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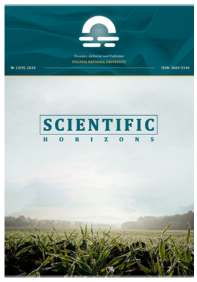

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The state of T- and B-cell links of specific immunity and activity of humoral factors of natural defence of sows and their piglets under the influence of *Saccharomyces Cerevisiae* yeast complex and enzymes

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Abstract. The immaturity of the immune system of newborn piglets causes significant losses in the postnatal period and is completely dependent on the mother's body, especially in the last period of pregnancy, due to increased metabolic processes and physiological immunosuppression. The study aimed to determine the activity of natural

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and adaptive defence factors in sows and piglets born from them under the influence of a feed additive containing *Saccharomyces cerevisiae* yeast and enzymes. The results of the research demonstrated that feeding sows during pregnancy and lactation, as well as piglets before weaning, had a positive effect on the immune function of the mother and offspring. Under the influence of these factors, the additive has an activating effect on the natural mechanisms of the humoral link of the body's nonspecific resistance, especially in sows. This was evidenced by the higher bactericidal and lysozyme activity of sow blood serum during pregnancy and lactation ($p < 0{,}05$-$0{,}001$) and a lower content of circulating immune complexes ($p < 0{,}05$), which indicates a decrease in the antigenic load on the mother's body, especially during the period of immunosuppression. Similar changes, but expressed to a lesser extent, were recorded in piglets, with higher BASK ($p < 0.05$) and lower CIC ($p < 0.05$). Feeding sows and piglets with yeast and enzymes during periods of low immune potential of their body had an activating effect on the state of adaptive immunity, in particular, cellular factors of specific body defence. This was evidenced by an increase in the number of T-lymphocytes (total, active and theophylline-resistant) and B-lymphocytes ($p < 0.05$-0.001) and an increase in their functional activity due to the redistribution of the receptor apparatus of immunocompetent cells – an increase in the number of T- and B-lymphocytes with low and medium receptor density and a decrease in undifferentiated cells ($p < 0.05$-0.001). Thus, the activating effect of the studied factors of the feed additive on the state of natural and adaptive defence factors in the body of sows and their offspring was established, which positively affects the formation of an immune response in periods of low immune potential of their body

Keywords: piglets; *Saccharomyces cerevisiae* yeast; probiotics; T- and B-lymphocytes; immunological tests

INTRODUCTION

The safety of piglets at an early age and during weaning is one of the most pressing issues in livestock production not only in Ukraine but also in most developed countries. The immune system is a major contributor to the viability of the organism. At the same time, in the context of modern intensive livestock farming, which is unilaterally focused solely on productive animal feeding, environmental stress, several stress factors and uncontrolled use of chemotherapeutic agents lead to a violation of metabolic homeostasis, a decrease in the level of cellular and humoral defence factors, the development of inflammation and immune deficiency, which can cause diseases. At the same time, in most cases, a violation of the quantitative and qualitative composition of the microbiocinosis of the intestinal tract is recorded and, as a result, the occurrence of bacterial imbalance in piglets. A pathologically altered microbial ecosystem can be a trigger for the development of the disease, contribute to its chronicity with the development and progression of metabolic and immune disorders, and the formation of endogenous infection reservoirs of various aetiologies and localisation. Therefore, there is a need to use appropriate remedies to correct impaired functions, and to restore microbiocinosis and the body's immune potential.

It is, therefore, necessary to develop and introduce into production safe products that can take a prominent place in the system of measures to ensure the biological protection of animals, especially young piglets. Scientists such as M. Elghandour *et al.* (2020), T. Pruduys and O. Vishchur (2022) believe that probiotic supplements, which are used as growth stimulants and are an alternative to feed antibiotics, largely meet these requirements. Probiotics are live bacteria or yeast cultures that are used to stabilise digestion, inhibit the growth of pathogens, and produce vitamins, enzymes amino acids and other biologically active substances.

An analysis of periodicals and specialised literature has shown that several major US, UK and European manufacturers have begun to supply the Ukrainian market with new-generation feed additives of various types: flavour and aroma substances, enzyme preparations, probiotics, prebiotics and others. At the same time, domestic producers, using modern technologies, are also entering the market for high-quality, safe, competitive feed additives. However, the successful use of such additives requires a high-quality comprehensive study of their efficacy and safety, as well as clear dosage recommendations. In this context, various yeast strains that can be used as probiotics, prebiotics, synbiotics and postbiotics are attracting particular attention. H. Vries *et al.* (2020) believe that the use of *Saccharomices cerevisiae* yeast in monogastric animals is of particular interest. The authors state that the main effect of adding yeast is to stimulate the formation of a rough membrane from disaccharides; anti-adhesive effect against pathogens; stimulation of nonspecific immunity; inhibition of toxins; and antagonistic effect against pathogens.

