%, which is 1.3-20.6% higher than in the other treatments (Table 1), indicating a lower degree of aggregate fragmentation under conventional plowing. Chisel local tillage reduced the proportion of large clods to 36.3%, while non-inversion tillage further decreased it to 21.8%, reflecting more intensive breakdown of large aggregates and the formation of a more uniform structure. The highest content of the agronomically valuable 5-3 mm fraction was observed under non-inversion tillage (18.7%), which is 10% higher than in the control. Disking maintained a high proportion of large aggregates >10 mm (41.1%), similar to ploughing, but exhibited a lower content of fine fractions (<1 mm).

***Table 1**. Effect of different tillage practices on soil aggregate content*

Soil layer, cm	Content of macroaggregate fractions, %; by diameter, mm							
	>10	10-7	7-5	5-3	3-2	2-1	1-0,5	0,5-0,25
Ploughing with PLN-4-35 at 25-27 cm (control)								
0-10	42.4	11.2	8.0	8.7	8.2	11.3	3.1	4.5
10-20	37.9	8.4	10.7	12.3	9.2	10.8	3.7	4.3
20-30	25.1	10.4	11.9	18.0	15.7	10.9	2.5	4.0
0-30	35.1	10.0	10.2	13.0	11.0	11.0	3.1	4.3
Chisel local tillage by PC-2.5 at 33-35 cm								
0-10	36.3	9.3	10.4	14.7	10.1	12.3	2.1	2.9
10-20	30.4	11.7	12.4	19.3	12.7	9.1	1.6	1.8
20-30	28.6	10.8	11.0	15.8	11.2	13.9	2.8	3.6
0-30	31.8	10.6	11.3	16.6	11.3	11.8	2.2	2.8
Non-moldboard tillage with PRN-31000 at 33-35 cm								
0-10	21.8	11.8	10.0	18.7	16.1	14.7	2.3	2.9
10-20	25.9	14.7	16.6	22.6	10.7	7.3	0.9	0.8
20-30	17.2	16.9	20.3	22.6	10.8	8.3	1.4	1.4
0-30	21.6	14.5	15.6	21.3	12.5	10.1	1.5	1.7
Disking by BDM-2.5 at 10-12 cm								
0-10	41.1	9.4	9.0	12.8	10.6	10.6	1.9	2.7
10-20	19.8	18.2	20.9	20.6	8.5	8.3	1.3	1.5
20-30	37.3	25.3	15.9	11.7	4.4	3.6	0.7	0.6
0-30	32.7	17.6	15.3	15.0	7.9	7.5	1.3	1.6

***Source:** developed by the authors*

More pronounced changes in soil aggregate composition were observed in the 10-20 cm layer under different tillage practices. In the control treatment, the proportion of aggregates >10 mm was 37.9%, whereas it decreased to 25.9% under non-inversion tillage and to 19.8% under disking. In the disking variant, there was a notable increase in the 10-7 mm (18.2%) and 7-5 mm (20.9%) fractions, indicating active fragmentation of structural units in this layer. Chisel local tillage was characterised by an increased content of the 5-3 mm fraction (19.3%), which is 7% higher than in the control. Under non-inversion tillage, the same fraction reached 22.6%, exceeding the control by 10.3%. The results obtained demonstrate that soil tillage systems exert a decisive influence on the structural organisation of the plough layer, particularly in the 20-30 cm horizon. The prevalence of large aggregates (>10 mm) under conventional ploughing indicates the formation of compacted clods, a characteristic feature of inversion tillage, which restricts root penetration and reduces soil porosity. Similar conclusions were reported by V. Steponavičienė *et al.* (2023), who found that ploughed Chernozem soils exhibited increased bulk density and limited aeration compared with non-inversion tillage.

In contrast, the high proportion of 7-5 mm and 5-3 mm aggregates under non-moldboard tillage suggests the development of a more stable and uniform aggregate structure across the profile. B. Liu *et al.* (2024) confirmed that conservation tillage enhances the continuity of soil pore space and promotes aggregate binding through organic carbon stabilisation. The dominance of intermediate fractions under non-inversion systems can thus be attributed to minimal mechanical disturbance combined with the preservation of biological activity, particularly fungal hyphae and bacterial exudates that act as natural aggregating agents. Moreover, A. Vasilchenko *et al.* (2023) demonstrated that reduced tillage fosters greater microbial biomass and enzymatic activity in deeper horizons, which supports the stabilisation of soil aggregates through polysaccharide and glomalin accumulation. The trend observed in this study aligns with the findings of P. Wojewodzki *et al.* (2024), who emphasised that non-inversion tillage increases macroaggregate stability by maintaining higher levels of labile organic matter and hyphal networks. Disking, despite increasing the 10-7 mm fraction, resulted in uneven aggregate distribution, implying that shallow mechanical treatment fails to improve structural integrity in deeper horizons. J. Pöhlitz *et al.* (2022) noted similar effects in light-textured soils, where surface disking improved only the upper layer while leaving subsurface layers compacted. Consequently, the present results confirm that conservation and non-moldboard systems are more effective for maintaining the structural stability of typical chernozem soils than conventional ploughing or shallow disking.

The obtained results demonstrated that ploughing with the PLN-4-35 maintained a predominance of large aggregates (>10 mm) throughout the 0-30 cm layer, reflecting the typical cloddy structure of conventionally inverted soil. This phenomenon is associated with intensive mechanical disturbance and insufficient disintegration of the lower horizons. E. Tobiašová *et al.* (2023) also reported that conventional moldboard systems tend to produce a high share of large, unstable clods in chernozem soils, reducing structural uniformity and aggregate stability. In their study on maize-sunflower rotations, the proportion of aggregates >10 mm exceeded 40%, which is consistent with the present findings. In contrast, the current experiment showed that chisel and non-moldboard tillage promoted the formation of medium-sized aggregates (7-3 mm), contributing to a more favorable soil structure. V. Lozanova and I. Dimitrov (2021) found that chisel loosening at 30-35 cm improved water infiltration by 15% and increased the share of stable aggregates within the 5-3 mm range compared with ploughing. Likewise, L. Wang *et al.* (2023) observed that non-inversion tillage maintained higher aggregate stability in dry continental climates due to reduced mechanical disruption and better root–soil interactions. These trends correspond well with the present study, where non-moldboard tillage resulted in a 4.6% higher content of 5-3 mm aggregates than under ploughing, suggesting enhanced structural uniformity in the 20-30 cm horizon.

Disking to 10-12 cm produced a markedly different pattern. In this treatment, the upper layers (0-10 cm) contained a higher proportion of agronomically valuable aggregates (0.25-10 mm), whereas the deeper layers showed structural degradation. Similar outcomes were described by T. Das *et al.* (2021), who noted that shallow disking tends to over-pulverise surface soil while leaving compacted subsurface layers. M. Ramadhan (2021) also confirmed that excessive fragmentation of the topsoil under disking leads to unstable aggregate formation and increased erosion risk. The current results support these observations, demonstrating a decline in structural quality with depth under disking. The structural coefficient obtained in the present research ranged from 1.3 to 1.6 in the top 0-10 cm layer under ploughing and disking, indicating a satisfactory but not optimal structure. M. Voitovyk *et al.* (2024) in long-term experiments at Bila Tserkva National Agrarian University similarly found that different tillage methods significantly influence soil aggregation dynamics in sunflower agroecosystems. Their results revealed that both ploughing and deep non-moldboard tillage increased the proportion of agronomically valuable aggregates (0.25-10 mm) by approximately 6% at the beginning of the vegetation period, followed by a decline by harvest time due to structural re-compaction. This pattern mirrors the findings of the current study. The increased content of >10 mm and <0.25 mm fractions at the end of the growing season may indicate partial degradation of aggregate stability under repeated mechanical and environmental impacts. Overall, the comparison of results confirms that moderate loosening without inversion, combined with controlled mechanical load, ensures optimal aggregate distribution and water stability in typical chernozem soils. These structural improvements can create favorable conditions for sunflower root growth and moisture retention, thereby supporting sustainable soil management and long-term productivity.

The study revealed significant differences in the content of agronomically valuable aggregates sized 10-0.25 mm depending on the primary tillage system (Fig. 1). In the plowing treatment (control), the total proportion of these aggregates in the 0-30 cm layer was 62.6%. Under chisel tillage, a notable increase was observed, with the content of 0.25-10 mm aggregates averaging 4.0% higher than the control, indicating a more balanced structural condition of the arable layer. Deep non-moldboard tillage had the most favorable effect on aggregate formation across all soil layers, with the mean proportion reaching 77.2%, which exceeded the control by 14.6%. The greatest increases were recorded in the 0-10 cm surface layer (76.5%) and the 20-30 cm layer (81.7%). These results confirm the effectiveness of this tillage practice in increasing the share of aggregates optimal for soil physical properties, thereby improving water infiltration, aeration, and creating favorable conditions for sunflower root system development.

In the disking variant, soil structure was characterised by high variability. On average, aggregates in the 0.25-10 mm range accounted for 66.2%, a proportion comparable to that observed under chisel local tillage but with more pronounced differences between soil layers. In the 10-20 cm soil layer, the share of these aggregates increased to 79.3%, whereas in the 20-30 cm soil layer it sharply decreased to 62.2%. This pattern indicates structural heterogeneity and greater susceptibility of aggregates to breakdown in deeper soil layers. To assess the statistical significance of the differences, an approximate least significant difference (LSD_{05}) was used: 0-10 cm – 6.3, 10-20 cm – 7.0, 20-30 cm – 7.2, 0-30 cm – 6.8. The differences between the non-inversion tillage (PRN-31000) and plowing (PLN-4-35) exceeded the LSD in all layers, indicating their statistical significance within the experiment. Differences between chisel and disk tillage were less pronounced and, in some cases, did not exceed the LSD.

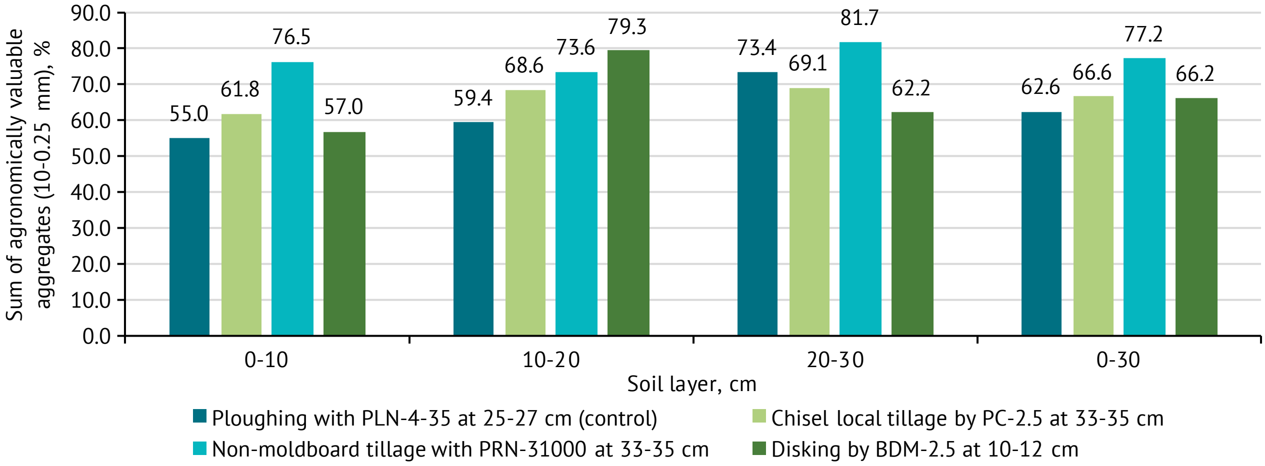

***Figure 1**. The content of agronomically valuable aggregates with a size of 0.25-10 mm, %*
***Source:** developed by the authors*

The results corroborate findings by I. Engell *et al.* (2022) and G. Kovács *et al.* (2023), who reported that conservation and non-inversion tillage maintain better aggregate stability and organic matter retention compared with conventional ploughing. Thus, the use of non-moldboard tillage in sunflower cultivation provides measurable improvements in the structural condition of typical chernozem soils. The obtained results demonstrate that different tillage systems substantially affect the proportion of agronomically valuable aggregates (0.25-10 mm), reflecting their influence on the physical and structural state of the chernozem. The higher proportion of such aggregates under non-moldboard tillage suggests improved soil aggregation and stability, which are critical indicators of soil quality and resilience to degradation. Similar outcomes were reported by Y. Kravchenko *et al.* (2022), who found that non-inversion tillage promoted the accumulation of medium-sized aggregates and enhanced aggregate-associated organic carbon in loamy chernozems. The authors explained this by reduced mechanical disturbance and greater microbial activity in the rhizosphere, which facilitated the cementation of particles into stable structural units. According to M. Malobane *et al.* (2021), chisel and strip tillage systems increase the proportion of water-stable macroaggregates compared to conventional ploughing by 8-15%, owing to the conservation of crop residues and improved pore connectivity. The moderate rise in aggregates of 0.25-10 mm observed in this experiment under chisel tillage (by 4.0% relative to control) corresponds well with their conclusions, confirming that partial soil loosening without inversion supports aggregate regeneration while maintaining aeration and moisture balance.

The pronounced improvement in aggregate formation under deep non-moldboard tillage aligns with findings by C. Wortmann and Y. Dang (2020), who observed enhanced aggregate stability and porosity in deep-loosened chernozem horizons due to reduced plow pan formation and increased biological aggregation. This indicates that loosening without soil turnover fosters a gradual reconstruction of natural structural horizons, which in the following study resulted in a 14.6% higher content of agronomically valuable aggregates compared to plowing. However, E. Farahani *et al.* (2022) reported that in some coarse-textured soils, excessive loosening can lead to temporary structural instability if organic matter is insufficient to sustain aggregate cohesion. This observation partly explains the variability seen in disking treatment in this article, where structural heterogeneity was apparent – especially the sharp decline of aggregates in the 20-30 cm layer – indicating the limited efficiency of shallow disk tillage for deeper profile improvement. The obtained patterns are consistent with the conclusions of A. Alinejadian-Bidabadi *et al.* (2021), who emphasised that soil aggregation is a dynamic process strongly governed by tillage intensity, residue management, and microbial activity. According to these authors, stable aggregates of 0.25-10 mm represent the optimal structural class for balancing aeration, water infiltration, and mechanical strength-parameters that determine the effective rooting of crops such as sunflower (*Helianthus annuus* L.). Thus, the increase in this fraction under non-inversion and chisel tillage in the following experiment indicates not only enhanced soil physical quality but also the potential for improved root development and yield stability.

The application of biopreparations had a distinct effect on the distribution of soil aggregate fractions in the 0-30 cm layer compared to the control. In the control treatment, the proportion of agronomically valuable aggregates (10-0.25 mm) averaged 62.6%, with a relatively high share of large clods (>10 mm, 25.0%) (Fig. 2). To assess the statistical significance of the differences, an approximate least significant difference (LSD) of 7.9% was applied. Considering this LSD_{05}, none of the treatments exceeded it relative to the control, indicating that the increase in the proportion of agronomically valuable aggregates was not statistically significant within the experiment. However, a tendency toward improved soil structure was observed with the application of Bacillus subtilis, Trichoderma, and a microbial consortium, which may have practical relevance with long-term use.

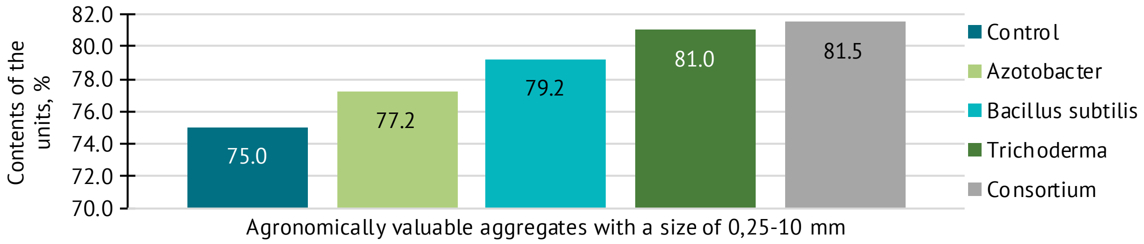

Figure 2. *Effect of biopreparation application on soil structural condition in sunflower crops in the 0-30 cm layer*
Source: *developed by the authors*

The obtained results clearly demonstrate that microbial inoculation modifies the soil's aggregate-size distribution by shifting it toward a finer and more stable structural state. Similar structural transformations were reported by B. Liu *et al.* (2024), who found that inoculation with Azotobacter chroococcum increased the proportion of microaggregates (2-1 mm) and enhanced soil aggregate stability through the accumulation of extracellular polysaccharides that cement mineral particles together. This agrees with the following findings, where Azotobacter inoculation increased the share of 1-2 mm aggregate to 17.5% compared to the control, indicating active biogenic aggregation processes. According to A. Ortiz and E. Sansinenea (2022), Bacillus subtilis strains secrete organic acids and biofilms that bind soil particles and stabilise medium-size fractions, particularly in the 3-5 mm range. A similar mechanism likely operated in the experiment in this article, where the 5-3 mm and 2-1 mm fraction under Bacillus subtilis treatment rose to 16.0% and 18.2%, respectively, suggesting enhanced formation of agronomically valuable aggregates.

The stronger effect observed under Trichoderma and microbial consortium treatments aligns with the conclusions of V. Bolokhovsky *et al.* (2024), who demonstrated that multi-strain inoculants based on Trichoderma harzianum intensify soil aggregation by stimulating fungal hyphal growth and increasing glomalin-related soil proteins. These biopolymers act as natural "glues," stabilising fine and medium-sized aggregates while reducing the presence of large clods. In this study, this mechanism was reflected in a decrease of large aggregates to 18.5-19.0% and an increase of 5-3 mm and 2-1 mm fraction up to 17.2-19.6%, indicating the development of a more uniform cloddy-granular structure. Comparable observations were made by A. Ansabayeva *et al.* (2025), who reported that integrated bioformulations containing Azotobacter, Bacillus, and Trichoderma enhanced soil porosity, aeration, and moisture retention by promoting the aggregation of soil particles into stable structural units. The results if this article confirm these conclusions, showing a consistent transition from a course, cloddy structure toward a finely aggregated one, which supports improved water infiltration and sunflower root growth. Thus, microbial inoculation, particularly using multifunctional consortia, can be regarded as a promising biotechnological tool for improving soil physical quality and structural resilience.