S. Bearson *et al.* (2023) highlight that the effect of the yeast cell wall on the immune system is known. These properties are attributed to substances in the middle layer of the yeast cell wall, glucans. These macromolecules can stimulate certain agents of the mammalian immune system, especially the inflammatory response and the reticuloendothelial system. The mechanism of stimulation of the immune response has been described and includes the binding of a specific glucan receptor on the surface of peripheral leukocytes and extravascular macrophages. The activation of this receptor by glucan stimulates the activation of its natural defence, which leads to a cascade reaction, primarily the production of cytokines by macrophages. C. Loving *et al.* (2023) noted that glucans are recognised as "immunoamplifiers". Glucans also significantly stimulate the phagocytic function of immune system cells. At the same time, T. Hjorth *et al.* (2023) reported an increase in the number of lactobacilli and a decrease in the number of bifidobacteria in the intestines of weaned piglets after feeding yeast, while A. Zbikowska *et al.* (2022) reported a decrease in the population of coliforms.

P. Han *et al.* (2024) showed that the preservation of normal intestinal morphology occurs due to the binding and reduction of pathogen colonisation in the gastrointestinal tract, which helps to improve the integrity of the intestinal mucosa and enhances the activity of the immune system. Additional studies conducted by W. Xiao *et al.* (2022) show that oral administration of *Saccharomices cerevisiae* to rats significantly enhances the synthesis of Ig A and the secretory component of immunoglobulins. Other studies by M. Marco *et al.* (2021) demonstrated the stimulating effect of Saccharomyces cerevisiae yeast on the content of immunoglobulins G and A in sow colostrum, which has a positive effect on the health and adaptive capacity of piglets during the early postnatal period. R. Domingos *et al.* (2021) determined that the addition of *Saccharomices cerevisiae* yeast as a probiotic to sow feed in the third trimester of pregnancy and during lactation reduced live weight loss at weaning, improved lactation, which had a positive effect on piglet weaning weight.

Therefore, it is of considerable interest to study the combined effect of the probiotic properties of yeast and a complex of enzymes on the body of sows and offspring. The study aimed to determine the effect of a feed additive containing *Saccharomyces cerevisiae* yeast and a complex of enzymes (protease, cellulase, xylanase, γ-amylase, β-glucanase, phytase) on the state of T- and B-cell specific defence and the activity of natural mechanisms of nonspecific resistance in sows and piglets born from them at critical periods of ontogeny.

MATERIALS AND METHODS

The study was conducted at the pig farm "Barkom" LLC, Sambir district, Lviv region. According to the principle of analogues, two groups of gestating sows of the Large White breed (2-3 farrowing) were formed, 8 animals in each group – control and experimental. The animals were kept in the same box, under the same feeding conditions and microclimate, which was maintained by an automated ventilation system. During the preparatory period (lasting one month), sows were kept in individual pens with individual drinkers and feeders. At the end of the preparatory period on the 85th day of farrowing, sows of the control group continued to receive standard feed (SF) balanced in terms of basic nutrients. The sows of the experimental group were additionally fed the feed additive "EnzActive Mix" in an amount of 0.3 kg/t of finished feed along with the SF. Five days before the scheduled farrowing, sows of both groups were transferred to the maternity ward, where they were kept in individual pens designed for parturition. Since then, the animals have been fed lactating sow feed. Sows of the experimental group received the feed additive "EnzActive Mix" in the amount of 0.3 kg/t of finished feed in addition to SF. After farrowing, the sows of the experimental and control groups were kept according to the specified feeding scheme. The experiment was started on the 85th day of sow farrowing and completed on the 28th day of lactation. The duration of the experiment was 58 days. During the experiment, the clinical condition of the animals was monitored, and the weight of the sows was determined by weighing them before farrowing and on the day of weaning. Feed consumption by sows during lactation was monitored.

Piglets born from sows of the control and experimental groups, starting from 5 days of age, received pre-starter and later starter feed in the corresponding periods of growth. At the same time, piglets of the experimental group were additionally fed the investigated feed additive in an amount of 0.5 kg/t of finished feed. The investigated feed additive EnzActive Mix is a unique combination of live yeast of the genus *Saccharomyces cerevisiae* and a complex of enzymes located under the layer of inactivated yeast cells. In particular, the product contains live yeast of the genus *Saccharomyces cerevisiae* with an activity of at least 1.5×10^10 CFU/g, as well as a complex of six enzymes: protease, cellulase, xylanase, α-amylase, β-glucanase, phytase (Patent No. 157586, TU U 10.9-00383320-029:2024).

The material for immunological studies was blood taken from sows from the jugular vein on the 85th and 112th day of pregnancy and the 21st day of lactation. In piglets born from sows of the experimental and control groups, blood was taken from the cranial vena cava at 5-, 14- and 28 days of age. The methods used in the study were those most suitable for the conditions described in the reference book, edition by V. Vlizlo *et al.* (2012) in the section on the study of the immunological status of animals. In heparin-stabilised blood, the total number of T-lymphocytes (T-lymphocytes) and the number of "active" T-lymphocytes (TA-RUL) were determined by the method of rosette formation with sheep erythrocytes. At the same time, their subpopulations were determined – T-helper (Th-RUL), theophylline-resistant (TR) and T-suppressor (Ts), theophylline-sensitive T-lymphocytes. The number of B-lymphocytes (EAC-RUL) is determined in the complementary rosette reaction with sheep erythrocytes. The presence of various markers and receptors on the surface of lymphocytes allows them to be differentiated from each other. The activity of rosette formation was determined by the density of receptors: 3-5 – receptors with low density; 6-10 – receptors with medium density; rosettes in the form of "morula" – receptors with high density. The number of T-cells with predominantly suppressor activity (TSA) was calculated by subtracting the number of theophylline-resistant T-cells (TR) from the total number of T-lymphocytes. The immunoregulatory index (IRI) was calculated as the ratio of theophylline-resistant T cells to theophylline-sensitive T cells. Indicators of phagocytosis of blood neutrophil granulocytes: phagocytic activity (PA), phagocytic number (PN) and phagocytic index (FI) were determined by the method of V.S. Guestev 1950 (Luzyk *et al.*, 2018).

In blood serum, the lysozyme activity (LASK) to the daily culture of *Micrococcus lysodeikticus* (strain VKM-109) was determined using the photonephelometric method, bactericidal activity (BASK) by a modified method, and the content of circulating immune complexes (CIC). All experimental animals were subjected to the least amount of stress and pain during the experiment. The blood sampling sites were treated with 70% alcohol to prevent infections from entering the injection sites. During the research, the requirements of ethical treatment of animals used in experimental studies were fully complied with (European convention for the protection of…, 1986; ISO/IEC 17025:2005, 2006). Statistical processing of the research results was performed using the standard Statistica package in Microsoft Excel 2013, assessing the reliability of the indicators ($p < 0{,}05$; $p < 0{,}01$; $p < 0{,}001$) by the Student's criterion.

RESULTS AND DISCUSSION

The results of the studies showed that feeding sows during the last month of pregnancy and lactation with a feed additive containing *Saccharomyces cerevisiae* yeast and a complex of enzymes had a significant effect on the activity of natural defence mechanisms (Table 1). In all periods of research after the use of the feed additive, the bactericidal and lysozyme activity of blood serum in sows of the experimental group was higher than in the control group. At the same time, the differences were more pronounced in the study of such an integral indicator of the humoral link of nonspecific resistance as the bactericidal activity of blood serum. Thus, the SBA in the blood of sows of the experimental group on the 112th day of farrowing and the 21st day of lactation was 3 ($p < 0.05$) and 4.8% ($p < 0.01$) higher, respectively, than in the animals of the control group. In the study of serum lysase activity, a significant increase (by 12%) in sows of the experimental group compared to the control group on the 112th day of pregnancy ($p < 0.001$) is noteworthy.

***Table 1**. Humoral factors of natural resistance in the blood of sows under the use of a feed additive (M ± m, n = 5)*

Indicators	Groups	Study period		
		before application	after application	
		85-day farrowing period	112-day farrowing period	21 days of lactation
LASK,	C	34.20 ± 1.50	30.00 ± 1.05	34.40 ± 1.63
	D	37.60 ± 0.93	42.00 ± 0.95***	37.80 ± 1.39
BASK,	C	31.10 ± 0.98	30.77 ± 0.41	31.78 ± 0.64
	D	34.04 ± 0.80	33.33 ± 0.83*	36.35 ± 1.17**
CIC, mmol/l	C	74.67 ± 2.60	80.20 ± 2.08	85.40 ± 2.29
	D	78.00 ± 1.70	77.20 ± 1.39	75.40 ± 3.57*

***Note:** differences are statistically significant to animals of the control group - *P < 0.05, **P < 0.01, ***P < 0.001*
***Source:** compiled by the authors*

These data indicate a stimulating effect of the studied factors contained in the feed additive on the activity of humoral factors of nonspecific resistance. Instead, the study of other natural defence factors, particularly the content of circulating immune complexes, revealed a significant decrease (by 11.7%) in the blood of sows of the experimental group on the 21st day of lactation ($p < 0.05$). The formation of immune complexes in the body is the result of the specific interaction of antigens with antibodies. A gradual increase of CIC in the blood of sows of the control group was recorded with an increase in the gestation period and during lactation. The results of these studies indicate the inhibitory effect of feed additive factors on the level of circulating immune complexes in the blood of sows of the experimental group. This is a positive factor for the body since an increase in the content of CICs and their long-term circulation in the body of animals can lead to systemic or organ pathology, as indicated by V. Zhurenko *et al.* (2021), C. Cacheiro-Llaguno *et al.* (2021).