CONCLUSIONS

The study results demonstrated that primary tillage technology significantly influences the formation of soil structure in sunflower (*Helianthus annuus* L.) cultivation. Conventional moldboard plowing (PLN-4-35 at 25-27 cm) produced the highest proportion of large aggregates (>10 mm) in the 0-30 cm layer (35.1%), but this was accompanied by a lower content of agronomically valuable 5-3 mm fractions, which may reduce structural resistance to water erosion. Chisel subsoiling (PC-2.5 at 33-35 cm) and deep non-inversion tillage (PRN-31000 at 33-35 cm) reduced the proportion of large clods and increased the 5-3 mm fraction by 3.6-8.3% compared to the control, creating more favorable conditions for root growth and water infiltration. Disking (BDM-2.5 at 10-12 cm) increased the proportion of medium aggregates (10-5 mm) in the upper horizon but showed limited effect on deeper layers, which may limit its long-term effectiveness.

Based on statistical assessment using the least significant difference (LSD_{05}), deep non-inversion tillage (PRN-31000) significantly improved the overall proportion of agronomically valuable aggregates in the 0-30 cm layer (77.2%) compared to conventional plowing – 62.6%, whereas differences between chisel and disking treatments were less pronounced and mostly did not exceed the LSD_{05} threshold – 6.3-7.2%, indicating non-significant effects. The application of microbial biopreparations contributed to improving soil structural status in sunflower crops. Their use led to a reduction in oversised aggregates (>10 mm) and a simultaneous increase in agronomically valuable fractions (0.25-10 mm), particularly in the 5-3 mm and 2-1 mm range. Among the treatments, the microbial consortium exhibited the most pronounced effect, yielding the highest proportion of optimally sized aggregates (81.5%) and promoting a more homogeneous and stable granular–cloddy structure. However, LSD_{05} analysis (7.9%) indicated that differences from the control were not statistically significant, suggesting that while trends were positive, further research is required to confirm significance.

In summary, deep non-inversion and chisel tillage were the most effective mechanical methods for maintaining chernozem fertility and promoting a stable cloddy structure under the experimental conditions. The integration of microbial biopreparations can enhance soil porosity, water infiltration, and aeration, creating favorable conditions for sunflower root development. Future studies should investigate the long-term effects of combined tillage and biopreparation applications on soil structural dynamics, biological activity, and sunflower yield under changing climatic conditions, with particular attention to microbiological processes within different structural fractions and their role in stabilising soil organic matter.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Ministry of Education and Science for the appreciation of the research area, the results of which are presented in this article and are the basis for the tasks of the project «Development of measures to ensure the sustainable productivity of agrophytocenoses under the influence of abiotic and biotic stress factors» (state registration number 0124U000457).

FUNDING

None.

CONFLICT OF INTEREST

None.

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Вплив способів обробітку ґрунту та біопрепаратів на структурний стан ґрунту

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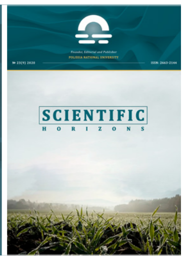
Анотація. Мета дослідження полягала у визначенні впливу різних технологій основного обробітку ґрунту та застосування біопрепаратів на структурний стан чорнозему у посівах соняшнику. У дослідженні були використані такі методи: польовий (закладка стаціонарного досліду за схемою рендомізованих блоків), лабораторний (визначення фракційного складу ґрунту методом сухого просіювання), статистичний (дисперсійний аналіз для оцінки достовірності різниць між варіантами). Отримані результати показали, що традиційна оранка забезпечує найвищий вміст великих агрегатів (>10 мм) у шарі 0-30 см (35,1 %), проте характеризується відносно низьким вмістом агрономічно цінних фракцій 5-3 мм, що зменшує стійкість структури до впливу ерозійних процесів. Чизельний локальний та безполицевий глибокі обробітки сприяли зниженню частки великих грудок і підвищенню вмісту оптимальних за розміром агрегатів на 3,6-8,3 % у порівнянні з контролем, що забезпечує кращий водно-повітряний режим і сприятливі умови для розвитку кореневої системи соняшнику. Застосування мікробних біопрепаратів сприяло подальшому покращенню структури ґрунту за рахунок зменшення частки брилистих фракцій та збільшення частки агрономічно цінних розміром 0,25-10 мм. Найбільш виражений ефект було зафіксовано при обробці консорціумом, що сприяло формуванню більш однорідної та стабільної грудкувато-зернистої структури, де кількість агрономічно цінних агрегатів склала 81,5 %. Практична цінність роботи полягає у визначенні ефективних прийомів обробітку ґрунту та застосування біопрепаратів для поліпшення структурного стану чорнозему типового в посівах соняшнику. Отримані результати можуть бути використані у виробничих умовах для збереження родючості ґрунтів, підвищення ефективності використання вологи та забезпечення екологічної стійкості агроекосистем

Ключові слова: системи основного обробітку; структурно-агрегатний склад ґрунту; чорнозем; агрофізичні властивості; соняшник; біологізація землеробства

SCIENTIFIC HORIZONS
Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 28(10), 54-66
UDC 630*6:574(477.41/.42) DOI: 10.48077/scihor10.2025.54



Productivity of modal forest stands in Ukrainian Polissia depending on the compliance of the main tree species with the native forest type

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Article's History:
Received: 29.05.2025
Revised: 03.09.2025
Accepted: 24.09.2025

Abstract. The study aimed to assess the composition and mensurational characteristics of near-native and secondary forest stands, compare their mean annual increment with native references, and clarify natural productivity patterns across site conditions. The analysis was based on forest inventory data combined with geoinformation resources. Productivity was assessed by comparing mean increment values and ranking natural productivity scores. The average species composition of compositionally near-native modal stands differed from that of the reference native stands across most forest-site types. In poor and fairly poor site conditions, a higher share of silver birch (*Betula pendula* Roth) was observed; in fairly rich site conditions, higher proportions of birch (*B. pendula*) and European hornbeam (*Carpinus betulus* L.); and in rich site conditions, a suite of native hard- and soft-broadleaved species. Secondary stands showed the following patterns: in poor site conditions they were dominated by jack pine (*Pinus banksiana* Lamb.) and birch (*B. pendula*); in fairly poor and fairly rich site conditions by birch (*B. pendula*); and in rich site conditions by hornbeam (*C. betulus*), northern red oak (*Quercus rubra* L.), Scots pine (*Pinus sylvestris* L.), black alder (*Alnus glutinosa* (L.) Gaertn.), and birch (*B. pendula*). The mean increment of modal Scots pine stands exceeded native references by 17-58% in poor site conditions and by 2-48% in fairly poor site conditions, depending on the soil moisture regime, whereas in fairly rich site conditions, modal stands close in composition to native forests fell short by 19-37%, while in rich site conditions the increments were similar. In the most widespread site types in poor, fairly poor, and fairly rich site conditions, modal native stands were more productive than

Suggested Citation:
Siruk, Yu., Siruk, I., & Turko, V. (2025). Productivity of modal forest stands in Ukrainian Polissia depending on the compliance of the main tree species with the native forest type. *Scientific Horizons*, 28(10), 54-66. doi: 10.48077/scihor10.2025.54.

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secondary ones; in rich site conditions, however, secondary stands prevailed by 13-16%. The productivity scores of modal stands differed substantially from those of the native reference scales: they were higher in poor and fairly poor site conditions but lower in rich site conditions. The highest natural productivity scores of secondary stands were recorded in fresh and moist rich site conditions and in fresh fairly poor site conditions. The obtained results provided a scientific basis for refining the scales of natural productivity and for typology-based planning of silvicultural measures

Keywords: forest site conditions; mean annual increment; tree species composition; secondary forest stand; native reference stands; productivity assessment scale

INTRODUCTION

The assessment of forest productivity in relation to stand composition and site conditions has acquired growing importance in light of climate change and the intensification of forest use. The productivity of native and secondary forest stands is a key indicator of ecosystem stability, carbon sequestration, and the efficiency of forest management strategies. In Ukrainian Polissia, where natural and post-disturbance stands coexist across diverse forest-site conditions, understanding how species composition and stand origin influence productivity remains a priority for sustainable forestry planning. The research of H. Pretzsch *et al.* (2023) showed that forest growth in Europe demonstrates divergent regional trends, largely due to climate-induced disturbances such as droughts and heatwaves, which significantly alter biomass accumulation patterns. These findings emphasise the need to investigate productivity not only by ecological region but also within typological frameworks reflecting site quality and stand composition.

Numerous studies have underlined that the stability and level of forest productivity are closely linked to the biological and structural diversity of stands. M. del Río *et al.* (2022) found that the mixture of two or more tree species increases resistance to interannual climate variability, contributing to more stable productivity. T. Hilmers *et al.* (2024) further demonstrated that structural diversity modifies crown biomass allocation and enhances growth efficiency, promoting resource-efficient and climate-resilient forests. Similarly, T. Wang *et al.* (2024) confirmed that stand structure plays a more decisive role in sustaining productivity stability than species diversity alone, highlighting that optimal canopy stratification and age heterogeneity are crucial for maintaining increment under changing environmental conditions. Climatic sensitivity varies considerably among tree species typical for Polissia. Research by P. Dukat *et al.* (2023) revealed that Scots pine (*Pinus sylvestris* L.) exhibits a pronounced physiological response to drought, manifested in reduced sap flow and photosynthetic activity, which directly limits its increment potential in poor site conditions. In contrast, *Ā. Jansons et al.* (2025) demonstrated that older hemiboreal stands, particularly those dominated by broadleaved species, retain higher carbon storage and long-term productivity, although they grow more slowly than secondary pine or birch forests. These conclusions support the principle that natural or near-natural stands provide greater ecological stability and contribute more effectively to carbon balance maintenance. At the policy level, the State Forest Resources Agency of Ukraine (2025) emphasised the gradual implementation of close-to-nature silvicultural approaches, reduction of reconstruction fellings, and greater reliance on natural regeneration processes. This reflects a broader shift in forest management philosophy from a raw-material focus to a multifunctional ecological framework.

Therefore, the scientific community increasingly recognises that the assessment of forest productivity must integrate ecological typology, site conditions, and stand origin. Comparative evaluation of native, near-native, and secondary formations provides a robust basis for refining natural productivity scales and guiding adaptive silvicultural strategies in Polissia. The aim of the research is to evaluate the average composition and average mensurational indicators (age, stock volume, increment) of compositionally close to native and secondary forest stands, to compare their mean annual increment with native reference stands, and to refine the scale of natural productivity across forest site conditions.

LITERATURE REVIEW

Forest stand productivity is one of the key indicators of the ecological and economic functionality of forest ecosystems, as well as an important measure of their long-term capacity to accumulate biomass and carbon. Within Ukrainian Polissia, traditionally characterized by a cold-humid climate, widespread pine forests, podzolic soils, and extensive coniferous and mixed forest areas, contemporary climatic and anthropogenic drivers may significantly alter the spatiotemporal dynamics of productivity (Snizhko *et al.,* 2024). When analyzing productivity and stability, it is essential to distinguish stand origin. In national forestry and mensurational practice, *native stands* are defined as those formed under minimal anthropogenic disturbance, with natural succession and a typical valuable species composition characteristic of specific forest formations. In contrast, *secondary stands* emerge following major disturbances (clear-cutting, fire, drainage, or changes in groundwater regime) and are often represented by fast-growing or secondary species combinations, modified in taxonomic and structural composition (Tkach *et al.*, 2024). According to national estimates, the area of secondary stands in lowland Ukraine reaches about 400,000 ha, with nearly 48% located in Polissia. In Polissia, stand origin directly affects the level and stability of productivity: empirical field studies indicate that mixed and partially restored stands (e.g., pine–birch combinations) may demonstrate higher bioproductivity compared with pure modal pine stands, though with a different sensitivity profile to fire risk or water deficit. To enhance structural stability and increase productivity in young secondary stands, close-to-nature silviculture is effective. This approach maximizes site potential by applying complex regeneration harvests in combination with measures that support natural regeneration of native species (Zhezhkun *et al.,* 2023). Ukrainian researchers emphasize that the foundation for increasing forest productivity should be the differentiation of forest management systems and silvicultural measures on a zonal-typological basis.

The forest cenoses of Ukrainian Polissia, depending on site type, are dominated by Scots pine (*Pinus sylvestris* L.), silver birch (*Betula pendula* Roth), pedunculate oak (*Quercus robur* L.), black alder (*Alnus glutinosa* (L.) Gaertn.), and aspen (*Populus tremula* L.). Scots pine (*P. sylvestris*), common in northern temperate latitudes, traditionally exhibits high plasticity regarding soil-moisture regimes and often ensures stable primary increment on the poor sandy soils of Polissia. However, its productivity is strongly constrained under extreme events, as droughts can significantly reduce increment and regeneration. This is confirmed by regional and interregional analyses of pine responses to climatic drivers and previous growth status (Mikalajūnas *et al.*, 2021). On poor and dry sites, pine stands often outperform more demanding species, but their sensitivity to frequent extremes (drought-induced dieback, windthrow, or pest outbreaks following stress) makes long-term stability of productivity vulnerable. Oak stands (*Q. robur* and *Q. petraea*) are characterized by slower initial growth, but under favorable soil and nutrient conditions, they form high long-term productivity and stable biomass stocks (Uhl *et al.*, 2022; Cerný *et al.*, 2024). Recent studies show that mixing oak with other species (particularly pine) may partly compensate for productivity losses under climate change, though the effects depend strongly on soil quality and local microclimatic conditions (Vospernik *et al.*, 2024). Oak forests provide more stable long-term carbon sequestration potential compared with secondary stands of fast-growing species, although their early productivity is often lower. Management interventions (site selection, species mixtures) are therefore crucial for enhancing total productivity in young stands (Sabatini *et al.*, 2019).

Birch (*B. pendula*) and aspen (*P. tremula*) are typical early successional species colonizing disturbed areas. They rapidly occupy open space, accelerate biomass accumulation, and improve soil fertility in the early stages of recovery. However, in the mid- to long-term, their productivity often falls short of target stands due to lower long-term carbon accumulation and faster dieback of groups under natural thinning (Martiník *et al.*, 2024). New modeling approaches and the development of site-index systems for birch have improved the ability to predict its productivity across different soils (Lee *et al.*, 2024). As pioneer species, birch and aspen enhance early cumulative productivity and support reclamation and soil improvement, but their long-term contribution to timber reserves and stability is limited. Thus, their optimal role is temporary within restoration systems or as components of mixed stands (Tullus *et al.*, 2025).

Black alder (*A. glutinosa*) is an important tree species that plays a key role in restoring degraded lands, particularly in Ukrainian Polissia (Lukyanets *et al.*, 2022). Its capacity for rapid growth, efficient nitrogen fixation, and soil-improving properties makes it promising for forestry (Anadon-Rosell *et al.*, 2022). Black alder thrives on moist soils, including floodplains, where its productivity can reach 10-15 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ depending on water regime and soil fertility. In mixed stands of black alder with other species such as willow (*Salix*), total biomass accumulation increases. For example, studies in Croatia revealed that alder–willow mixtures produced greater total biomass than alder monocultures (Bogdan *et al.*, 2017), highlighting the positive effect of species coexistence in enhancing productivity and ecosystem stability. In general, forest productivity in Ukrainian Polissia depends on the interaction between climate, site conditions, and species composition. Scots pine dominates poor soils but is vulnerable to drought stress, while oak and black alder provide higher long-term productivity and carbon storage on richer sites. Birch and aspen enhance early biomass accumulation but have limited long-term potential. Mixed and near-natural stands offer greater stability and efficiency, confirming the importance of close-to-nature and typology-based management for sustaining productivity across diverse forest conditions.

MATERIALS AND METHODS

The database of the production association Ukrderzhlisproekt (n.d.) served as the primary source of data for the analysis. The general population of forest-covered plots belonging to the structural subdivisions of the the State Specialized Forest Enterprise Forests of Ukraine (n.d.) that territorially fall within Ukrainian Polissia includes: parts of Volyn, Rivne, Khmelnytskyi, Zhytomyr, Kyiv, Chernihiv, and Sumy regions. A geospatial analysis was conducted using data from the Ukrainian Research Institute of Forestry and Agroforestry (n.d.)

and the State Forest Fund of Ukraine (2025), which made it possible to establish the territorial affiliation of the forest fund of the forestry divisions of the Northern Forestry Enterprise, Polissya Forestry, Stolychny Forestry, and Podillya Forestry to the Ukrainian Polissya region. The query and analysis were conducted using the Lisovporiadnyk software in two stages for each forest site type (Aleksiiuk *et al.*, 2019). At the first stage, the average tree species composition of native (including those close to and distant from the reference native structure) and secondary stands was determined for each forest type. The correspondence of the main tree species to the native species of a given forest type was determined programmatically by using the query "native species of the forest type" in the "Derived Indicators" section. Stands where the main species matched the native species of the forest type were classified as native; otherwise, they were classified as secondary. At the second stage, the average mensurational indicators of modal stands - both those corresponding and not corresponding to the main species of native stands of a given forest type - were calculated for the most widespread forest site conditions.

The average tree species composition was determined as the ratio of cumulative growing stock of component species using the query in the "Characteristics of Tree Species Components" section, following the standard forest inventory methodology (Ukrderzhlisproekt, n.d.). The average age and average volume stock per hectare were determined programmatically: average age was calculated as a weighted mean of the main species values across compartments, and average growing stock per hectare was obtained as a weighted mean of the cumulative values of the first and second canopy layers of each stand unit. The mean annual increment (MAI) was calculated as the ratio of the average growing stock per hectare to the average age. The basic unit of analysis was the forest subcompartment. The sample sizes of stands across forest site types were as follows: A_0 – 0.1 thousand subcompartments, A_1 (n.d.) 14.8 thousand, A_2 (n.d.) 90.6 thousand, A_3 (n.d.) 11.2 thousand, A_4 (n.d.) 6.3 thousand, A_5 (n.d.) 7.1 thousand, B_1 (n.d.) 1.9 thousand, B_2 (n.d.) 247.1 thousand, B_3 (n.d.) 196.6 thousand, B_4 (n.d.) 65.7 thousand, B_5 (n.d.) 16.9 thousand, C_2 (n.d.) 99.0 thousand, C_3 (n.d.) 133.5 thousand, C_4 (n.d.) 89.0 thousand, C_5 (n.d.) 9.8 thousand, D_2 (n.d.) 16.5 thousand, D_3 (n.d.) 11.1 thousand, D_4 (n.d.) 1.9 thousand, and D_5 (n.d.) 0.1 thousand. The assessment scale of natural productivity by forest site conditions was developed through ranking productivity scores separately for native and secondary stands (Turkevych *et al.*, 1973). Productivity scores were defined by ranking MAI values for native and secondary stands independently. Comparisons of productivity between native and secondary stands across forest site conditions were made based on MAI indicators.

RESULTS AND DISCUSSION

Based on the analysis of forest inventory data from more than 130,000 subcompartments within Ukrainian Polissia, it was established that in poor site conditions, the most productive stands are modal Scots pine forests in fresh and moist sites, where the MAI per hectare exceeds 4 m^3 (Table 1).