According to the authors of A. Krogh (2019), the immune system is a complex of organ and tissue defences that, together with other body systems, maintain a specific homeostasis of the internal environment. This function of the immune system is carried out through the cooperative interaction of natural and specific defence mechanisms. The last trimester of pregnancy in sows, as noted by M. Ballester *et al.* (2023), is one of the critical periods that significantly affects the state of the immune system of their body, as well as the offspring. Violation of the formation of the immune response in the body of gestating sows leads to the production of offspring with signs of congenital immunodeficiency. Given this, it is necessary to use appropriate immunotropic agents, in particular in the form of feed additives, to restore metabolic homeostasis and the immune function of the animal body.

Similar results were observed in the determination of humoral factors of natural defence in piglets born from sows of the control and experimental groups (Table 2). However, the differences were less pronounced, especially concerning such indicators as serum lysozyme activity and CIC content. There were only trends towards an increase in lysosomal activity and a decrease in the content of CIC in the blood serum of piglets of the experimental group compared to the control group. At the same time, the use of the feed additive had a significant effect on the bactericidal activity of blood serum in the experimental group. Thus, as can be seen from the data presented in Table 2, in all periods of the study, the BASK in piglets of the experimental group was higher compared to the control group. At the same time, the differences were significant at 14 and 28 days of age ($p < 0.05$). Thus, feeding piglets of the experimental group with a pre-starter feed of *Saccharomyces cerevisiae* yeast and a complex of enzymes has an activating effect on such an integral indicator of natural resistance as the bactericidal activity of blood serum. This is positive given that the studies by E. Heuß *et al.* (2019) confirm that the synthesis of humoral immunity factors in piglets increases in the early stages of their development, especially by the age of two months. A gradual increase in LAC in piglets with age was also recorded compared to the values of this indicator in newborns. In monogastric animals, the mechanism of action of *Saccharomyces cerevisiae* yeast is explained by the fact that its addition to the diet stimulates the formation of disaccharides on cell membranes, with a non-adhesive effect against pathogens, activation of nonspecific defence, weakening of toxins, and an anthoganistic effect against pathogens. The competition between yeast and pathogens for binding to intestinal cells may explain the positive effects of yeast, from adhesion to cytopathogenic effects on cells. M. Tintoré *et al.* (2023) confirmed that the constant presence of the active serotype of *Saccharomices cerevisiae* in the piglet digestive tract has an immunostimulatory effect and can protect piglets against immunological challenges.

Table 2*. Humoral factors of natural resistance of young piglets with the use of feed additive (M ± m, n = 5)*

Indicators	Groups	Study period		
		before application	after application	
		5 days after birth	14 days after birth	28 days after birth
LASK,	C	38.67 ± 0.88	34.20 ± 1.49	41.0 ± 0.71
	D	41.00 ± 2.08	37.6 ± 0.93	42.60 ± 0.51
BASK,	C	28.71 ± 0.78	28.81 ± 0.48	29.5 ± 0.28
	D	32.08 ± 1.53	32.60 ± 1.36*	33.66 ± 1.56*
CIC, mmol/l	C	72.67 ± 2.03	66.20 ± 4.45	68.60 ± 2.99
	D	70.67 ± 2.03	62.8 ± 2.56	67.0 ± 1.58

Note: *differences are statistically significant concerning animals of the control group - *P < 0.05, **P < 0.01, ***P < 0.001*
Source: *compiled by the authors*