Table 1*. Average mensurational characteristics of modal stands corresponding to the main species of forest types in poor site conditions*

Forest site conditions	Tree species composition	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
A_0	100% -Scots pine	50	43	0.86
A_1	100% –Scots pine, <5% (n.d.) silver birch	50	134	2.68
A_2	100% –Scots pine, <5% (n.d.) silver birch	47	200	4.26
A_3	90% –Scots pine, 10% (n.d.) silver birch	46	186	4.04
A_4	90% –Scots pine, 10% (n.d.) silver birch	50	137	2.74
A_5	90% –Scots pine, 10% (n.d.) silver birch	70	100	1.43

Source: *developed by the authors*

It should be noted that, compared with the data in Table 1, average tree species composition of modal stands in fresh and moist poor site conditions of Ukrainian Polissia, according to V. Tkach *et al.* (2024), reveals a relatively lower proportion of silver birch: occurring sporadically in fresh sites and up to 5% in moist sites. In comparison with findings reported by researchers I. Turkevych *et al.* (1973) half a century ago, who also confirmed the highest productivity of native reference Scots pine stands in these site conditions, the MAI per unit area of modal stands is now 17% higher in A_2 and as much as 47% higher in A_3. It is also worth noting the comparatively higher MAI of modal Scots pine stands in other forest site conditions: 27% higher in A_1, 58% in A_4, and 55% in A_5.

The productivity of secondary stands in dry poor site conditions is lower compared with modal Scots pine (*P. sylvestris* L.) stands, with MAI reduced by 9%. Secondary stands are also less productive in fresh and moist poor site conditions, where their increment falls short of modal stands by 9% and 21%, respectively. Conversely, in very dry and very wet poor site conditions, secondary stands demonstrate higher MAI: in A_0 by 33% and in A_5 by 51% (Tables 1-2). The tree species composition of secondary stands in dry and very dry poor site conditions is dominated mainly by jack pine (*Pinus banksiana* Lamb.), whereas in other site conditions silver birch (*B. pendula* Roth) prevails.

***Table 2**. Average mensurational characteristics of secondary forest stands in poor site conditions*

Forest site conditions	Tree species composition	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
A_0	60% – jack pine, 40% (n.d.) Scots pine	53	68	1.28
A_1	50% – jack pine, 30% (n.d.) silver birch, 20% (n.d.) Scots pine, <5% (n.d.) Crimean pine (*Pinus nigra* subsp. *pallasiana*)	45	110	2.44
A_2	70% (n.d.) silver birch, 10% (n.d.) Scots pine, 10% – jack pine, 10% – black locust *(Robinia pseudoacacia L.)*. <5% (n.d.) Crimean pine	40	155	3.88
A_3	80% (n.d.) silver birch, 10% (n.d.) Scots pine, 10% – European aspen	38	122	3.21
A_4	90% (n.d.) silver birch, 10% (n.d.) Scots pine, <5% (n.d.) European aspen, black alder	33	92	2.79
A_5	80% (n.d.) silver birch, 20% (n.d.) Scots pine, <5% (n.d.) European aspen, black alder	37	107	2.89

***Source:** developed by the authors*

According to long-term studies in Northern and Eastern European countries, the MAI of Scots pine (*P. sylvestris* L.) on poor sandy soils ranges from 4 to 6 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ (Varnagiryte-Kabašinskienė *et al.*, 2015). Ukrainian studies demonstrate similar productivity values for modal stands in poor site conditions. The MAI of modal stands corresponding to the main species of the native forest type in fairly poor site conditions, based on current forest inventory data, demonstrates higher productivity compared with native reference Scots pine stands (Turkevych *et al.*, 1973). In dry fairly poor site conditions, the MAI was 32% higher; in fresh fairly poor site conditions (n.d.) 7% higher; in moist site conditions (n.d.) 2% higher; in wet site conditions (n.d.) 42% higher; and in very wet site conditions (n.d.) 48% higher. With regard to productivity across moisture regimes, the most productive forest site conditions are fresh sites, whereas the least productive are very wet sites (Table 3).

***Table 3**. Average mensurational characteristics of modal stands corresponding to the main species of forest types in fairly poor site conditions*

Forest site conditions	Tree species composition	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
B_1	100% -Scots pine, <5% (n.d.) silver birch	50	199	3.98
B_2	90% -Scots pine, 10% - silver birch, <5% (n.d.) pedunculate oak	51	268	5.25
B_3	90% -Scots pine, 10% - silver birch, <5% (n.d.) pedunculate oak, black alder	51	236	4.63
B_4	80% -Scots pine, 20% - silver birch, <5% (n.d.)black alder	48	172	3.58
B_5	80% -Scots pine, 20% - silver birch, <5% (n.d.)black alder	63	131	2.08

***Source:** developed by the authors*

The tree species composition of modal stands corresponding to the main species of forest types in fresh, moist, wet, and very wet fairly poor site conditions differs somewhat from the data reported by V. Tkach *et al.* (2024). In fresh fairly poor site conditions, a higher proportion of silver birch (*B. pendula* Roth) and pedunculate oak (*Q. robur* .) was observed; in moist sites, black alder (*A. glutinosa* (L.) Gaertn.) appeared in the composition; while in wet and very wet sites, silver birch (*B. pendula* Roth) was markedly more abundant along with the presence of black alder (*A. glutinosa* (L.) Gaertn.). In the composition of secondary stands in fairly poor site conditions, silver birch (*B. pendula* Roth) predominates. The MAI of secondary stands in most moisture regimes, except for very wet sites, is lower than that of modal Scots pine stands by 7-21% (Table 4). In very wet sites, however, secondary birch stands exhibit a higher MAI, exceeding that of modal Scots pine stands by 11%.

***Table 4**. Average mensurational characteristics of secondary forest stands in fairly poor site conditions*				
Forest site conditions	**Tree species composition**	**Mean age, years**	**Mean stand volume, $m^3 \cdot ha^{-1}$**	**Mean annual increment (MAI), $m^3 \cdot ha^{-1}$**
B_1	40% – silver birch, 30% –Scots pine, 20% (n.d.) pedunculate oak, 10 % – Norway spruce (*Picea abies* (L.) H. Karst.) <5% (n.d.) black locust	42	139	3.31
B_2	70% – silver birch, 10% –Scots pine, 10% (n.d.) pedunculate oak, 10% – European aspen, <5% (n.d.) black locust, Norway spruce	45	195	4.33
B_3	60% – silver birch, 10% –Scots pine, 10% (n.d.) pedunculate oak, 10 % – European aspen, 10 % – black alder, <5% (n.d.) Norway spruce	47	171	3.64
B_4	70% – silver birch, 10% –Scots pine, 10 % – black alder, 10 % – European aspen	38	127	3.34
B_5	80% – silver birch, 10% -Scots pine, 10 % – black alder, <5% (n.d.) European aspen	46	108	2.35

Source: *developed by the authors*

According to studies conducted in Lithuania by E. Linkevičius *et al.* (2023), the MAI of Scots pine (*P. sylvestris* L.) on sandy loam soils is approximately 5.2 $m^3 \cdot ha^{-1} \cdot yr^{-1}$. Silver birch (*B. pendula* Roth) also demonstrates high productivity under fairly poor site conditions. In comparison, data obtained in Ukraine indicate that the MAI of Scots pine on sandy loam soils is about 4.5 $m^3 \cdot ha^{-1} \cdot yr^{-1}$, while that of silver birch is 5.0 $m^3 \cdot ha^{-1} \cdot yr^{-1}$. These values highlight certain differences in productivity across Central Europe (Martiník *et al.*, 2018).

In fairly rich site conditions of Ukrainian Polissia, dry moisture regimes are atypical. Native stands in fresh and moist fairly rich site conditions are generally complex in structure, with Scots pine (*P. sylvestris*) prevailing in the upper canopy layer and European hornbeam (*Carpinus betulus* L.) dominating the lower layer. In wet and very wet fairly rich site conditions, black alder (*A. glutinosa* (L.) Gaertn.) is typically the dominant species. The composition of modal stands corresponding to the main species of forest types in fresh and wet fairly rich site conditions differs somewhat from the findings of V. Tkach *et al.* (2024): in fresh sites, a higher share of silver birch (*B. pendula*) occurs in the upper canopy layer and a lower share of hornbeam (*C. betulus*) in the lower layer, while in wet sites, silver birch (*B. pendula*) accounts for a substantially greater proportion. The average mensurational characteristics of modal stands corresponding to the main species of forest types in fairly rich site conditions are presented in Table 5.

***Table 5**. Average mensurational characteristics of modal stands corresponding to the main species of forest types in fairly rich site conditions*				
Forest site conditions	**Tree species composition 1st canopy layer / 2nd canopy layer**	**Mean age, years**	**Mean stand volume, $m^3 \cdot ha^{-1}$**	**Mean annual increment (MAI), $m^3 \cdot ha^{-1}$**
C_2	70% – Scots pine, 20% (n.d.) pedunculate oak, 10% – silver birch, <5% (n.d.) European hornbeam, European aspen / 70% – European hornbeam, 10% – Norway spruce, 10% (n.d.) pedunculate oak, 10% – Scots pine, <5% (n.d.) silver birch, small-leaved lime (*Tilia cordata* Mill.), Norway maple (*Acer platanoides* L.)	55	273	4.96
C_3	50% – Scots pine, 30% (n.d.) pedunculate oak, 10% – silver birch, 10% – black alder, <5% (n.d.) European hornbeam, European aspen, Norway spruce / 70% – European hornbeam, 20% (n.d.) pedunculate oak, 10% – Norway spruce, <5% (n.d.) silver birch, Scots pine, small-leaved lime	52	218	4.19
C_4	80% – black alder, 20% – silver birch, <5% (n.d.) Scots pine, European aspen, pedunculate oak	45	169	3.76
C_5	80% – black alder, 20% – silver birch, <5% (n.d.) Scots pine, European aspen	51	154	3.02

Source: *developed by the authors*

The highest values of MAI in modal stands corresponding to the main species of forest types were recorded in fresh and moist fairly rich site conditions. The MAI of modal stands corresponding to the main species of forest types is lower in all fairly rich site conditions than in native reference stands: in fresh sites by

30%, in moist sites by 37%, in wet sites by 19%, and in very wet sites by 26%. In tree species composition of secondary stands, pedunculate oak (*Q. robur* .) is most common in fresh fairly rich site conditions, while silver birch (*B. pendula* Roth) dominates in more humid site conditions (Table 6). The MAI of secondary stands across all mesic site types is lower compared with modal stands corresponding to the main species of fairly rich site conditions: in fresh sites by 20%, in moist sites by 8%, in wet sites by 4%, and in very wet sites by 11%.

Table 6*. Average mensurational characteristics of secondary forest stands in fairly rich site conditions*

Forest site conditions	Tree species composition 1st canopy layer / 2nd canopy layer	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
C_2	40% (n.d.) pedunculate oak, 20% – silver birch, 20% –Scots pine, 10% – European hornbeam, 10% – European aspen, <5% (n.d.) Norway spruce, northern red oak (*Quercus rubra* L.), black alder / 80% – European hornbeam, 10% – Norway spruce, 10% (n.d.) pedunculate oak, <5% (n.d.) Scots pine, Norway maple	53	211	3.98
C_3	40% – silver birch, 20% (n.d.) pedunculate oak, 10% – black alder, 10% – European aspen, 10% –Scots pine, 10% – European hornbeam, <5% (n.d.) Norway spruce, northern red oak, European ash (*Fraxinus excelsior* L.) / 80% – European hornbeam, 10% – pedunculate oak, 10% – silver birch, <5% (n.d.)Norway maple, small-leaved lime	51	196	3.84
C_4	60% – silver birch, 20% – black alder, 10% – European aspen, 10% – Scots pine, <5% (n.d.)pedunculate oak, Norway spruce, white willow (*Salix alba* L.)	41	148	3.61
C_5	70% – silver birch, 20% – black alder, 10% – European aspen, <5% (n.d.) Scots pine, white willow	50	134	2.68

Source: *developed by the authors*

According to A. Terentiev *et al.* (2023), the MAI of Scots pine (*P. sylvestris* L.) on loamy soils varies from 5 to 8 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ at the age of 60-80 years. These values may change depending on specific site conditions, particularly humus content and soil moisture (Aldea *et al.*, 2021). The MAI of pedunculate oak (*Q. robur* .) on loamy soils is approximately 4-6 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ at the age of 80-100 years (Kazimirović *et al.*, 2024). Compared with other species, silver birch (*B. pendula* Roth) demonstrates faster growth in fairly rich site conditions. The MAI of black alder (*A. glutinosa* (L.) Gaertn.) on loamy soils reaches about 6-8 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ at the age of 50-70 years. Alder is especially productive at a young age. Rich site conditions are comparatively the least represented in Ukrainian Polissia, dry sites are absent altogether in the region. In the tree species composition of modal stands corresponding to the main species of forest types in fresh and moist rich site conditions, pedunculate oak (*Q. robur*) typically dominates the upper canopy layer, accounting for 30-40% of the total volume, while hornbeam (*C. betulus* L.) dominates the lower canopy. In wet and very wet rich site conditions, black alder (*A. glutinosa*) prevails in simple-structured stands (Table 7).

Table 7*. Average mensurational characteristics of modal stands corresponding to the main species of forest types in rich site conditions*

Forest site conditions	Tree species composition 1st canopy layer / 2nd canopy layer	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
D_2	40% (n.d.) pedunculate oak, 10% – European hornbeam, 10% – European aspen, 10% – silver birch, 10% – European ash, 10% – Norway maple, 10% – small-leaved lime, <5% (n.d.) Norway spruce, Scots pine/ 70% – European hornbeam, 20% – Norway spruce, 10% (n.d.) Norway maple, <5% (n.d.) small-leaved lime	53	202	3.81
D_3	30% (n.d.) pedunculate oak, 10% – European hornbeam, 10% – European aspen, 10% – silver birch, 10% – European ash, 10% – Norway maple, 10% – small-leaved lime, 10% – black alder, <5% (n.d.) Norway spruce / 70% – European hornbeam, 20% – Norway spruce, 10% (n.d.) Norway maple, <5% (n.d.) small-leaved lime	54	204	3.78
D_4	70% – black alder, 10% pedunculate oak, 10% – silver birch, 10% – European ash, <5% (n.d.) European aspen, small-leaved lime, European hornbeam	47	179	3.81
D_5	90% – black alder, 10% – silver birch, <5% (n.d.) European ash, white willow	54	172	3.19

Source: *developed by the authors*

The tree species composition of modal stands corresponding to the main species of forest types in fresh and wet rich site conditions differs substantially from the data of V. Tkach *et al.* (2024), showing greater species diversity and a lower share of the main species (n.d.) pedunculate oak (*Q. robur* .) and black alder (*A. glutinosa* (L.) Gaertn.). The MAI of modal stands corresponding to the main species of forest types does not vary significantly among fresh, moist, and wet rich site conditions. Native reference stands of rich site conditions demonstrate considerably higher increments, with the highest productivity recorded in moist rich site conditions. Based on current forest inventory data, the MAI of modal stands corresponding to the main species is lower than that of native reference stands by nearly 41% in fresh sites, by 51% in moist sites, by 30% in wet sites, and by 45% in very wet sites. Regional studies have shown that the optimal productivity range of oak stands in Polissia is between 5 and 12 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ depending on age and site index. The highest increments are reached in intermediate-aged stands (~35 years), after which current increment stabilizes or slightly declines.

In the tree species composition of secondary stands, hornbeam (*C. betulus* L.) dominates in fresh and moist rich site conditions, black alder (*A. glutinosa*) in wet sites, and silver birch (*B. pendula* Roth) in very wet sites (Table 8). The productivity of secondary stands compared with modal stands corresponding to the main species of forest types is higher in all moisture regimes of rich site conditions except wet ones. In fresh rich site conditions, the MAI of secondary stands exceeds that of modal stands by 16%, in moist sites by 13%, and in very wet sites by 14%.

***Table 8**. Average mensurational characteristics of secondary forest stands in rich site conditions*

Forest site conditions	Tree species composition 1st canopy layer / 2nd canopy layer	Mean age, years	Mean stand volume, $m^3 \cdot ha^{-1}$	Mean annual increment (MAI), $m^3 \cdot ha^{-1}$
D2	20% – European hornbeam, 20% – northern red oak, 20% – Scots pine, 10% (n.d.) pedunculate oak, 10% – silver birch, 10% – European ash, 10% – European aspen, <5% (n.d.) Norway spruce, small-leaved lime / 70% – European hornbeam, 20% – Norway maple, 10% – Norway spruce, <5% (n.d.) small-leaved lime	48	217	4.52
D3	20% – European hornbeam, 10% – northern red oak, 10% – Scots pine, 10% (n.d.) pedunculate oak, 10% – silver birch, 10% – European ash, 10% – European aspen, 10% – black alder, 10% – small-leaved lime, <5% (n.d.) Norway spruce / 50% – European hornbeam, 20% – Norway maple, 20% – Norway spruce, 10% (n.d.) pedunculate oak, <5% (n.d.) small-leaved lime	51	222	4.35
D4	40% – black alder, 20% – European ash, 20% – silver birch, 10% – pedunculate oak, 10% – European aspen, <5% (n.d.) European hornbeam, small-leaved lime	48	177	3.69
D5	40% – silver birch, 20% – black alder, 20% – white willow, 10% – Scots pine, <5% (n.d.) European aspen	58	215	3.71

***Source:** developed by the authors*

Local studies indicate that in Ukrainian Polissia hornbeam (*C. betulus* L.) is characterised by relatively high mean increment values on fertile soils in middle-aged stands; however, its productivity declines markedly with age. This defines its role as an accompanying rather than a main species in the highly productive oak forests of the region. Northern red oak (*Q. rubra* L.) in Europe and North America shows high growth rates on fertile soils. Typical MAI values range between 7 and 12 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ in middle-aged stands (40-90 years), with peak values exceeding 12 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ on particularly nutrient-rich sites under proper tending regimes (Nicolescu *et al.*, 2020; Štefančík & Pástor, 2023). Summarizing the data on the MAI of modal stands corresponding to the main species of forest types and ranking them revealed that the productivity scores of forest site types derived from the Ukrderzhlisproekt (n.d.) database differ substantially from the evaluation scale compiled by researchers of the Ukrainian Research Institute of Forestry and Forest Melioration (URIFFM) for native reference stands (Turkevych *et al.*, 1973) (Fig. 1).

The highest productivity scores of native reference stands were recorded in moist rich site conditions (100), fresh fairly rich site conditions (92), moist fairly rich site conditions (87), and fresh rich site conditions (82). In contrast, analysis of forest inventory materials revealed that the highest productivity scores are currently observed in modal stands of fresh fairly poor site conditions (100), fresh fairly rich site conditions (94), moist fairly poor site conditions (88), fresh poor site conditions (81), and moist fairly rich site conditions (80). A comparison of the two evaluation scales shows that consistent scores are found only in fairly rich site conditions. In poor and fairly poor site conditions, modal stands now have substantially higher productivity scores compared to the data reported for native reference stands of

Ukrainian Polissia. However, in rich site conditions, the situation is the opposite – modal stands corresponding to the main native species of forest types exhibit lower scores than native reference stands.

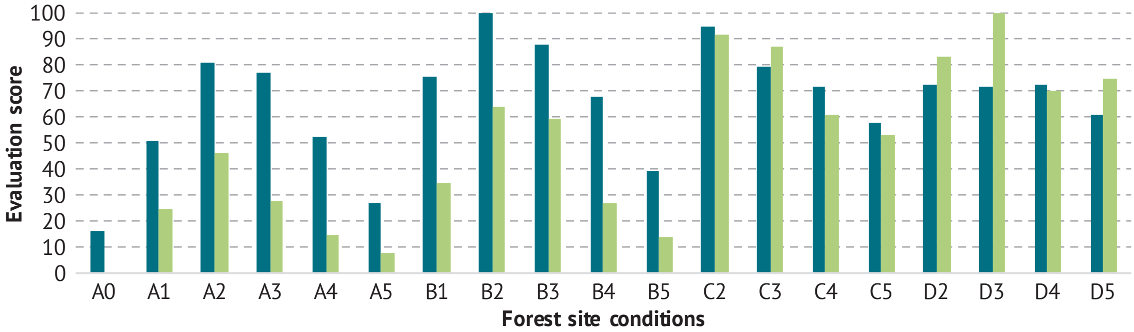

Figure 1. *Evaluation scale of productivity of native forest stands under site conditions of Ukrainian Polissia*
Source: *developed by the authors based on Ukrderzhlisproekt (n.d.) and I. Turkevych et al. (1973)*

Across different regions of Ukraine, the gap between modal and reference stands is consistently evident and is mainly driven by relative density of stocking, site index class, stand origin, and the correspondence of the main species to the forest type. For Ukraine as a whole, the actual realization of site potential averages 50-75%, indicating significant reserves. A comparison of the productivity evaluation scales of modal stands corresponding to the main native species of forest types and secondary stands, based on the analysis of the relational database of Ukrderzhlisproekt (n.d.), revealed certain differences. These were particularly pronounced in the productivity scores under rich site conditions (Fig. 2). The highest productivity scores of secondary stands were recorded in fresh rich site conditions (100), moist rich site conditions (96), fresh fairly poor site conditions (96), and fresh and moist fairly rich site conditions (88 and 86, respectively).

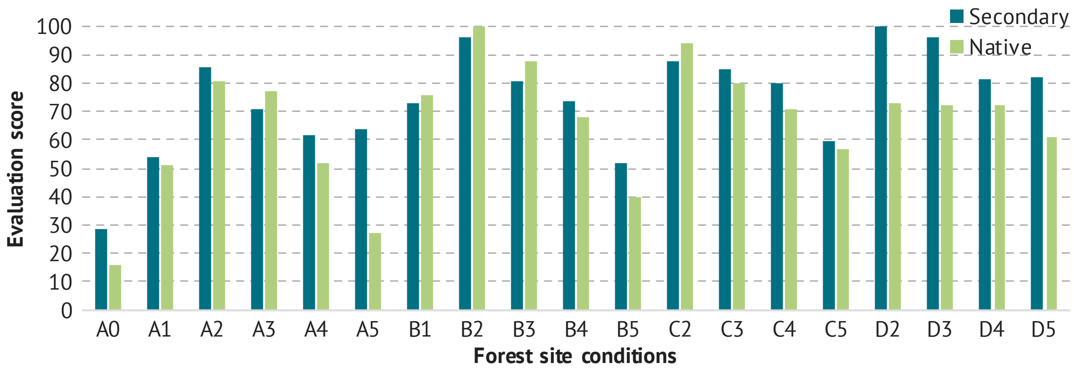

Figure 2. *Evaluation scale of productivity of modal stands corresponding to the main native species of forest types and secondary stands under site conditions of Ukrainian Polissia*
Source: *developed by the authors*

A comparison of these results with independent regional studies provides partial confirmation: native stands of target species in their "appropriate" forest types consistently achieve higher growing stock in middle- and older-age classes than secondary stands (Musienko *et al.*, 2021). This aligns with our conclusion on the differentiation of productivity scales between modal and reference stands. In spruce forests of the Ukrainian Carpathians, it has been shown that the transition from less fertile to more fertile site types sharply increases potential growing stock, with reference high-density plots exceeding modal ones several times. This further confirms that species–site correspondence and high relative density of stocking determine the upper limits of productivity, where native structures have a clear advantage (Lavnyy & Matusevych, 2022). Although secondary stands in favorable site conditions may temporarily demonstrate high productivity scores due to the rapid early growth of pioneer species, in the long term native stands are more productive in terms of growing stock and stability of increment in middle- and older-age classes, provided high density and proper silvicultural care are maintained. Accordingly, a strategy for enhancing productivity should be based on reducing the proportion of secondary stands and moving toward the structure and composition of native forest stands (Zhezhkun *et al.*, 2023).

In summary, the analysis of forest inventory data across Ukrainian Polissia revealed clear differentiation of productivity between modal, secondary, and native reference stands depending on forest-site conditions. Modal Scots pine stands demonstrated the highest mean annual increment in poor and fairly poor sites, while in rich site conditions secondary mixed stands slightly outperformed modal ones due to the presence of fast-growing species. However, native reference stands remain superior in terms of long-term stability and biomass accumulation, particularly in fertile and moist environments. These findings confirm that productivity is strongly dependent on the correspondence of dominant species to site type and that enhancing forest productivity requires gradual transformation of secondary formations toward structures and compositions characteristic of native forests.

CONCLUSIONS

The average tree species composition of modal stands differs from that of native reference stands in most forest types of Ukrainian Polissia. When the main species corresponds to the native forest type, modal stands in poor and fairly poor site conditions include a higher proportion of silver birch (*B. pendula* Roth); in fairly rich site conditions, higher proportions of silver birch and hornbeam (*C. betulus* L.); and in rich site conditions, a range of native hardwood and softwood species. In secondary stands, jack pine (*P. banksiana* Lamb.) and silver birch dominate in poor site conditions; silver birch dominates in fairly poor and fairly rich site conditions; while hornbeam (*C. betulus* L.), northern red oak (*Q. rubra* L.), Scots pine (*P. sylvestris* L.), black alder (*A. glutinosa* (L.) Gaertn.), and silver birch prevail in rich site conditions.

The mean annual increment of modal Scots pine stands in poor and fairly poor site conditions is higher than in native reference stands: by 17-58% in poor sites and by 2-48% in fairly poor sites, depending on the moisture regime. In fairly rich site conditions, the mean increment of modal stands corresponding to the main species is lower than in native reference stands by 19-37% across all site types, whereas in rich site conditions the increments of modal and native stands are similar. In the most widespread types of poor, fairly poor and fairly rich site conditions, the mean increment of modal stands corresponding to the native species exceeds that of secondary stands. By contrast, in fairly rich site conditions, secondary stands are more productive than modal stands corresponding to the native species in the most common site conditions, by 13-16%.

The productivity scores of modal stands differ considerably from the evaluation scale developed for native reference stands. Consistency was observed only in fairly rich site conditions conditions. In poor and fairly poor site conditions conditions, modal stands currently exhibit significantly higher productivity scores compared with native reference stands of Ukrainian Polissia, whereas in rich site conditions conditions the opposite trend is evident. The highest productivity scores of secondary stands were recorded in fresh and moist fairly rich site conditions, as well as in fresh fairly poor site conditions. Future research should focus on long-term monitoring of productivity dynamics under changing climatic and hydrological conditions, with particular attention to carbon balance and resilience indicators of modal and secondary stands. Expanding comparative analyses using remote sensing and process-based models would allow refinement of productivity assessment scales and support the development of adaptive, typology-based strategies for sustainable forest management in Ukrainian Polissia.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Продуктивність модальних деревостанів Українського Полісся залежно від відповідності головних деревних порід типу природного лісу

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Анотація. Дослідження мало на меті оцінити склад і таксаційні характеристики наближених до природних та вторинних деревостанів, порівняти їх середній річний приріст із природними еталонними насадженнями та уточнити закономірності природної продуктивності за різних типів лісорослинних умов. Аналіз базувався на матеріалах лісовпорядкування, поєднаних із геоінформаційними ресурсами. Продуктивність оцінювалася шляхом порівняння середніх значень приросту та ранжування показників природної продуктивності. Середній видовий склад деревостанів, наближених за композицією до природних, відрізнявся від еталонних природних насаджень у більшості типів лісорослинних умов. У бідних і досить бідних умовах спостерігалася більша частка берези повислої (*Betula pendula* Roth); у досить багатих – підвищена частка берези (*B. pendula*) та грабу звичайного (*Carpinus betulus* L.); а в багатих умовах переважали комплекси аборигенних твердих і м'яколистяних порід. Вторинні деревостани характеризувалися такими закономірностями: у бідних умовах вони були переважно представлені сосною Банкса (*Pinus banksiana* Lamb.) та березою (*B. pendula*); у досить бідних і досить багатих – переважно березою (*B. pendula*); а в багатих умовах – грабом (*C. betulus*), червоним дубом (*Quercus rubra* L.), сосною звичайною (*Pinus sylvestris* L.), вільхою чорною (*Alnus glutinosa* (L.) Gaertn.) та березою (*B. pendula*). Середній приріст модальних насаджень сосни звичайної перевищував еталонні природні показники на 17-58 % у бідних лісорослинних умовах і на 2-48 % у досить бідних, залежно від режиму зволоження ґрунту. У досить багатих умовах приріст насаджень, наближених за складом до природних, був нижчим на 19-37 %, тоді як у багатих умовах показники приросту були подібними. У найпоширеніших типах лісорослинних умов – бідних, досить бідних і досить багатих – модальні природні деревостани виявилися продуктивнішими за вторинні, тоді як у багатих умовах вторинні насадження переважали на 13-16 %. Показники природної продуктивності модальних насаджень суттєво відрізнялися від еталонних шкал: вони були вищими у бідних і досить бідних умовах, але нижчими – у багатих. Найвищі значення природної продуктивності вторинних деревостанів спостерігалися у свіжих і вологих багатих лісорослинних умовах, а також у свіжих досить бідних умовах. Отримані результати стали науковою основою для уточнення шкал природної продуктивності та типологічно обґрунтованого планування лісогосподарських заходів

Ключові слова: лісорослинні умови; середній річний приріст; видовий склад деревостанів; вторинний деревостан; еталонні природні насадження; шкала оцінювання продуктивності

SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 28(10), 67-76

UDC 636.09: 636.034/.8.003:616.36

DOI: 10.48077/scihor10.2025.67

Metabolic disorders as a factor influencing morphological and productive parameters in Holstein cows

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Article's History:

Received: 10.06.2025

Revised: 20.08.2025

Accepted: 24.09.2025

Abstract. The aim of the study was to establish the relationship between polymorbid pathology, morphological changes in the liver, and the productivity of animals at different lactations. A complex of clinical, morphological, histological, and cytometric methods was applied. A comparative analysis was conducted between the control and experimental groups of cows in their first, second, and third lactations. A total of 327 animals were examined, among which pathological conditions were detected in 60% of first-lactation cows, 53.57% of second-lactation cows, and 47.27% of third-lactation cows. For the morphological study, animals with combined metabolic disorders were selected, namely ketosis in combination with endometritis, mastitis, or hypocalcaemia. It was found that the proportion of such combinations was 20.95%, 17.85%, and 14.54% in the first, second, and third lactations, respectively. The average daily milk yield in the experimental groups was lower than in the control groups, while body weight significantly ($p < 0.05$) decreased across all age groups. The experimental animals showed an increase in both absolute and relative liver mass ($p < 0.001$), indicating functional hypertrophy of the organ. Histological examination revealed disruption of lobular architecture, diffuse vacuolisation of hepatocytes, areas of necrosis, infiltration of portal tracts, and the development of periportal fibrosis. In cows with a combination of ketosis and mastitis, signs of chronic hepatitis were observed, whereas in those with ketosis and hypocalcaemia, hepatosis with macrovesicular steatosis predominated. Cytometric analysis demonstrated a significant increase in the volume of hepatocytes and their nuclei ($p < 0.05$; $p < 0.01$) along with a decrease in the nuclear-to-cytoplasmic ratio, confirming the development of fatty degeneration. The degree of morphological alterations intensified with age and the duration of the lactation period. The practical value of the study lay in establishing morphological and cytometric criteria of liver lesions under polymorbid conditions, which could be applied to diagnose the level of metabolic load, predict disease progression, and develop preventive measures in animal husbandry

Keywords: lactation; ketosis-endometritis; ketosis-mastitis; ketosis-hypocalcemia; liver; morphology

Suggested Citation:

Huralska, S., & Olishevskyi, V. (2025). Metabolic disorders as a factor influencing morphological and productive parameters in Holstein cows. *Scientific Horizons*, 28(10), 67-76. doi: 10.48077/scihor10.2025.67.

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INTRODUCTION

Modern animal husbandry is undergoing a stage of profound transformation caused by both global economic changes and the consequences of military actions that have significantly affected the agricultural sector of Ukraine. The restoration of productive cattle herds and the improvement of their health are strategic objectives, as this sector forms the basis of food security by ensuring stable production of milk, meat, and other livestock products (Kotykova *et al.*, 2024). Against this background, the issues of prevention and early diagnosis of metabolic disorders, particularly liver pathologies in high-yielding dairy cows, are of special importance, as they substantially affect productivity, reproductive ability, and overall health.

During the transition period, which encompasses the final weeks of gestation and the first weeks after calving, profound metabolic changes occur in the cow's body aimed at meeting the energy demands of lactation (Huralska *et al.*, 2025a). As emphasised by M. Arshad and J. Santos (2024), this period is critical for maintaining physiological balance, since even a short-term energy deficit leads to the activation of pathological metabolic mechanisms. Fatty hepatosis is one of the leading causes of hepatic dysfunction and the related diseases and mortality in cattle. A. Vlizlo *et al.* (2024) reported that this disorder is most frequently registered in high-producing dairy cows during the postpartum period when energy demands reach their maximum. Its development is caused by an excessive influx of non-esterified fatty acids into the liver and intensified mobilisation of lipid reserves from body tissues. As a result, the hepatic parenchyma begins to accumulate triglycerides intensively, leading to a decrease in metabolic activity and a disturbance of energy metabolism (Zhang *et al.*, 2023).

Predominantly, fatty hepatosis develops within the first four weeks after calving, when the organism experiences the maximum load associated with the onset of lactation. M. Tharwat *et al.* (2025) demonstrated that at this stage an excess of triglycerides, combined with hormonal fluctuations, creates favourable conditions for the development of steatosis and inflammatory processes in the hepatic tissue. When the rate of triglyceride synthesis exceeds their removal, these compounds, together with cholesterol esters, accumulate in hepatocytes. Under normal conditions, triglycerides are removed from the liver through the secretion of very-low-density lipoproteins or hydrolysis; however, this mechanism is impaired under metabolic disorders (Osada *et al.*, 2024).

Alongside lipid imbalance, such animals exhibit increased formation of ketone bodies, resulting in endogenous intoxication, appetite suppression, reduced milk yield, and overall exhaustion. A particular danger is posed by the subclinical form of ketosis, when external signs of pathology are absent but productivity and reproductive capacity are significantly reduced. M. Bauer and W. Jagusiak (2022) noted that such latent forms of ketosis often remain unnoticed but cause the greatest economic damage to farms. The liver has a high compensatory potential; however, its reserves are limited. When glycogen, cofactors, and antioxidant systems are depleted, a state of decompensation develops, deepening structural and functional disorders. O. Olishevskyi and S. Huralska (2025) indicated that the combination of metabolic, inflammatory, and degenerative processes forms a complex polymorbid syndrome that leads to significant morphofunctional changes in the liver – from fatty degeneration and cytoplasmic vacuolisation to necrosis, fibrosis, and architectural disorganisation. The severity of these changes directly depends on the combination of diseases and the lactation period.

Thus, metabolic disturbances during the transition period in dairy cows, particularly the development of fatty hepatosis, represent one of the most serious challenges of modern dairy farming. Excessive lipid accumulation in the liver, energy metabolism disruption, and ketosis formation lead to reduced productivity, impaired reproductive function, and the development of polymorbid conditions. The aim of the study was to investigate the effect of polymorbid pathology of various combinations on the morphological and functional state of the liver in cows of different lactations, to determine the nature of structural alterations, and to establish their relationship with the level of animal productivity.

LITERATURE REVIEW

Fatty liver degeneration (hepatic lipidosis) is one of the most common metabolic disorders in dairy cattle, leading to substantial economic losses due to reduced milk yield, impaired reproductive performance, and increased culling rates (Melendez & Pinedo, 2024). Researchers have noted that both the incidence and severity of this disorder have increased in recent years, which may be a consequence of intensive selection for high productivity. Such genetic selection is accompanied by the emergence of pleiotropic genes associated with a higher predisposition to obesity, ketosis, and other metabolic complications. Although the high productivity of modern cows ensures considerable milk yields, it simultaneously reduces the organism's adaptive reserves and resistance to metabolic stress.

T. Swartz *et al.* (2021) and C. Zhang *et al.* (2024) emphasised that fatty liver degeneration is not merely a consequence of excessive lipid loading but rather a complex pathogenetic process linked to disturbances in energy metabolism, oxidative stress, and inflammatory responses. An excess of triglycerides in hepatocytes causes disruption of intracellular organelles, particularly mitochondria, thereby diminishing the liver's detoxification capacity and its ability to synthesise essential metabolites. This state leads to profound systemic dysfunctions, including impaired immune responses and increased susceptibility to infections. At the same time,

D. Giannuzzi *et al.* (2021) drew attention to the difficulties of early diagnosis of this disorder. Liver biopsy remains the gold standard; however, due to its invasiveness and technical complexity, it is unsuitable for large-scale screening. Therefore, the search for non-invasive biomarkers that would allow assessment of the degree of hepatic lipid infiltration at early stages remains an important direction in contemporary research.

Studies by Z. Cheng *et al.* (2023) revealed that impairment of hepatic function can markedly shorten the lifespan of dairy cows. Although under favourable conditions these animals are capable of living for more than 20 years, in modern high-yielding herds the average productive lifespan is only about three years after the first calving. In primiparous cows, inflammatory alterations in the liver were already detected at the beginning of the first lactation, later progressing to fibrosis. The authors concluded that each subsequent lactation accelerates the "ageing" process of hepatic tissue, aggravating metabolic and immune dysfunctions and thereby increasing the risk of premature culling. According to D. Giannuzzi *et al.* (2021), hepatic lipidosis is closely associated with ketosis, which is a common metabolic disorder in cows during the transition period. Both conditions develop as a result of a negative energy balance, when the energy required for lactation exceeds nutrient intake. Early detection of these disorders is a key factor in reducing their impact on herd productivity and improving profitability.