To objectively assess the level of natural and adaptive immunity in animals, it is known that first- and second-level tests should be used. Given this, the authors of the study determined the cellular factors of specific immunity. The functional basis of the animal immune system is immunocompetent blood cells – lymphocytes. They are carriers of immunological memory and precursors of antibody-forming cells. Researchers such as H. Sun *et al.* (2022) believe that immunity decreases during pregnancy because the natural mechanism of its suppression, namely cellular immunity, is activated during this period. The gestational period is considered a biological model of the process of periodic or permanent immunisation of a pregnant female with autoantigens. The normal course of pregnancy is primarily associated with the immune recognition of semihalogenated foetal and placental antigens by the mother's immunocompetent cells. The mother's T-lymphocytes recognise foetal antigens. This antigen-specific immune response to paternal antigens leads to the proliferation and accumulation of individual T-cell clones. In many studies of T lymphocyte subpopulations conducted by M. Ballester *et al.* (2023), a significant decrease in the number of T helper and T suppressor cells was found with an increased value of the T suppressor/T helper ratio. T-cell function, as assessed by their colony-forming activity and proliferative response to antigen stimulation, decreases. The B-cell response and immunoglobulin production were also found to be suppressed, with a decrease in the total number of B-lymphocytes.

H. Struemper *et al.* (2022) found an increase in B-lymphocyte function accompanied by an increase in serum immunoglobulin levels. According to K. Rio-Aige *et al.* (2021), immunoglobulins in pregnant females transfer from the blood to the mammary gland shortly before delivery and can reach a concentration there ten times higher than their blood level. In these conditions, as a result of a decrease in the effector and helper functions of T cells, the risk of developing infections and malignant tumours increases, and a violation of the suppressor function of T lymphocytes leads to the appearance of “forbidden” lymphocytes clones, loss of autotolerance and the development of autoimmune diseases. The mechanisms for maintaining the body’s immune homeostasis formed in the course of evolution are often unable to perform their functions, which leads to the emergence of immune pathology, mostly immunodeficiency. Therefore, it is advisable to use immunostimulating drugs during pregnancy to increase the overall resistance of the animal body.

Determination of the quantitative composition of T- and B-lymphocytes in the blood of sows and piglets born from them was carried out to assess the level of specific immunity. The data in Table 3 show that the number of T-cells and their populations in the blood of sows of the control group did not change significantly during all physiological periods of the study. Instead, some statistical changes were recorded in the blood of sows of the experimental group, which were fed a feed additive in addition to standard feed. In particular, the total number of TE-RUL in the blood of sows of the experimental group on the 112th day of pregnancy and on the 21st day of lactation was 3.6 ($p < 0.01$) and 4.2% ($p < 0.001$) higher, respectively, than in the control group. At the same time, the increase in the total number of T-lymphocytes in the blood of sows of the experimental group during the indicated periods of research occurred against the background of a probable increase in low-avid TE-RUL and a decrease in functionally inactive cells. Differences in other populations of TE-RULs in the blood of sows of the experimental group compared to the control group were not significant.

***Table 3**. The number of T-cell lymphocytes in the blood of sows with the use of feed additive, (M ± m, n = 5)*

Indicators	Groups of animals	Study period		
		before application	after application	
		85-day farrowing period	112-day farrowing period	21st day lactation
TE-RUL, 0	C	59.00 ± 1.04	58.60 ± 0.87	58.4 ± 0.50
	D	57.40 ± 0.50	55.00 ± 0.44**	54.2 ± 0.37***
3-5	C	35.80 ± 1.15	36.40 ± 0.81	37.4 ± 0.67
	D	36.80 ± 1.01	39.60 ± 0.92*	41.0 ± 0.70**
6-10	C	3.60 ± 0.24	3.60 ± 0.24	3.00 ± 0.31
	D	3.80 ± 0.37	4.00 ± 0.32	3.80 ± 0.37
M	C	1.60 ± 0.40	1.40 ± 0.24	1.20 ± 0.2
	D	2.00 ± 0.44	1.40 ± 0.24	1.00 ± 0.44
%	C	41.00 ± 1.04	41.4 ± 0.87	41.60 ± 0.50
	D	44.60 ± 0.50	45.0 ± 0.44**	45.80 ± 0.37***

Note: *TE-RUL – total T-lymphocytes, *P < 0.05, **P < 0.01, ***P < 0.001*
Source: *compiled by the authors*

Similar changes, but expressed to a lesser extent, were noted in the study of T-active lymphocytes in the blood of sows of the experimental group under the influence of the feed additive (Table 4). Thus, on the 112th day of pregnancy and the 21st day of lactation, a significantly higher total number of T-active lymphocytes was found in the blood of sows of the experimental group compared to the control group. The increase in the number of TA-RUL in the blood of sows of the experimental group was accompanied by a simultaneous increase in the proportion of T-active lymphocytes with low avidity and a decrease in inactive TA-RUL ($p < 0.05$; $p < 0.01$). These data indicate a stimulating effect of the studied feed additive on the number of total and active T-lymphocytes in the blood. At the same time, an increase in the number of low-avidity TE-RUL was recorded in the blood of sows of the experimental group, indicating the activating effect of the factors contained in the additive on the functional state of the receptor apparatus of immunocompetent cells.