C. Zhang *et al.* (2023) further clarified that fatty liver degeneration is accompanied not only by triglyceride accumulation but also by structural tissue alterations, including fibrosis. This process results from excessive synthesis of extracellular matrix components in response to hepatocellular damage, disrupting lobular architecture and reducing the liver's synthetic and metabolic functions. Despite numerous studies, the pathogenesis of fibrosis in fatty liver degeneration remains insufficiently elucidated, opening new perspectives for further morphological and biochemical research. The study of the morphofunctional state of the liver in Holstein cows under metabolic and chronic disorders is particularly relevant, as this organ plays a central role in maintaining energy, protein, and lipid metabolism. Evaluation of body weight dynamics, hepatic structure, and function enables timely diagnosis of early stages of metabolic imbalance, development of preventive strategies, and enhancement of recovery efficiency in high-producing cows during the postpartum period.

MATERIALS AND METHODS

The study was conducted during 2022-2025 at PJSC PC "Podillia" (Dzyhivka village, Mohyliv-Podilskyi district, Vinnytsia region). The research had a comprehensive production-experimental design and was performed in accordance with the Law of Ukraine No. 3447-IV (2006), the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986), and the provisions of the Universal Declaration on Animal Welfare (2007). Ethical review of the study protocol was carried out following the recommendations of S. Huralska *et al.* (2025b).

The research was conducted on Holstein cows aged 3-7 years at different stages of lactation. The total sample included 327 animals, of which 105 were in the first lactation, 112 in the second, and 110 in the third. All cows were maintained under identical housing conditions, received balanced diets, and followed a standard milking routine in an "electronic herringbone" parlour system. For comparative analysis, the animals were divided into three control groups (clinically healthy) and three experimental groups (diagnosed with polymorbid pathologies), each corresponding to a specific lactation. The experimental groups included cows with ketosis combined with one of three concurrent disorders – endometritis, mastitis, or hypocalcaemia. Inclusion criteria comprised the presence of clinical signs of metabolic disorders confirmed by laboratory indicators and the absence of infectious or traumatic lesions. Exclusion criteria included cachexia, non-metabolic systemic inflammation, chronic hepatopathies, or postoperative changes.

Clinical examinations were performed using conventional veterinary diagnostic methods. Ketosis was diagnosed with the Ketotest® (KetoLact, Germany) rapid test and confirmed by laboratory determination of β-hydroxybutyrate in blood plasma (threshold >1.2 mmol/L). Endometritis was identified through clinical examination, vaginal inspection, and cytological evaluation of discharges. Mastitis was diagnosed using the *California Mastitis Test (CMT)* and somatic cell count in milk. Hypocalcaemia was detected photometrically by measuring total serum calcium (<2.0 mmol/L). Additionally, in the experimental animals, total protein, glucose, triglycerides, and alanine aminotransferase (ALT) activity were determined as indicators of hepatic functional status.

Morphological analysis of the liver was performed on samples collected from animals subjected to forced slaughter. Tissue specimens were fixed in 10% neutral formalin, dehydrated through graded alcohols, and embedded in paraffin. Sections of 5-7 μm thickness were prepared using a Leica RM2235 microtome. Staining was performed with haematoxylin and eosin to assess general architecture, Van Gieson's method to identify connective tissue elements, and Sudan III to visualise lipid inclusions. Microscopic examination was carried out using a Carl Zeiss Primo Star light microscope at ×400 and ×1000 magnifications. Morphological assessment included evaluation of lobular architecture, hepatocyte vacuolisation, necrotic changes, portal infiltration, connective tissue proliferation, and fibrosis development. Cytometric measurements were conducted using the Image Scope digital morphometric system (Aperio Technologies, USA). For each specimen, no fewer than 100 hepatocytes were analysed across 10 randomly selected fields of view. The following parameters were determined:

- mean hepatocyte volume (V_x, μm^3);
- mean nuclear volume (V_n, μm^3);
- nuclear-to-cytoplasmic ratio ($NCR = V_n/V_x$).

These indices were used for quantitative assessment of hepatocellular hypertrophy, lipid degeneration, and tissue disorganisation. Live body weight was measured individually before morning milking using Axis BCA-1500 electronic scales. Average daily milk yield was calculated from data of the automated Milk Master control system (GEA Farm Technologies, Germany) over 10 consecutive days during the stable lactation period. The analysed parameters included mean body weight, absolute and relative liver mass, milk yield, and body condition score (BCS) on a five-point scale. Data processing was carried out using Statistica 6.0 software (StatSoft Inc., USA). For each parameter, the mean (M), standard error (m), and significance level (p) were calculated using Student's t-test. Differences between groups were considered statistically significant at $p < 0.05$, $p < 0.01$, and $p < 0.001$. Graphical visualisation was performed in Microsoft Excel 2021.

RESULTS AND DISCUSSION

In the examined cows, 60% of pathologies were recorded among 105 animals of the first lactation, 53.57% among 112 animals of the second lactation, and 47.27% among 110 animals of the third lactation. For the experiment, animals with polymorbid pathology were selected, namely the following combinations: ketosis–endometritis, ketosis–mastitis, and ketosis – hypocalcaemia. In cows of the first lactation, these pathologies accounted for 20.95%, in the second – 17.85%, and in the third – 14.54%. The average daily milk yield in the experimental group was 43.26 ± 2.02 kg ($p < 0.05$), 50.06 ± 1.51 kg, and 49.07 ± 2.14 kg, respectively. In the control group, the yield was 48.07 ± 1.56 kg, 51.40 ± 1.41 kg, and 50.27 ± 2.12 kg, respectively (Fig. 1).

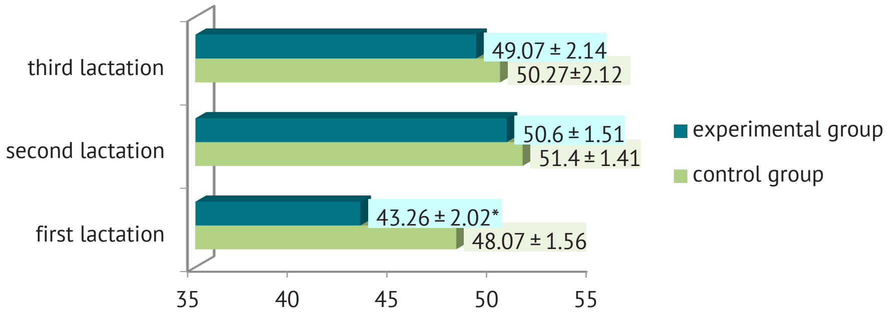

***Figure 1**. Average daily milk yield in experimental groups of animals, kg*

***Note:** p < 0.05 compared with control*

***Source:** developed by the authors*

The average body weight in the control group during the first lactation was 567.83 ± 5.67 kg, while in the experimental group of the same age this indicator was significantly lower ($p < 0.05$) and amounted to 533.66 ± 5.95 kg. A similar pattern was observed during the second and third lactations (Table 1).

***Table 1** Body weight indices of cows with polymorbid pathology (M ± m)*

Animal groups	Body weight, kg		
	first lactation	second lactation	third lactation
Control	567.83 ± 5.67	633.83 ± 7.47	661.67 ± 9.77
Experimental	533.66 ± 5.95*	556.33 ± 10.51*	570.66 ± 9.89*

***Note:** p < 0.05 compared with control*

***Source:** developed by the authors*

In cows, the liver is located on the right side of the abdominal cavity, adjoining the diaphragm. In clinically healthy animals, it has a reddish-brown colour and a soft consistency. In cows of the experimental group, the liver was enlarged, yellowish or yellow-brown in colour, and soft in texture. The absolute liver mass in the control group of cows during the first, second, and third lactations primarily depended on the animals' body weight indices. In cows of the experimental groups at different lactations, a significant ($p < 0.001$) increase in the absolute mass of the organ was observed compared with the control, whereas the body weight indices, as previously noted, were significantly ($p < 0.05$) lower relative to the control (Fig. 2).

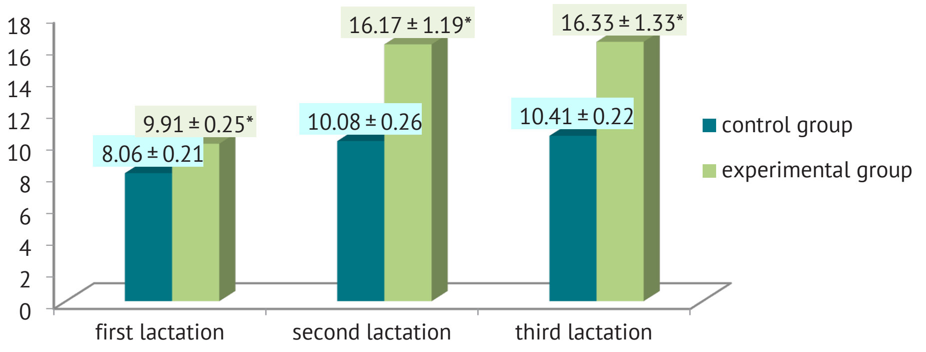

Figure 2*. Absolute liver mass of cows with polymorbid pathology, kg*
Note: *p < 0.05 compared with control*
Source: *developed by the authors*

With high statistical significance (p < 0.001), the relative liver mass values predominated in the experimental groups across all lactations. Thus, in cows of the control group during the first lactation, this indicator was 1.42 ± 0.04, whereas in the experimental group it was 1.86 ± 0.06 (p < 0.001). The highest value of relative liver mass was recorded in experimental cows during the second lactation, amounting to 2.91 ± 0.22 (p < 0.001), which was 1.83 times higher compared with the corresponding control group (Fig. 3).

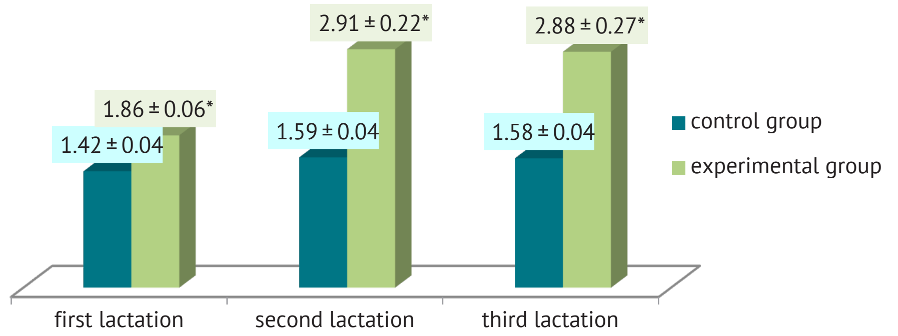

Figure 3*. Relative liver mass of cows with polymorbid pathology*
Note: *p < 0.05 compared with control*
Source: *developed by the authors*

Histological examination of the liver in cows from the control groups revealed normal histoarchitectonics. The parenchyma of the organ consisted of polygonal lobules, with connective tissue septa between them being poorly developed. The lobules were formed by hepatic plates composed of hepatocytes, which perform most of the metabolic functions of the liver. At the corners of the hepatic lobules (between three adjacent lobules), triads consisting of a vein, an artery, and a bile duct were observed. It was established that in cows of the first lactation, the most frequent combination was ketosis with endometritis. Histological examination of the liver revealed moderate diffuse vacuolisation of hepatocyte cytoplasm, areas of diffuse necrosis, and lymphocytic–macrophage infiltration of the portal tracts. Disorganisation of hepatic plates and disturbance of lobular architecture were also noted. In cases of ketosis combined with hypocalcaemia, the hepatic plate structure was preserved; however, pronounced vacuolisation of hepatocytes, widespread necrosis, and slight lymphocytic–macrophage infiltration were observed. Such alterations indicate significant functional overload and damage to the hepatic parenchyma. In the combination of ketosis and mastitis, pronounced diffuse vacuolisation of hepatocytes (signs of severe fatty degeneration), moderate diffuse necrosis, and accumulation of inflammatory cells were observed, indicating the development of focal chronic hepatitis.

In cows of the second lactation with ketosis combined with endometritis, enlargement and structural changes of the portal tracts, areas of fibrosis around central veins, accumulation of inflammatory cells, and dilation of bile ducts were detected. These changes indicated chronic inflammation with the development of periportal fibrosis. The combination of ketosis and hypocalcaemia in cows of the second lactation was accompanied by pronounced diffuse vacuolisation of hepatocyte cytoplasm (macrovesicular steatosis), active necrosis, slight diffuse lymphocytic–macrophage infiltration with eosinophils, and proliferation of connective tissue around the portal tracts. The obtained results indicated a severe form of hepatosis with signs of chronic inflammation and initial fibrosis, reflecting pronounced metabolic stress. In cows of the third lactation, the most frequently registered combination was ketosis with mastitis. Microscopic examination revealed signs of hepatosis with elements of chronic inflammation and fibrosis, confirmed by the presence of lymphocytes, macrophages, and connective tissue proliferation. Cytometric examination showed that hepatocytes differed in size and in the volume of their cytoplasm and nuclei. Analysis of these parameters demonstrated a significant increase in the mean hepatocyte and nuclear volumes in animals of the experimental groups across all lactations (Figs. 4, 5).

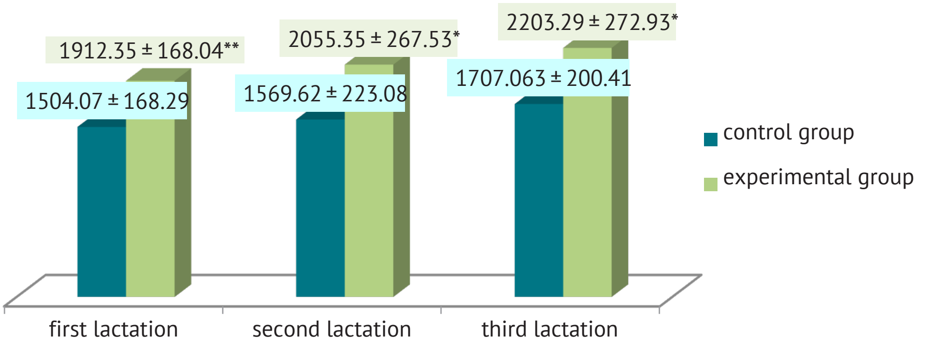

***Figure 4**. Hepatocyte volume indices in control and experimental groups, μm³*
***Note:** p < 0.05 compared with control*
***Source:** developed by the authors*

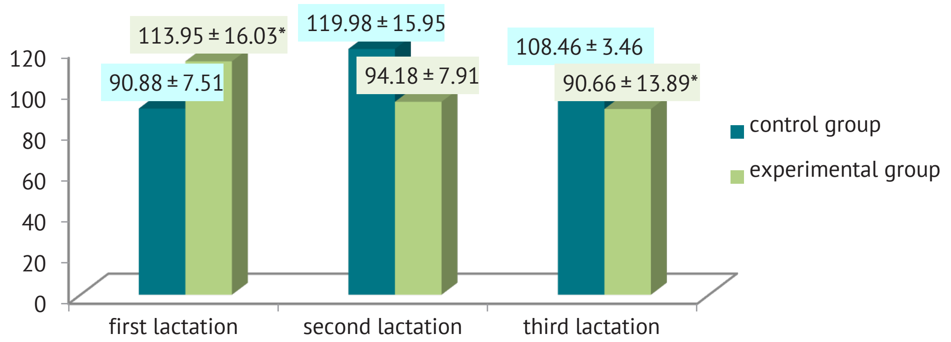

***Figure 5**. Hepatocyte nuclear volume indices in control and experimental groups, μm³*
Note: p < 0.05 compared with control
***Source:** developed by the authors*

In the experimental animals, as noted, hepatocellular damage was observed. In these cows, a significant increase in the volume of hepatocytes was recorded. According to cytometric data, in cows of the first lactation, the hepatocyte volume in the control group was 1504.07 ± 168.29 μm³, whereas in the experimental group it reached 1912.35 ± 168.04 μm³ ($p < 0.01$). In animals of the second and third lactations, this parameter also showed an increase ($p < 0.05$). A significant difference was also noted in the nuclear volume of hepatocytes between the control and experimental groups. Thus, in the first lactation, the experimental group exhibited a 1.25-fold ($p < 0.05$) increase compared with the control, whereas in the second and third lactations, the nuclear volume of hepatocytes was significantly lower – by 1.27 and 1.2 times, respectively. The nuclear-to-cytoplasmic ratio (NCR) of hepatocytes in all experimental groups with ketosis decreased compared with the control (Fig. 6). This indicates an increase in cytoplasmic volume relative to the nucleus, caused by the accumulation of lipid inclusions, vacuolisation, and the development of fatty degeneration.

In the experimental animals of the first lactation, a tendency towards a decrease in the nuclear-to-cytoplasmic ratio (NCR) was observed, while in the second and third lactations the decrease was significant ($p < 0.01$). In clinically healthy cows of the second lactation, the NCR value was 0.086 ± 0.014, whereas in the experimental animals it was 0.053 ± 0.008 ($p < 0.01$), being 1.62 times lower compared with the control. Summarising the results, it can be stated that polymorbid pathology in cows causes pronounced morphofunctional alterations in the liver, ranging from fatty degeneration and necrotic lesions of hepatocytes to the formation of fibrosis. The intensity of these pathological processes depends both on the combination of diseases and on the lactation period.

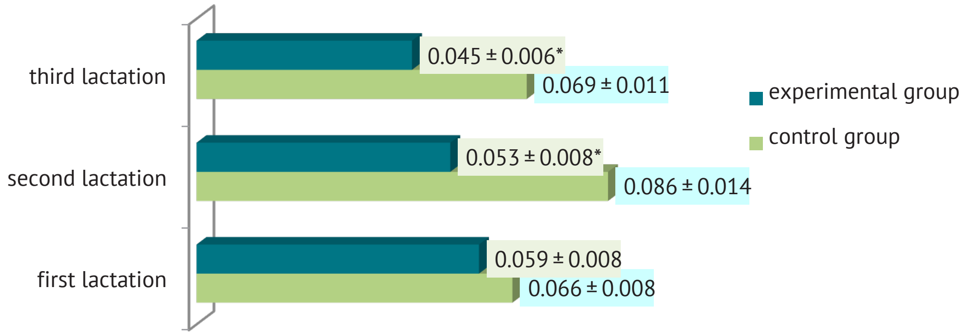

***Figure 6**. Nuclear-cytoplasmic ratio*

***Note:** $p < 0.05$ compared with control*
***Source:** developed by the authors*

The obtained results confirmed that the transition period in cows is a critical stage characterised by profound metabolic changes that significantly affect the condition of the liver. According to D. Kang *et al.* (2025), about 45-60% of dairy cows experience metabolic disorders during this period. U. Arshad and J. Santos (2024) reported that hepatic lipidosis develops in 40-50% of dairy cows in the first weeks of lactation. This stage is critical due to the substantial physiological and hormonal changes associated with the transition from rest to active lactation. In the present study, the frequency of detected pathologies was similar – 60% in cows of the first lactation, 53.57% in the second, and 47.27% in the third – which confirms the trends described in the literature. Hepatic pathology in dairy cows remains a relevant problem in modern animal husbandry since the liver plays a key role in maintaining energy balance during the transition period. According to K. Aksoy *et al.* (2025), the detection of hepatic lesions of varying degrees in 46% of examined samples indicates the widespread occurrence of both subclinical and clinical forms of hepatopathies among high-producing cows. The most common findings were inflammatory processes, whereas fibrosis and necrosis were rare, suggesting that most morphological changes are reversible if metabolic correction and diagnosis are performed in time. It should be noted that histopathological studies of the bovine liver still lack unified approaches for the quantitative evaluation of tissue damage, as most research is based on selective sample analysis, which can introduce bias in data interpretation (Hellen & Karpen, 2023). This highlights the need to standardise morphometric assessment methods for hepatocytes, fibrosis, and steatosis to ensure greater objectivity and comparability of results.