***Table 4**. The number of T-active lymphocytes in the blood of sows with the use of feed additive, (M ± m, n = 5)*

Indicators	Groups of animals	Study period		
		before application	after application	
		85-day farrowing period	112-day farrowing period	21st daylactation
TA-RUL, 0	C	76.60 ± 0.92	76.20 ± 0.86	75.20 ± 0.37
	D	74.20 ± 0.58	73.6 ± 0.40*	72.80 ± 0.37**
3-5	C	17.20 ± 1.11	19.60 ± 0.74	19.60 ± 0.67
	D	19.20 ± 0.73	21.20 ± 0.48	21.60 ± 0.64

Table 4. Continued

Indicators	Groups of animals	Study period		
		before application	after application	
		85-day farrowing period	112-day farrowing period	21st daylactation
6-10	C	5.20 ± 0.58	3.20 ± 0.37	4.80 ± 0.66
	D	5.80 ± 0.58	4.20 ± 0.37	4.40 ± 0.50
M	C	1.00 ± 0.31	1.00 ± 0.31	0.40 ± 0.24
	D	0.8 ± 0.37	1.00 ± 0.31	1.20 ± 0.20
%	C	23.40 ± 0.92	23.80 ± 0.86	24.80 ± 0.37
	D	25.80 ± 0.58	26.40 ± 0.40*	27.20 ± 0.37**

Note: *TA-lymphocytes – total T-lymphocytes, *P < 0.05, **P < 0.01, ***P < 0.001*
Source: *authors' development*

In the study of individual regulatory subpopulations of T-lymphocytes in the blood of sows under the influence of the feed additive, similar changes were also obtained (Table 5). A significant increase in the total number of theophylline-resistant T-lymphocytes in the blood of sows of the experimental group was recorded, especially on the 21st day of lactation. At the same time, on the 112th day of farrowing in the blood of sows of this group, a significantly higher number of Th-RUL with medium receptor density was found, and on the 21st day of lactation – low avidity, against the background of a decrease in the proportion of inactive forms. Under the influence of the studied feed additive, a tendency to increase the number of theophylline-sensitive subpopulations of T-lymphocytes was revealed. These changes in the number of T-lymphocytes in the blood of sows of the experimental group led to an increase in the immunoregulatory index, which characterises the ratio of T-helper to T-suppressor, but the differences were not significant. At the same time, the results of these studies indicate the activating effect of feed additive factors on the receptor apparatus of T lymphocytes by redistributing avidity and expanding the receptor field of immunocompetent cells.

Table 5*. The amount of T-helper and T-suppressor in the blood of sows with the use of feed additive, (M ± m, n = 5)*

Indicators	Groups of animals	Study period		
		before application	after application	
		85-day farrowing period	112-day farrowing period	21st day lactation
Th-RUL, 0	C	76.40 ± 0.58	76.4 ± 0.50	75.00 ± 0.54
	D	76.20 ± 0.86	73.6 ± 0.50**	72.00 ± 0.54**
3-5	C	20.00 ± 0.54	19.8 ± 1.01	21.2 ± 0.48
	D	22.60 ± 1.20	21.0 ± 0.70	24.80 ± 0.86**
6-10	C	2.60 ± 0.24	3.0 ± 0.31	2.0 ± 0.31
	D	3.00 ± 0.31	4.4 ± 0.24**	2.2 ± 0.37
M	C	0.60 ± 0.24	0.80 ± 0.37	1.00 ± 0.32
	D	0.60 ± 0.40	1.00 ± 0.32	1.00 ± 0.32
%	C	23.20 ± 0.58	23.60 ± 0.50	24.2 ± 0.37
	D	24.20 ± 0.86	26.40 ± 0.50**	28.0 ± 0.54***
T-suppressors	C	17.60 ± 1.03	17.60 ± 1.40	16.80 ± 0.58
	D	20.40 ± 1.73	18.00 ± 0.77	18.60 ± 1.24
IRI	C	1.34 ± 0.098	1.38 ± 0.144	1.44 ± 0.06
	D	1.40 ± 0.600	1.47 ± 0.058	1.50 ± 0.01

Note: *Th-RUL, IRI – immunoregulatory index; *P < 0.05, **P < 0.01, ***P < 0.001*
Source: *compiled by the authors*

The study of the number of B-lymphocytes (EAC-RUL) and the determination of their functional activity characterises the level of the humoral link of immunity. The analysis of the data in Table 6 shows that the use of a feed additive in sows during pregnancy and lactation had a similar effect on the number of B lymphocytes and their functional state as in the study of T lymphocytes and their regulatory populations. However, these changes were more pronounced. In particular, the number of B-lymphocytes in the blood of sows on the 112th day of farrowing and the 21st day of lactation was 4.6 ($p < 0.001$) and 5.2% ($p < 0.001$) higher, respectively, than in the control group. Regarding the degree of differentiation of this cell population, an increase in the number of low avid B-lymphocytes ($p < 0.01$-0.001) and a decrease in undifferentiated cells ($p < 0.001$) were observed in the blood of sows of the experimental group compared to their number in animals of the control group.