The obtained data correspond to findings from other studies confirming significant metabolic and hormonal changes during the period from late gestation to early lactation (McGuckin *et al.*, 2023). During this time, active lipid mobilisation from fat depots increases the metabolic load on the liver and may lead to steatosis, ketosis, and hepatodystrophy. According to Takahashi *et al.* (2021), lipid metabolism and lipoprotein profiles in cows vary depending on age and number of lactations, supporting the following results that demonstrated differences among cows of the first, second, and third lactations. Older cows showed a greater tendency for triglyceride accumulation in hepatocytes and a higher susceptibility to metabolic disorders. Histological findings by K. Theinert *et al.* (2022) are consistent with the following results, indicating that fat accumulation in the liver during the early postpartum period is a reversible process that gradually decreases toward the end of the lactation cycle. At the same time, lipidosis was found to correlate positively with the degree of cellular degeneration and inflammation. This study also confirmed that fibrosis occurred more frequently in older cows with a higher number of lactations, reflecting the cumulative effect of prolonged metabolic stress. These results have practical importance for monitoring hepatic condition in animals of different age groups.

Liver lesions in dairy cows are multifactorial and result from complex metabolic shifts occurring during the transition period. The detected morphological changes – from mild fatty infiltration to moderate hepatitis – confirm the reversibility of the pathological process and underline the importance of early diagnosis. The data obtained are consistent with the observations of L. Vogel *et al.* (2024), who considered postpartum lipid mobilisation in cows a natural model of metabolic stress, analogous to chronic liver diseases in humans. A decrease in the NCR in experimental animals compared with controls indicates the predominance of cytoplasmic alterations over nuclear ones, which may be caused by the accumulation of triacylglycerols and the development of fatty degeneration. These findings confirm the data of C. Zhang *et al.* (2024), who reported that hepatic lipidosis is not merely a consequence of excess fat accumulation but also a manifestation of systemic metabolic disorders accompanied by oxidative stress, inflammatory response, and damage to cellular organelles.

The link between the development of lipidosis and ketosis was also confirmed, as both conditions are driven by negative energy balance in the postpartum period. In animals with pronounced morphological changes in the liver, reduced synthetic function of the organ was observed, which may lead to decreased productivity, impaired reproductive performance, and increased susceptibility to infections. These observations are in line with P. Melendez and P. Pinedo (2024), who reported significant economic losses associated with hepatoses in high-producing dairy cows. The detected cytological alterations can be regarded as morphological markers of disrupted adaptive mechanisms during the transition period. As noted by Z. Cheng *et al.* (2023), such animals exhibit accelerated "ageing" of hepatic tissue, reducing the productive lifespan of cows. The obtained results morphologically confirmed this mechanism, revealing signs of degeneration and initial fibrosis, as described by C. Zhang *et al.* (2023).

Thus, the conducted research demonstrated that fatty liver degeneration represents a typical morphological response to metabolic stress during the transition period, and its severity may serve as an indicator of the intensity of energy deficit. The results expand the understanding of the morphofunctional characteristics of the liver in dairy cows during the transition period, confirming the close relationship between inflammatory reactions and age-related physiological features of animals.

CONCLUSIONS

In cows with polymorbid pathology during the first, second, and third lactations, a significant ($p < 0.05$) decrease in live body weight was observed compared with the control groups – by 37.17 kg, 77.5 kg, and 91.01 kg, respectively. This indicates a disruption of energy metabolism and loss of structural reserves in the organism as a result of metabolic stress. The absolute and relative liver mass in the experimental groups was significantly higher ($p < 0.001$) compared with the control, indicating oedematous changes, infiltration, and accumulation of lipid inclusions in the hepatic parenchyma. The highest relative liver mass (2.91 ± 0.22) was recorded in cows of the second lactation, exceeding the control value by 1.83 times. Histological examination revealed, in animals of the experimental groups, disturbances in the architecture of hepatic lobules, diffuse vacuolisation of hepatocyte cytoplasm, focal necrosis, lymphocytic–macrophage infiltration, and development of fibrosis, indicating a combination of fatty degeneration with chronic hepatitis and periportal fibrosis. Cytometric analysis demonstrated a significant increase in hepatocyte and nuclear volumes in the experimental animals. In the control group of cows during the first lactation, the nuclear volume was 90.88 ± 7.51 μm^3, whereas in the experimental group it reached 113.95 ± 16.03 μm^3 ($p < 0.05$).

At the same time, a tendency toward a decrease in the nuclear-to-cytoplasmic ratio (NCR) was observed in the cows of the first lactation, and a significant reduction ($p < 0.01$) was recorded in the second and third lactations. In particular, during the second lactation, the NCR decreased from 0.086 ± 0.014 in the control to 0.053 ± 0.008 in the experimental group. This finding reflects the expansion of cytoplasm caused by lipid infiltration and the progression of fatty degeneration. A promising direction for further research is the determination of correlations between cytometric parameters of hepatocytes, biochemical markers of liver function, and clinical manifestations of ketosis, which will contribute to improving the diagnosis and prevention of hepatosis in dairy cows.

ACKNOWLEDGEMENTS

The authors express their sincere gratitude to PJSC PC "Podillia", Dzyhivka village, Mohyliv-Podilskyi district, Vinnytsia region, for the opportunity and assistance provided in conducting this research.

FUNDING

None.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Метаболічні розлади як чинник змін морфологічних і продуктивних показників у корів голштинської породи

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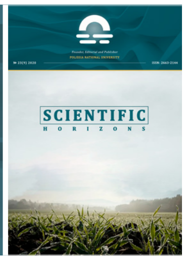
Анотація. Метою роботи було встановити взаємозв'язок між поліморбідною патологією та морфологічними змінами печінки і продуктивністю тварин різних лактацій. У дослідженні застосовано комплекс клінічних, морфологічних, гістологічних і цитометричних методів. Проведено порівняльний аналіз показників у контрольних та дослідних групах корів першої, другої і третьої лактацій. Обстежено 327 тварин, серед яких у корів першої лактації патології виявлено у 60 %, другої – у 53,57 %, третьої – у 47,27 %. Для морфологічного досліду було відібрано тварин із поєднаними метаболічними захворюваннями, а саме кетозом у комбінації з ендометритом, маститом або гіпокальціємією. Встановлено, що питома частка таких комбінацій становила 20,95 %, 17,85 % і 14,54 % відповідно за першої, другої та третьої лактації. Середньодобові надої у дослідних групах були нижчими, ніж у контрольних, а маса тіла достовірно ($p < 0,05$) зменшувалась у всіх вікових групах. У дослідних тварин відмічали підвищення абсолютної і відносної маси печінки ($p < 0,001$), що свідчить про функціональну гіпертрофію органа. Гістологічно встановлено порушення архітектоніки часточок, дифузну вакуолізацію гепатоцитів, ділянки некрозу, інфільтрацію портальних трактів та розвиток перипортального фіброзу. У тварин із поєднанням кетозу та маститу виявляли ознаки хронічного гепатиту, тоді як при кетозі з гіпокальціємією переважали прояви гепатозу з макровезикулярним стеатозом. Цитометричний аналіз показав достовірне збільшення об'єму гепатоцитів і їх ядер у дослідних тварин ($p < 0,05$; $p < 0,01$) при одночасному зниженні ядерно-цитоплазматичного відношення, що підтверджує розвиток жирової дистрофії. Ступінь морфологічних порушень посилювався із віком і тривалістю лактаційного періоду. Практична цінність роботи полягає у встановленні морфологічних та цитометричних критеріїв ураження печінки при поліморбідних патологіях, що може бути використано для діагностики ступеня метаболічного навантаження, прогнозу перебігу захворювань і розробки профілактичних заходів у тваринництві

Ключові слова: лактація; кетоз-ендометрит; кетоз-мастит; кетоз-гіпокальціємія; печінка; морфологія

SCIENTIFIC HORIZONS
Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 28(10), 77-84
UDC 631.559:633.14
DOI: 10.48077/scihor10.2025.77



Soil microbiological activity in winter rye crops under different fertilisation systems and biopreparations

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Article's History:
Received: 21.04.2025
Revised: 18.08.2025
Accepted: 24.09.2025

Abstract. The aim of the study was to determine the effect of different fertilisation systems in combination with biological preparations on soil microbiological activity under winter rye crops in the Polissia region of Ukraine. The methodology was based on a field experiment conducted during 2019-2021 at the research plots of Polissia National University. Two fertilisation systems were used – biological and organo-mineral with different ratios of components (50:50 and 75:25) – as well as a mineral system for comparison. Soil microbiological activity was evaluated using the linen decomposition method at a depth of 0-20 cm, and the results were processed by analysis of variance. The study established that the highest levels of biological activity were observed under the organo-mineral system with an equal proportion of organic and mineral components, where microbial activity exceeded the control by 8-10%. It was demonstrated that the biopreparations Trichodermin, Organik D2M, and

Suggested Citation:
Polishchuk, V., Klymenko, T., Stotska, S., & Pototska, S. (2025). Soil microbiological activity in winter rye crops under different fertilisation systems and biopreparations. *Scientific Horizons*, 28(10), 77-84. doi: 10.48077/scihor10.2025.77.

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Mochevyn K No. 2 positively affected soil microflora development, enhanced enzymatic processes, and contributed to the stability of microbial communities. It was also found that, even without the application of mineral fertilisers, the use of biological preparations significantly increased microbial activity, whereas the mineral system maintained a lower but stable level of response. The generalisation of results confirmed the synergistic effect of combining organic and mineral nutrient sources, which ensured a balanced microbiological environment and sustained soil fertility. The practical value of the study lies in the potential use of the findings to optimise fertilisation systems and integrate biopreparations into cereal crop production technologies in the Polissia zone of Ukraine to enhance the ecological efficiency of agriculture

Keywords: soil microflora; organo-mineral nutrition; enzymatic activity; biological decomposition; agroecological stability; biologisation of agriculture; microbial consortia

INTRODUCTION

Maintaining soil microbiological activity is a fundamental condition for the sustainable functioning of agroecosystems and for ensuring food security. The activity of soil microorganisms determines the rate of mineralisation of organic residues, the transformation of nutrients, the formation of humus, and the overall fertility of the soil. Within the framework of intensive farming systems dominated by mineral fertilisers, there is a significant risk of microbiota degradation, decreased enzymatic activity, and deterioration of soil physico-chemical properties. Therefore, assessing the influence of fertilisation systems and biological preparations on soil biological activity is essential for developing environmentally safe technologies for cereal cultivation, particularly for winter rye.

Recent research increasingly emphasises that a combination of organic and mineral nutrient sources creates optimal conditions for the development of microbial communities. W. Liu *et al.* (2023) demonstrated that the application of organic amendments significantly enhances microbial diversity, increases the abundance of cellulolytic bacteria, and stimulates enzymatic activity across various agroecosystems. In the study by V. Seitz *et al.* (2024), it was shown that the combined use of organic and mineral fertilisers promotes the formation of stable microbial networks, improves nutrient cycling, and enhances agroecosystem resilience to external stress factors. Similar results were obtained by X. Chen *et al.* (2025), who proved that organic fertilisers slow down excessive mineralisation of organic matter and ensure the stability of microbial communities, which is key to the long-term maintenance of soil fertility. The research of J. Behr *et al.* (2023) confirmed that the introduction of microbial consortia in winter rye crops stimulates rhizosphere biota and increases the availability of macro- and microelements. In an extensive review, D.-C. Țopa *et al.* (2025) summarised the results of more than 120 studies and emphasised that integrated fertilisation systems combined with biopreparations deliver the highest ecological efficiency, balancing crop productivity with the restoration of soil biological functions.

Ukrainian researchers have made a substantial contribution to the study of organic matter mineralisation processes. L. Tsentylo (2019) found that indicators of soil microbiological activity serve as sensitive markers of agroecosystem sustainability, and that the intensity of biological processes significantly increases under organo-mineral fertilisation systems. The study by V. Ivanina and O. Tabachuk (2023) showed that the application of organo-mineral fertilisers on typical chernozem soils of the Forest-Steppe zone leads to an increase in microbial biomass and higher dehydrogenase activity. Similar findings were reported by Y. Borko *et al.* (2025), who noted that the use of biopreparations in cereal production enhances soil enzymatic activity by 20-30% and improves ecological condition. Moreover, P. Lykhovyd (2024) confirmed in their meta-analysis that the biological activity of Ukrainian soils depends on the cultivation and fertilisation system; organo-mineral combinations stimulate the formation of stable microbial communities and prevent degradation processes.

The analysis of these studies indicates that most contemporary research focuses on the beneficial effects of organic fertilisers and biological agents on microbial activity. However, the optimal ratio of organic and mineral components in fertilisation systems for specific cereal crops remains insufficiently studied. Despite available data on maize, soybean, and wheat, there is a lack of research addressing microbiological processes in winter rye under the conditions of the Polissia region of Ukraine. The degree of influence of different biological preparations – particularly *Trichodermin*, *Organik-D2M*, and potassium humate – on soil microbiological activity under varying proportions of organic and mineral nutrients also requires clarification. Therefore, studying the dynamics of soil microbiological activity under different fertilisation systems and biological agents in winter rye crops is crucial for improving modern environmentally oriented agricultural technologies.

The aim of the study was to determine the effects of various fertilisation systems – biological, organo-mineral, and mineral – in combination with biological preparations on the microbiological activity of soil in winter rye cultivation under the conditions of the Ukrainian Polissia region.

MATERIALS AND METHODS

The field experiment was carried out during 2019-2021 at the experimental plots of Polissia National University. The object of the study was winter rye (*Secale cereale* L.). Two fertilisation systems were investigated – biological and organo-mineral with different ratios of organic to mineral components (50:50 and 75:25) – in combination with the following biopreparations: Trichodermin, Potassium Humate, Organik-D2M, Mochevyn K No. 1, and Mochevyn K No. 2. In addition to the biological and organo-mineral fertilisation systems, a mineral system ($N_{50}P_{40}K_{70}$) was included for comparative analysis. This treatment involved the application of nitrogen, phosphorus, and potassium at rates of 50, 40, and 70 kg ha^{-1} respectively, corresponding to the regionally recommended fertilisation standards for winter rye. The mineral system served as a reference to evaluate the compensatory and synergistic effects of biopreparations under conditions of mineral nutrient dominance.

Soil microbiological activity was assessed by determining the percentage of linen fabric decomposition at a depth of 0-20 cm. The linen samples were placed in triplicate, and the results were processed statistically using analysis of variance (ANOVA). Winter rye of the variety Khlibne was sown according to standard agronomic practices recommended for the Polissia region. Foliar application of the biopreparations was carried out twice during the intensive growth phase, in accordance with the manufacturers' recommendations. All applied preparations were included in the official State Register of Pesticides and Agrochemicals Approved for Use in Ukraine (n.d.).

Preparations

1. Trichodermin, solution (1 L/ha) – a biological fungicide designed to protect crops from a wide range of fungal and bacterial diseases. It suppresses pathogenic agents transmitted through soil and plant residues.

2. Mochevyn K No. 1, solution (1 L/ha) – the active ingredients are macroelements (NPK) and microelements (0.1%). It promotes root system development, increases plant biomass, and enhances plant immunity.

3. Mochevyn K No. 2, solution (1 L/ha) – the active ingredients are macroelements (NPK) and microelements (1 g/L). It reduces plant water demand, increases drought resistance, stimulates the formation of additional shoots, and accelerates maturation.

4. Organik-D2M, solution (1 L/ha) – the active ingredients are: N – 2.0-3.0%, P_2O_5 – 1.7-2.8%, K_2O – 1.3-2.0%, total calcium – 2.0-6.0%, and organic substances – 65-70% (in terms of carbon content). It strengthens plant immunity against various diseases, enhances seed germination and vigour, reduces nitrate accumulation in fruit and vegetable products, inhibits the uptake of heavy metals and radionuclides by plants, increases the content of easily available nutrients in the soil, and promotes higher microbiological activity.

5. Potassium Humate, solution (2 L/ha) – contains macroelements (NPK) and microelements (0.3-2.5 g/L). It improves plant tolerance to drought and frost, contributing to better growth and development.

The experimental layout for the organic and organo-mineral fertilisation systems is presented in Table 1.

***Table 1**. Experiment design*

Variant No.	Treatment name	Preparation / treatment	Application rate, L/ha
1	Control	Water treatment	–
2	Trichodermin	Biological fungicide	1.0
3	Mochevyn K No. 1	Complex of macro- and microelements (NPK + 0.1% microelements)	1.0
4	Mochevyn K No. 2	Complex of macro- and microelements (NPK + 1 g/L microelements)	1.0
5	Organik-D2M	Organo-mineral biostimulator	1.0
6	Potassium Humate	Humic preparation	2.0

***Source:** compiled by the authors*

The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

The obtained results indicated that, under the biological control variant without the application of mineral fertilisers, the indicators of soil microbiological activity were the lowest (Fig. 1). The control treatment demonstrated a level of 87.38% in 2019, followed by a decline to 38% in 2020 and a partial recovery to 63.69% in 2021. The application of biopreparations ensured a consistent increase in microbiological activity throughout all experimental years. In particular, Trichodermin enhanced microbial activity to 97.06% in 2019 and 70.12% in 2021, which exceeded the control by 10-12%. A similar trend was observed under the application of Mochevyn K No. 2, where activity reached 72.74% in 2021, while Organik-D2M and Potassium Humate demonstrated activity levels of approximately 70%.