***Table 6**. The number of B-lymphocytes in the blood of sows with the use of feed additive, (M ± m, n = 5)*

Indicators	Groups of animals	Study period		
		before application	after application	
		85-day farrowing period	112-day farrowing period	21st day lactation
EAC-RUL, 0	C	59.60 ± 0.50	59.20 ± 0.37	59.00 ± 0.31
	D	59.00 ± 0.44	54.60 ± 0.24***	53.80 ± 0.37***
3-5	C	28.60 ± 0.67	31.70 ± 0.96	31.60 ± 0.50
	D	30.00 ± 0.84	36.60 ± 0.67**	37.60 ± 0.92***
6-10	C	7.60 ± 0.40	6.20 ± 0.37	7.40 ± 0.50
	D	7.40 ± 0.50	6.60 ± 0.50	6.60 ± 0.50
M	C	4.20 ± 0.37	2.80 ± 0.58	2.00 ± 0.31
	D	3.60 ± 2.24	2.20 ± 0.37	2.000 ± 0.31
%	C	40.40 ± 0.51	40.80 ± 0.37	41.0 ± 0.31
	D	41.00 ± 0.44	45.40 ± 0.24***	46.20±0.37***

***Note:** EAC-RUL – B lymphocytes, *P < 0.05, **P < 0.01, ***P < 0.001*
***Source:** compiled by the authors*

Thus, the positive effect of the studied factors contained in the feed additive on the state of B-cell immunity in sows in different physiological periods was established. In particular, their stimulatory effect on the number of B lymphocytes and their functional activity was established. According to P. Han *et al.* (2024), an increase in the number of B-lymphocytes in the blood of sows during periods of low immune potential of their body is a positive phenomenon, as these immunocompetent cells largely provide humoral immunity by synthesising specific antibodies (immunoglobulins) and also affect the activity of some populations of T-lymphocytes in cellular immunity reactions.

When determining the state of T- and B-cell links of specific defence in the blood of piglets obtained from sows of the control and experimental groups, a similar pattern of changes in the quantitative and functional state of immunocompetent cells was revealed, especially at 14 and 28 days of age (Table 7). The results of the studies showed that the total number of T-lymphocytes and their regulatory populations in the blood of piglets of the experimental group at 5 days of age did not differ significantly from the control group, indicating that there was no significant effect of feed additive factors on the formation of the cellular link of transcolostral immunity in sows and the state of the T- and B-cell immunity of piglets. Instead, in the blood of piglets of the experimental group at 14 and 28 days of age, the number of TE-RULL was significantly higher than in the control group. At the same time, a significantly higher number of low-avidity and a lower number of inactive T-ROOL were recorded during these periods of research.

***Table 7**. The amount of TE-RUL in the blood of piglets with the use of feed additive, (M ± m, n = 5)*

Indicators	Groups of animals	Study period		
		before application	after application	
		5 days after birth	14 days after birth	28 days after birth
TE-RUL, 0	C	69.33 ± 0.33	69.20 ± 0.37	69.0 ± 0.44
	D	68.33 ± 0.89	73.60 ± 2.11	66.8 ± 0.73*
3-5	C	26.0 ± 0.57	26.60 ± 0.25	27.0 ± 0.54
	D	27.33 ± 0.33	28.60 ± 0.67*	28.8 ± 0.37*
6-10	C	3.33 ± 0.33	2.80 ± 0.20	3.00 ± 0.31
	D	2.66 ± 0.33	2.60 ± 0.40	2.8 ± 0.37
M	C	1.33 ± 0.33	1.40 ± 0.24	1.00 ± 0.31
	D	1.66 ± 0.33	1.20 ± 0.20	1.20 ± 0.20
%	C	30.66 ± 0.33	30.80 ± 0.37	31.0 ± 0.44
	D	31.66 ± 0.88	32.40 ± 0.50*	32.8 ± 0.37*

***Note:** TE-RUL – total T-lymphocytes, *P < 0.05, **P < 0.01, ***P < 0.001*
***Source:** compiled by the authors*

A similar pattern of changes, but expressed to a lesser extent, was recorded when determining the number of T-active lymphocytes in the blood of piglets (Table 8). It should be noted that at 5 and 14 days of age, only trends in these changes were detected in the blood of piglets of the experimental group. At the same time, at 28 days of age, a significant increase in the number of T-active lymphocytes was recorded in the blood of piglets of this group against the background of a decrease in inactive TA-RUL.