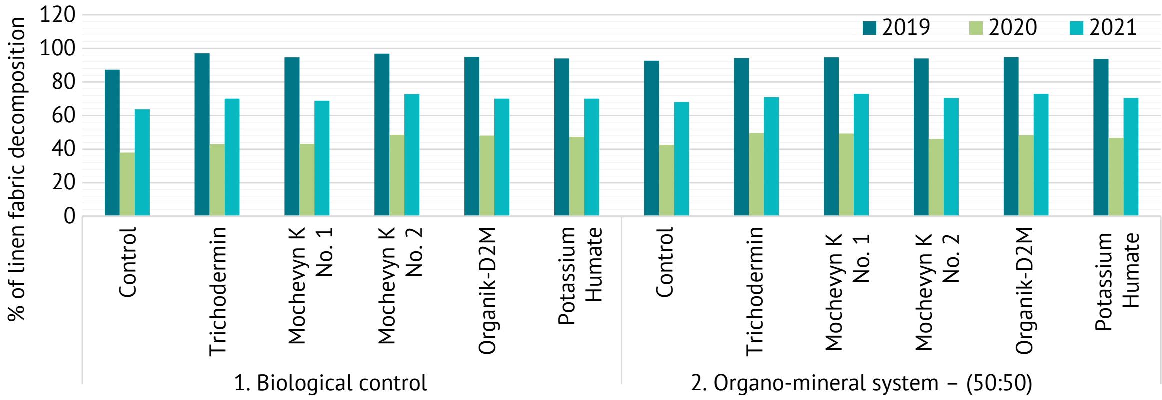

***Figure 1**. Soil microbiological activity in winter rye crops under biological and organo-mineral fertilisation systems with biopreparations, % of linen fabric decomposition*
***Source:** compiled by the authors*

Thus, even in the absence of mineral fertilisers, biopreparations positively influenced the development of soil microflora, particularly in the variants where Trichodermin and Mochevyn K No. 2 were applied. Under an equal ratio of organic and mineral fertilisers, soil microbial activity was the highest among all studied fertilisation systems. The control in 2021 accounted for 68.13%, whereas the variants treated with biopreparations exceeded this value by 3-5%. Specifically, Trichodermin ensured activity at 70.93%, Mochevyn K No. 1 at 73%, Organik-D2M at 73%, and Potassium Humate at 70.5%. On average, over the three years of the study, the organo-mineral fertilisation system (50:50) combined with Organik-D2M and Trichodermin demonstrated the highest biological activity. These findings confirmed the advisability of combining organic and mineral components to optimise soil microbiological processes.

The combination of 75% organic and 25% mineral fertilisers noticeably stimulated soil microbiota (Fig. 2). In the control variant, microbial activity reached 66.11% (2021), whereas under the application of Trichodermin, the value increased to 66.55%, and under Organik-D2M – to 71.73%. The application of Mochevyn K No. 1 and Potassium Humate provided activity levels of 70.0-70.1%, exceeding the control by 5-6%. The highest microbiological activity was recorded in 2021 under the Organik-D2M treatment, where activity reached 71.73%. These results indicate that the partial incorporation of mineral elements alongside organic inputs creates favourable conditions for the development of microorganisms and contributes to enhanced soil fertility.

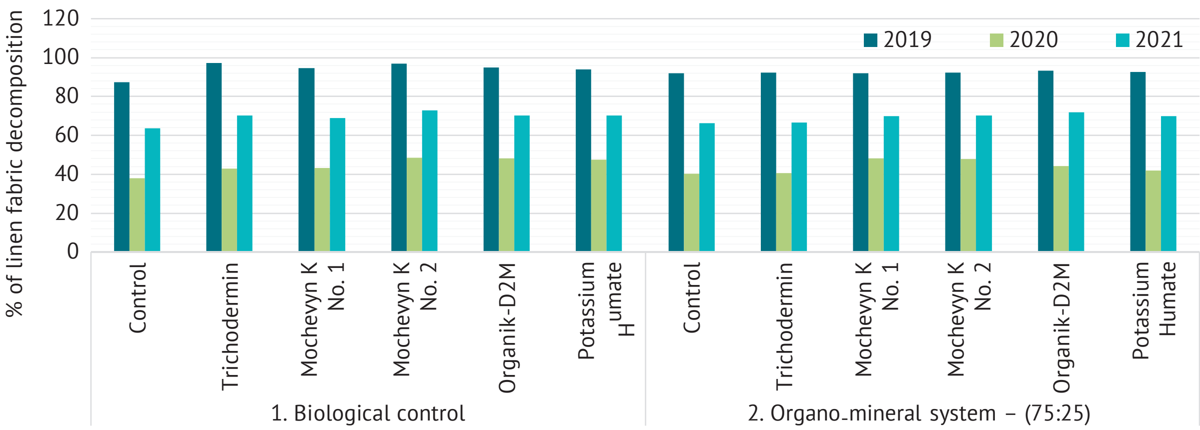

***Figure 2**. Soil microbiological activity in winter rye crops under the organo-mineral fertilisation system and biopreparations, % of linen fabric decomposition*
***Source:** compiled by the authors*

When mineral fertilisers were applied, microbial activity was slightly lower than under organo-mineral systems, yet it exceeded the level observed in the biological control (Fig. 3). The control treatment recorded 67.27% in 2021, whereas under the influence of Trichodermin, the indicator reached 71.23%, under Mochevyn K No. 1 – 70.25%, Organik-D2M – 71.11%, and Potassium Humate – 71.21%. The highest activity was observed with Organik-D2M (71.11%), indicating the mitigating effect of biopreparations on the mineral load of the soil and their ability to stimulate microbial development.

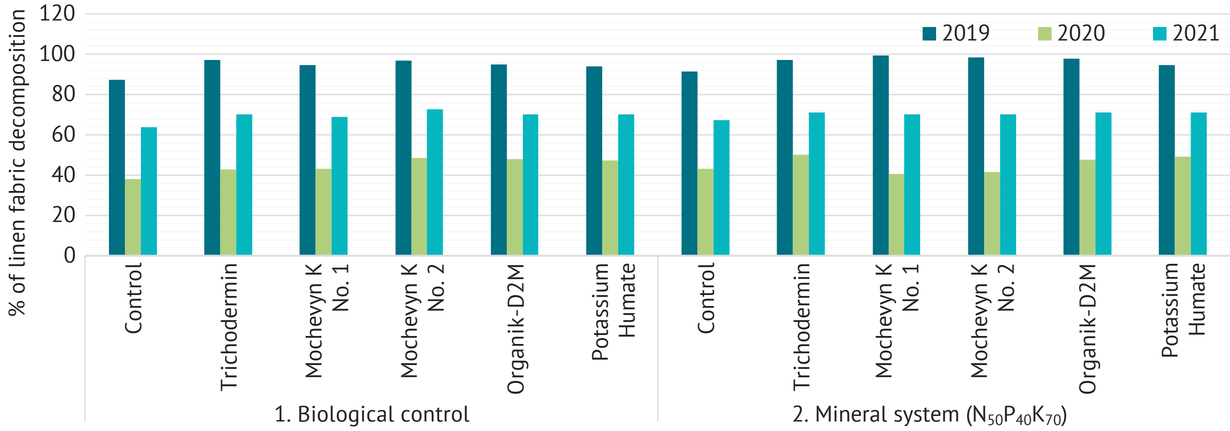

Figure 3. *Soil microbiological activity in winter rye crops under the mineral fertilisation system and biopreparations, % of linen fabric decomposition*

Source: *compiled by the authors*

Summarising the obtained results, all fertilisation systems involving biopreparations had a positive effect on soil microbiological activity; however, the extent of this effect depended on the ratio of organic and mineral components. The highest values were observed in variants combining organic and mineral inputs, confirming their synergistic influence on soil microbiota. The application of biopreparations, particularly Trichodermin and Organik-D2M, enhanced the activity of organic matter decomposers, intensified enzymatic processes, and improved the overall biological condition of the soil.

It was established that even in the complete absence of mineral fertilisers, the use of biopreparations led to a significant increase in microbial activity compared with the control, indicating the high potential of biological preparations in maintaining soil fertility. Nevertheless, the combination of organic and mineral nutrient sources in a 50:50 ratio proved to be the most effective, as it created a balanced environment for the development of microbial communities and stable mineralisation processes. Under this system, activity exceeded the control by an average of 8-10%, confirming its suitability for environmentally oriented agriculture. The findings demonstrate that the regulation of soil microbiological activity can be achieved through a rational integration of organic, mineral, and biological components within fertilisation systems. Biopreparations serve not only as plant growth stimulants but also as key agents maintaining the functional balance of soil microorganisms, ensuring sustainable nutrient cycling and the long-term preservation of fertility in the chernozem and sod-podzolic soils of the Polissia region of Ukraine.

The results of the study confirmed that the combination of organic and mineral fertilisation systems with biopreparations is an effective factor in enhancing soil microbiological activity. This pattern aligns with the findings of P. Cong *et al.* (2025), who reported that the application of organic amendments stimulates the growth of decomposer microorganisms and improves the structural and functional stability of microbial communities, even in saline soils. The data obtained in the present study demonstrated a similar tendency: organic components and biopreparations increased the percentage of linen fabric decomposition, indicating the activation of cellulose-based organic matter degradation processes.

The meta-analysis by D.P. Bebber and V.R. Richards (2022) emphasised that combined nutrient systems promote greater microbial diversity and enhance functional interactions among microorganisms. The results obtained for winter rye crops revealed a comparable relationship: microbiological activity under the organo-mineral system (50:50) exceeded that of the biological control, highlighting the positive influence of combining different nutrient sources. Similarly, Z. Yu *et al.* (2025) observed that the partial substitution of mineral fertilisers with organic inputs increases soil enzyme activity and improves crop quality, thereby supporting the rationale for an integrated fertilisation approach. According to A. Shamshitov *et al.* (2025) and X. Pan *et al.* (2025), the use of organic fertilisers fosters more stable microbial communities in the rhizosphere of leguminous crops, particularly under conditions of increased carbon availability. A similar trend was observed for winter rye, where the organic components of the nutrient system ensured long-term stability in soil biotic activity. Z. Wang *et al.* (2025) reported that the combined application of microbial agents and organic fertilisers enhances humus content and improves soil quality on saline-alkaline lands. The consistently high levels of microbiological activity identified under the organo-mineral system in this study suggest a broadly positive effect of such combinations across different agroclimatic conditions.

The findings of C.A. Zeiner *et al*. (2024) demonstrated that even in urban agroecosystems, organic composts enhance dehydrogenase and urease enzyme activities. This observation aligns with the results obtained for potassium humate and Organik-D2M, which stimulated enzymatic processes and maintained high microbial activity throughout the three years of experimentation.

Ukrainian researchers M. Voitovyk and M. Zhovtun (2024) demonstrated that soil biological activity depends on the fertilisation system, confirming that organic components contribute to maintaining agroecological balance. The results of the present experiment supported this pattern, as the highest activity was recorded when mineral fertilisers were partially substituted with organic inputs. Similar conclusions were presented by Y. Borko *et al*. (2025), who noted that biological preparations combined with fertilisers enhance soil microflora activity and maize yield. The application of Trichodermin and Organik-D2M produced a comparable positive effect for winter rye crops. The study by O. Kuts *et al*. (2022) confirmed that the excessive use of mineral fertilisers reduces enzymatic activity and disrupts microbial balance. These findings align with the observations obtained in this research, where the mineral system demonstrated lower biological activity compared with the organo-mineral system.

Overall, the analysis of current studies indicates that combined fertilisation systems incorporating biopreparations form functionally stable microbial communities, improve soil structure, and contribute to the sustainable regeneration of its fertility. The findings highlight the need for further biologisation of cereal cultivation technologies and for scientifically substantiated optimisation of organic and mineral component ratios within nutrient management systems.

CONCLUSIONS

The conducted research demonstrated that soil microbiological activity serves as a sensitive indicator of fertilisation system efficiency and the level of agroecosystem ecological stability. Over the three-year observation period, it was established that the combination of organic and mineral components in fertilisation systems created the most favourable conditions for the development of soil microflora. The organo-mineral system with an equal ratio of components (50:50) provided the highest biological activity, exceeding the control treatments by an average of 8-10%. This finding indicates a synergistic effect between available nutrient forms and organic carbon sources, stimulating mineralisation and humification processes. The application of biopreparations, particularly Trichodermin, Organik-D2M, and Mochevyn K No. 2, increased microbial activity across all fertilisation systems, reduced the negative impact of mineral load, and improved the condition of soil microflora. These preparations enhanced enzymatic activity, accelerated the decomposition of organic matter, and contributed to the potential increase in soil fertility. The exclusive use of organic fertilisers also had a positive effect on soil biota; however, under combined fertilisation, the effect was more stable and consistent throughout the study years. The obtained results confirm the necessity of transitioning from one-sided mineral nutrition to integrated fertilisation schemes that combine biological agents with organic and mineral fertilisers. Prospects for further research include investigating the impact of biopreparations on the activity of specific groups of soil microorganisms, determining the dynamics of enzymatic processes during different phenological stages of winter rye development, and assessing long-term changes in the structure of microbial communities under the influence of combined fertilisation systems.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Мікробіологічна активність ґрунту в посівах жита озимого за різних систем удобрення та біопрепаратів

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Анотація. Метою дослідження було визначити вплив різних систем удобрення у поєднанні з біопрепаратами на мікробіологічну активність ґрунту під посівами жита озимого в умовах Полісся України. Методологія роботи ґрунтувалася на польовому експерименті, який проводився протягом 2019-2021 років на дослідних ділянках Поліського національного університету. Було використано дві системи удобрення – біологічну та органо-мінеральну з різним співвідношенням компонентів (50:50 і 75:25), а також мінеральну систему як порівняльний варіант. Для оцінки мікробіологічної активності застосовувався метод розкладання лляного полотна у шарі ґрунту 0-20 см, результати оброблялися методами дисперсійного аналізу. У ході дослідження було встановлено, що найвищі показники біологічної активності спостерігалися за органо-мінеральної системи удобрення із рівним співвідношенням органічної та мінеральної складових, де активність мікроорганізмів перевищувала контроль на 8-10 %. Було доведено, що біопрепарати Триходермін, Органік Д2М і Мочевин К №2 позитивно впливали на розвиток мікрофлори, посилювали ферментативні процеси та сприяли стабільності мікробних угруповань. Проаналізовано, що навіть без внесення мінеральних добрив застосування біопрепаратів забезпечувало суттєве підвищення активності мікроорганізмів, тоді як мінеральна система мала нижчий, але стабільний рівень дії. Узагальнення результатів підтвердило синергетичний ефект поєднання органічних і мінеральних елементів живлення, який забезпечує збалансоване мікробіологічне середовище та підтримує родючість ґрунту. Практична цінність роботи полягає у можливості використання отриманих результатів для оптимізації систем удобрення та впровадження біопрепаратів у технології вирощування зернових культур у зоні Полісся України з метою підвищення екологічної ефективності землеробства

Ключові слова: ґрунтова мікрофлора; органо-мінеральне живлення; ферментативна активність; біологічна деструкція; агроекологічна стабільність; біологізація землеробства; мікробні консорціуми

SCIENTIFIC HORIZONS
Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 28(10), 85-92
UDC 633.12:632.954
DOI: 10.48077/scihor10.2025.85

Control of segetal vegetation in the agrocenosis of common buckwheat

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Article's History:
Received: 11.05.2025
Revised: 02.09.2025
Accepted: 24.09.2025

Abstract. The aim of the study was to determine the effectiveness of herbicides in controlling segetal vegetation in the agrocenosis of common buckwheat (*Fagopyrum esculentum* Moench.) while considering their influence on crop condition and yield formation. The methodology involved a field experiment conducted at the Educational and Research Field of Polissia National University during 2021-2025, which included five variants of herbicide control, namely the use of the graminicide Norvel Extra alone and in combination with the preparations Horizon, Tsukron+, and Helianthex. Herbicide effectiveness was assessed through quantitative weed

Suggested Citation:
Hurmanchuk, O., Plotnytska, N., Nevmerzhytska, O., Hrytsiuk, N., & Tymoshchuk, T. (2025). Control of segetal vegetation in the agrocenosis of common buckwheat. *Scientific Horizons*, 28(10), 85-92. doi: 10.48077/scihor10.2025.85.

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composition at three observation periods, and yield was measured according to standard agronomic procedures with an untreated control. The study found that the structure of weed infestation was dominated by grass species, accounting for 77.2% of the total weed population. The application of Norvel Extra alone ensured a technical efficiency of 77.1%, whereas its combinations with Horizon, Tsukron+, and Helianthex provided weed control ranging from 88.5% to 95.5%. A strong correlation was observed between yield preservation and weed suppression, with yield retention levels of 23.5-42.6% compared to the control. The results indicated that the highest performance was achieved when Tsukron+ and Helianthex were combined with the graminicide, due to their selective activity against both grass and broadleaf species. The practical value of the study lies in the potential use of its results by agronomists, crop consultants, and agricultural producers to optimise buckwheat herbicide management systems and improve crop productivity under Forest-Steppe conditions in Ukraine

Keywords: crops; weeds; herbicide; efficiency; yield; protection technologies

INTRODUCTION

Buckwheat (*Fagopyrum esculentum* Moench.) is one of the leading cereal crops with significant nutritional, melliferous, and agroecological importance. Although its share in global crop production remains limited, this crop is an essential component of Ukraine's national food security. Increasing buckwheat yield and ensuring the stability of its production are strategic objectives for the agricultural sector, given the reduction in sown areas and low profitability across most regions. Buckwheat cultivation also performs an ecological function, improving soil structure, promoting the accumulation of organic matter, and serving as a valuable preceding crop for other species. One of the key factors in enhancing buckwheat productivity is the effective control of weeds, which significantly affect plant growth, development, and yield. Therefore, the search for optimal herbicides for buckwheat agrocenoses remains a relevant research direction.

Recent studies have demonstrated significant changes in approaches to buckwheat cultivation technology, particularly concerning the use of herbicides and biological preparations. According to V. Moisiienko *et al.* (2023), yield improvement in buckwheat directly depends on balanced nutrition and foliar feeding, yet weed competition remains a crucial limiting factor even under optimal fertilisation. Research by Q. Wang *et al.* (2024) confirmed that optimising herbicide types and concentrations is a key element in increasing the intensity of buckwheat cultivation without compromising grain quality. Ukrainian researchers have also focused considerable attention on agronomic factors affecting buckwheat productivity. Yu. Mashchenko and I. Semeniaka (2018) established that the correct selection of preceding crops, adherence to crop rotation, and technological discipline are critical for achieving stable yields. O. Vavrynovych and O. Kachmar (2019) noted that changes in the species composition of buckwheat weed flora depend not only on soil fertility but also on the fertilisation system, which influences weed germination dynamics during the growing season.

International research in recent years has concentrated on issues of herbicide resistance and the search for environmentally safe methods of weed management. T.A. Gaines *et al.* (2020) outlined the principal biochemical mechanisms underlying the evolution of weed resistance to herbicidal active substances, highlighting the need for developing new compounds to maintain agro-technological efficiency. Similar conclusions were drawn by T. Randell-Singleton *et al.* (2025), who determined that herbicide selection for buckwheat must be based on an assessment of selectivity to avoid phytotoxic effects on the crop. Y. Vieites-Álvarez *et al.* (2024) demonstrated that different genotypes of common (*Fagopyrum esculentum*) and Tartary buckwheat (*Fagopyrum tataricum*) exhibit varying abilities to exert allelopathic suppression of weeds, opening prospects for biological weed management.

A significant contribution to the study of varietal characteristics of buckwheat was made by *P.* Karazhbei *et al.* (2022), who focused on the creation of high-yielding and adaptive varieties resistant to abiotic stresses. Meanwhile, H. Debski *et al.* (2018) found that certain herbicides, including glyphosate and fluazifop-P-butyl, can alter the flavonoid content in buckwheat plants, which requires careful management to avoid negative impacts on product quality.

Thus, the current level of scientific research confirms that effective weed management in buckwheat crops remains a complex and multifaceted challenge. Alongside breeding and agronomic measures, improving herbicide control systems is an essential area for ensuring environmental safety, biodiversity conservation, and yield enhancement. Therefore, the aim of this study was to determine the effectiveness of herbicides for controlling segetal vegetation in the agrocenosis of common buckwheat (*Fagopyrum esculentum* Moench.) while considering their influence on crop development and productivity.

MATERIALS AND METHODS

Field studies were carried out during 2021-2025 at the Educational and Research Field of Polissia National University, located 20 km north of Zhytomyr, in the village of Velyka Horbasha, Zhytomyr District, Zhytomyr Region.

The soil at the experimental site was predominantly sandy loam, sod-podzolic, characterised by the following parameters: humus content (according to Tyurin and Kononova, DSTU 7828:2015, 2016) – 1.07-1.22%; easily hydrolysable nitrogen (according to Kornfield, DSTU 7863:2015, 2016) – 56-67 mg/kg of soil; available phosphorus (according to Chirikov, DSTU 4115:2002, 2003) – 107-175 mg/kg of soil; exchangeable potassium (according to Chirikov, DSTU 4115:2002, 2003) – 74-105 mg/kg of soil; and soil pH – 5.6-6.5. Weather conditions during the research period slightly deviated from long-term averages but did not have a significant influence on the development of buckwheat.

Buckwheat in the experiment was cultivated according to the conventional soil tillage technology. The preceding crop was winter wheat. After harvesting the predecessor, stubble cultivation was performed to a depth of 7-10 cm. Once weed seedlings and volunteer wheat appeared, deep ploughing was conducted to a depth of 23 cm. In spring, moisture preservation and pre-sowing cultivation were carried out. Buckwheat sowing took place from the third decade of May to the first decade of June using the variety Syn 3/02. The seeding rate was 2.8 million grains per hectare, and sowing was conducted with an SZ-3.6 seed drill. Certified seed material treated with a fungicidal preparation was used. During sowing, fertiliser NPK 10:26:26 was applied at a rate of 80 kg/ha. The studied herbicides were applied using a backpack sprayer at the 12-14 BBCH growth stage with a working fluid rate of 200 L/ha. During the growing season, pest control measures were taken when necessary, particularly against aphids. Throughout the research period, the application of fungicides was not required, as no significant signs of disease were observed in buckwheat plants. The species composition of weeds present in the buckwheat agrocenosis was determined using the Weed Identifier Atlas (Veselovsky *et al.*, 1988). The evaluation of herbicide effectiveness against weeds was conducted according to the following experimental design:

1. Weedy control (treatment with water);
2. Norvel Extra, EC (active ingredient: quizalofop-P-ethyl 125 g/L) – 1.0 L/ha;
3. Horizon, EC (active ingredients: phenmedipham – 91 g/L, desmedipham – 71 g/L, and ethofumesate – 112 g/L) – 0.7 L/ha, followed after 10 days by Norvel Extra, EC, 1.0 L/ha;
4. Tsukron+, SL (active ingredient: clopyralid 300 g/L) – 0.2 L/ha, followed after 10 days by Norvel Extra, EC, 1.0 L/ha;
5. Helianthex, SC (active ingredient: halauxifen-methyl 68.5 g/L) – 0.04 L/ha, followed after 10 days by Norvel Extra, EC, 1.0 L/ha.

The size of each experimental plot was 50 m^2, with four replications and a one-row sequential layout. Weed infestation assessments in buckwheat crops were performed three times: the first – before herbicide application, the second – 30 days after application, and the third – prior to harvest. Herbicide efficacy was calculated on the 30th day after treatment, using the initial weed density as a control. The calculation of herbicide efficiency employed a correction formula relative to the control. Buckwheat yield was determined for each treatment variant in accordance with the methodology described by S. Tribel (2001). The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

Since buckwheat is one of the main grain crops in Ukraine, improving its cultivation techniques enables producers to increase productivity per hectare. In modern technological maps for buckwheat cultivation, the protection section mainly focuses on controlling certain pest species and grass weeds, while information on disease management is almost absent. A similar situation applies to the control of broadleaf weeds, as there are no registered herbicides for their effective suppression. Therefore, the present study aimed to investigate the possibility of herbicidal control of both broadleaf and grass weed species in buckwheat crops. As a result of assessing the weed infestation within the buckwheat phytocenosis, it was found that the majority of segetal plants belonged to grass species, which accounted for more than 70% of the total (Fig. 1).

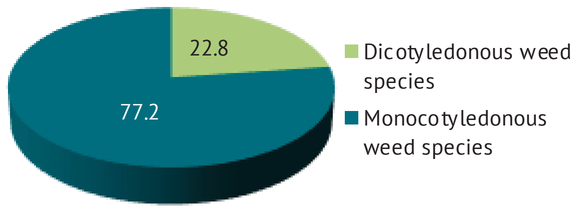

Figure 1. *Ratio of monocotyledonous and dicotyledonous weed species in common buckwheat crops, 2021-2025*
Source: *developed by the authors*

The most numerous weed species in buckwheat crops were green foxtail (*Setaria viridis*), yellow foxtail (*Setaria pumila*), barnyard grass (*Echinochloa crus-galli* L.), and witchgrass (*Panicum capillare* L.). Among the broadleaf weeds, the following species were identified: common lambsquarters (*Chenopodium album* L.), wild mustard (*Sinapis arvensis* L.), creeping thistle (*Cirsium arvense* L.), black-bindweed (*Polygonum convolvulus* L.), and spotted lady's thumb (*Persicaria maculosa* Gray), among others (Fig. 2).

As a result of applying the studied preparations in buckwheat crops, a high level of effectiveness was observed in controlling unwanted vegetation. The initial weed infestation of the buckwheat stands averaged 65.4 plants per m^2 (Table 1).

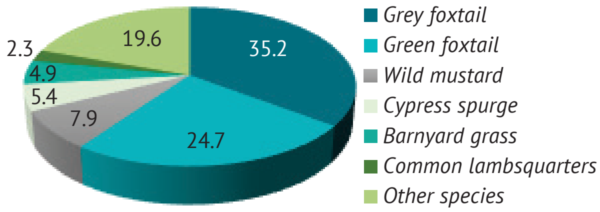

***Figure 2**. Structure of weed infestation in common buckwheat crops, 2021-2025*
***Source:** developed by the authors*

***Table 1**. Effect of herbicides on weed infestation in common buckwheat crops (2021-2025)*

Experimental variant	Number of monocotyledonous and dicotyledonous weed species, pcs/m²			Technical efficiency, %
	initial	30 days after treatment	before harvest	
Weedy control (water treatment)	65.5	74.9	78.0	–
Norvel Extra, EC, 1.0 L/ha	65.2	17.1	19.5	77.1
Horizon, EC, 0.7 L/ha, followed after 10 days by Norvel Extra, EC, 1.0 L/ha	63.9	8.4	9.3	88.5
Tsukron+, SL, 0.2 L/ha, followed after 10 days by Norvel Extra, EC, 1.0 L/ha	66.2	3.4	5.0	95.5
Helianthex, SC, 0.04 L/ha, followed after 10 days by Norvel Extra, EC, 1.0 L/ha	66.1	4.2	5.5	94.4
$LSD_{0.5}$	0.06	0.1	0.1	–

***Source:** developed by the authors*

In the control variant, the number of weeds increased to 74.9 plants per m² on the 30th day after the first observation and reached 78.0 plants per m² before harvesting. The application of the graminicide Norvel Extra at a rate of 1.0 L/ha provided almost complete control of grass-type segetal species; however, some dicotyledonous weeds remained, resulting in an overall efficiency of 77.1% compared to the control. In the treatment with Horizon (0.7 L/ha) followed after 10 days by Norvel Extra (1.0 L/ha), the technical efficiency reached 88.5%. The use of Tsukron+ and Helianthex, followed by the graminicide application, demonstrated the highest weed suppression, achieving 95.5% and 94.4% effectiveness, respectively. Due to the reduced weed pressure on the buckwheat agrocenosis, a significant increase in crop yield indicators was observed (Table 2).

***Table 2**. Effect of post-emergence herbicides on the yield of common buckwheat (2021-2025)*

Experimental variant	Application rate, L/ha	Yield, t/ha	Yield preserved	% relative to weedy control
Weedy control (water treatment)	–	1.15	–	–
Norvel Extra, EC, 1.0 L/ha	1.0	1.42	0.27	23.5
Horizon, EC, 0.7 L/ha, followed after 10 days by Norvel Extra, EC, 1.0 L/ha	0.7 + 1.0	1.50	0.35	30.4
Tsukron+, SL, 0.2 L/ha, followed after 10 days by Norvel Extra, EC, 1.0 L/ha	0.2 + 1.0	1.64	0.49	42.6
Helianthex, SC, 0.04 L/ha, followed after 10 days by Norvel Extra, EC, 1.0 L/ha	0.04 + 1.0	1.61	0.46	40.0
$LSD_{0.5}$	–	0.01	0.01	–

***Source:** developed by the authors*

In the control variant, this indicator was the lowest, amounting to 1.15 t/ha. The other experimental variants demonstrated significantly higher yield values. The application of the graminicide Norvel Extra at a rate of 1.0 L/ha resulted in yield preservation of 0.27 t/ha, corresponding to 23.5% compared to the control. A slightly higher buckwheat yield of 1.50 t/ha was obtained in the treatment involving Horizon followed after 10 days by Norvel Extra, providing a yield increase of 30.4%. The highest yield values – 1.64 t/ha and 1.61 t/ha – were recorded in the variants where Tsukron+ and Helianthex were followed by Norvel Extra, respectively, allowing yield preservation at 42.6% and 40.0% compared to the weedy control. This study contributes to the development of plant protection technologies by proposing effective solutions for weed management and yield enhancement in buckwheat cultivation.

The results of the present research demonstrated high herbicidal control efficiency against segetal vegetation in the agrocenosis of common buckwheat, which is consistent with findings from previous studies emphasising the crucial role of technological optimisation in improving crop productivity. In the study by I. Tkalich *et al.* (2019), it was shown that the growth intensity and yield of buckwheat significantly depended on the application of rational agrotechnical practices, among which timely weed control played a decisive role. The authors noted that in areas with high weed infestation, yield losses exceeded 40%, which aligns with the current results indicating the adverse effect of segetal vegetation on yield formation.

According to Z. Hrytsaienko and A. Datsenko (2014), the use of biological preparations contributed to increasing buckwheat productivity by stimulating growth processes and enhancing the crop's competitive ability against weeds. The results obtained in this experiment confirm the effectiveness of an integrated approach, where herbicidal control is combined with optimal plant nutrition and biostimulation, ensuring yield preservation of up to 40-42%. These findings highlight the necessity of comprehensive management of the phytosanitary condition of the buckwheat agrocenosis to achieve sustainable economic efficiency.

A comparison with the study by V. Onychko *et al.* (2015) revealed that the interaction between sowing rate, fertilisation level, and herbicide control determines the final crop yield. In their research, the optimal plant density and fertiliser application promoted the formation of a more developed leaf surface, enabling buckwheat to compete more effectively with weeds. A similar pattern was observed in the present experiment: under conditions of reduced weed pressure and sufficient nutrient supply, buckwheat showed an increased nutrient uptake efficiency and a higher level of photosynthetic activity.

At the same time, V. Khomina and O. Pastukh (2016) emphasised the importance of agroecological factors in buckwheat cultivation under mixed cropping systems, where weed control is achieved through mutual suppression between crops. The current results partially align with their conclusions, as in both cases the key factor was the reduction of competition for light and nutrients. However, herbicide application in this study provided a faster and more predictable effect, which offers a practical advantage under production conditions.

Particular attention should be given to the findings of I. Straholis *et al.* (2019), who highlighted the response of different buckwheat varieties to the combined use of biological preparations and mineral fertilisers. The authors established that the resistance of varieties to stress conditions, including weed competition, increased due to balanced nutrition. A similar phenomenon was observed in the present study: yield improvement in the herbicide-treated variants was accompanied by enhanced growth parameters, confirming the importance of an integrated crop management approach.

The results of R. Tobiasz-Salach *et al.* (2018) demonstrated that foliar fertilisation of buckwheat affects not only yield quantity but also the chemical composition of the grain. This aspect is significant in the context of herbicide application, as improved weed control efficiency must coincide with the preservation of the biochemical quality of the produce. In the present study, no negative impact of herbicides on crop productivity was detected, confirming the safety of the recommended herbicide combinations.

Similar results were reported by A. Słomka *et al.* (2017), who described the positive effects of biostimulants on buckwheat seed productivity. The authors showed that hormonal regulation in flowers promoted fertilisation and seed formation, partially compensating for losses caused by weed competition. In this study, herbicide application also contributed to an increase in the total number of seeds per plant, indirectly confirming the importance of reducing biotic stress to realise the crop's yield potential. The findings of A. Płażek *et al.* (2019) are also noteworthy, as they demonstrated the effect of high temperatures on buckwheat embryogenesis. Their research indicated that under stressful conditions, ovule development disturbances and reduced seed germination may occur. The results obtained in the present study indicate that effective herbicidal control not only improves the phytosanitary condition of the agrocenosis but also indirectly mitigates environmental stress effects by reducing competition, which enhances reproductive organ formation.

Therefore, the findings confirm that herbicidal control of segetal vegetation in the buckwheat agrocenosis is a crucial element of modern cultivation technology. Its efficiency depends on integration with the fertilisation system, varietal characteristics, and soil biological activity level. The consistency of these results with the conclusions of contemporary researchers supports the scientific and practical reliability of the findings, while the observed differences highlight the need for further testing of new herbicide combinations under various climatic conditions to ensure stable yield improvement in buckwheat cultivation.

CONCLUSIONS

Under the conditions of the Educational and Research Field of Polissia National University, the agrocenosis of common buckwheat was predominantly infested with grass weed species. The proportion of monocotyledonous weeds accounted for 77.2% of the total undesirable vegetation. The dominant representatives of the grass flora were grey foxtail (*Setaria pumila*), green foxtail (*Setaria viridis*), and barnyard grass (*Echinochloa crus-galli*). Among dicotyledonous weeds, the most common were wild mustard (*Sinapis arvensis*), cypress spurge (*Euphorbia virgata*), and common lambsquarters (*Chenopodium album*). The application of all tested herbicides resulted in a significant reduction of weed pressure within the buckwheat agrocenosis. In the variant where the graminicide Norvel Extra was applied at a rate of 1.0 L/ha, almost complete control of grass weeds (98.9%) was achieved, allowing for yield preservation of 23.5%. The treatment combining Horizon with a subsequent application of Norvel Extra provided control over both grass and broadleaf weeds at 88.5%, resulting in a 30.4% yield increase compared to the control.

The most effective treatments were those combining Tsukron+ and Helianthex with Norvel Extra applied 10 days later. The technical efficiency in these variants reached 95.5% and 94.4%, respectively, relative to the initial weed infestation, while yield increased by 42.6% and 40.0%. The results of this research confirm the high efficiency of herbicidal control of segetal vegetation in buckwheat agrocenoses and highlight the potential for further studies aimed at identifying herbicides with diverse mechanisms of action to ensure sustainable and environmentally safe weed management in buckwheat cultivation.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Контроль сегетальної рослинності в агроценозі гречки посівної

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Анотація. Метою дослідження було визначення ефективності гербіцидів для контролю сегетальної рослинності в агроценозі гречки посівної (*Fagopyrum esculentum* Moench.) з урахуванням їх впливу на стан культури та формування врожайності. Методологія роботи передбачала закладання польового досліду на навчально-дослідному полі Поліського національного університету протягом 2021-2025 рр., де оцінювали п'ять варіантів гербіцидного контролю, включаючи використання граміцициду Норвел екстра окремо та в комбінації з препаратами Горизонт, Цукрон+ і Геліантекс. Ефективність гербіцидів визначали за динамікою кількісного складу бур'янів у трьох обліках, а врожайність встановлювали за стандартною методикою з урахуванням контрольного варіанта. У результаті дослідження було виявлено, що у структурі забур'яненості посівів гречки переважали злакові види, частка яких становила 77,2 %. Було встановлено, що застосування лише граміциду Норвел екстра забезпечувало 77,1 % технічної ефективності, тоді як його поєднання з препаратами Горизонт, Цукрон+ і Геліантекс сприяло контролю 88,5-95,5 % бур'янів. Було проаналізовано залежність урожайності гречки від рівня забур'яненості та відзначено збереження врожаю на рівні 23,5-42,6 % порівняно з контролем. Було узагальнено, що найвищу результативність забезпечували варіанти з використанням Цукрон+ і Геліантекс у поєднанні з граміцидом, що зумовлено їх вибірковою дією на широколисті й злакові види. Практична цінність роботи полягає у можливості використання результатів агрономами, консультантами та виробниками сільськогосподарської продукції для оптимізації системи гербіцидного захисту гречки та підвищення її врожайності в умовах Лісостепу України

Ключові слова: посіви; бур'ян; гербіцид; ефективність; урожайність; технології захисту

Журнал
«НАУКОВІ ГОРИЗОНТИ»

Том 28, № 10
2025

Відповідальний редактор:
О. Кільніцька

Підписано до друку з оригінал-макета 24.09.2025
Ум. друк. арк. 11
Тираж 100 прим.

Видавництво: Поліський національний університет
10008, б-р Старий, 7, м. Житомир, Україна
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Journal
"SCIENTIFIC HORIZONS"

Volume 28, No. 9
2025

Managing Editor:
O. Kilnitska

Signed to the print with the original layout 24.09.2025
Conventional Printed Sheet 11
Circulation 100 copies

Publisher: Polissia National University
10008, 7 Staryi Bvld., Zhytomyr, Ukraine
Tel. (0412) 22-04-17
E-mail: info@sciencehorizon.com.ua
https://sciencehorizon.com.ua/en