***Table 8**. The number of TA-RUL in the blood of piglets with the use of feed additive, (M ± m, n = 5)*

Indicators	Groups of animals	Study period		
		before application	after application	
		5 days after birth	14 days after birth	28 days after birth
TA-RUL, 0	C	79.33 ± 0.66	78.6 ± 0.60	78.0 ± 0.70
	D	79.0 ± 0.15	77.4 ± 0.50	75.6 ± 0.74*
3-5	C	15.33 ± 1.33	17.8 ± 0.86	17.8 ± 0.86
	D	16.2 ± 0.73	19.2 ± 0.66	19.4 ± 0.67
6-10	C	4.33 ± 0.57	3.0 ± 0.54	3.6 ± 0.24
	D	4.0 ± 0.57	2.6 ± 0.24	4.0 ± 0.25
M	C	1.0 ± 0.0	0.60 ± 0.24	0.60 ± 0.24
	D	0.66 ± 0.33	0.80 ± 0.20	1.00 ± 0.31
%	C	20.66 ± 0.66	21.4 ± 0.50	22.0 ± 0.70
	D	21.0 ± 1.15	22.6 ± 0.50	24.4 ± 0.78*

***Note:** TA-RUL – total T-lymphocytes, *P < 0.05, **P < 0.01, ***P < 0.001*
***Source:** compiled by the authors*

In the study of other subpopulations of T-lymphocytes (theophylline-resistant and theophylline-sensitive) in the blood of piglets under the influence of the feed additive, the differences concerning the animals of the control group were less pronounced (Table 9). At the same time, a greater number of T-helper cells and their low-avid forms in the blood of piglets of the experimental group at all periods of the study, and especially at 28 days of age, is noteworthy, but the differences concerning the control group were not significant. At all periods of the study, the IRI in the blood of piglets of the experimental group was higher than in the control group, indicating an increase in lymphocytic activity, but the differences were not significant.

***Table 9**. The number of T-helper and T-suppressor cells in piglet blood after feed additive application, (M ± m, n = 5)*

Indicators	Groups of animals	Study period		
		before application	after application	
		5 days after birth	14 days after birth	28 days after birth
T-helper, 0	C	78.66 ± 0.88	78.6 ± 1.28	78.4 ± 0.97
	D	77.0 ± 0.57	76.4 ± 0.81	76.0 ± 0.70
3-5	C	18.66 ± 0.33	19.0 ± 1.04	17.6 ± 0.87
	D	20.0 ± 1.52	20.8 ± 1.01	20.2 ± 0.96
6-10	C	2.33 ± 0.33	2.2 ± 0.24	3.4 ± 0.24
	D	2.66 ± 0.66	2.4 ± 0.24	3.2 ± 0.37
M	C	0.33 ± 0.33	0.20 ± 0.20	0.60 ± 0.24
	D	0.33 ± 0.33	0.40 ± 0.24	0.60 ± 0.24
%	C	21.33 ± 0.88	21.4 ± 1.28	21.6 ± 0.97
	D	23.0 ± 0.57	23.6 ± 0.81	24.0 ± 0.70
T-suppressors,	C	9.33 ± 0.88	9.4 ± 0.24	9.0 ± 0.94
	D	8.66 ± 1.2	9.8 ± 0.58	8.4 ± 0.67
IRI	C	2.13 ± 0.04	2.28 ± 0.17	2.50 ± 0.27
	D	1.83 ± 0.41	2.43 ± 0.12	2.93 ± 0.20

***Note:** Th-RUL, IRI – immunoregulatory index; *P < 0.05, **P < 0.01, ***P < 0.001*
***Source:** compiled by the authors*

Table 10 shows the data on the determination of the number and functional activity of antigen-independent B-lymphocytes in the blood of piglets. The analysis of the study results showed that the investigated feed additive caused similar changes in the number of B-lymphocytes in the blood of early-age piglets as were found in the determination of other populations of immunocompetent cells. However, these changes were more pronounced in the blood of piglets before weaning at 28 days of age. A significantly higher number of B-lymphocytes and their high-avidity forms and a lower number of functionally inactive EAC-RUL were recorded in the blood of piglets of the experimental group compared to the control group ($p < 0.05$).

***Table 10**. The amount of EAC-RUL in the blood of piglets with the use of feed additives, (M ± m, n = 5)*

Indicators	Groups of animals	Study period		
		before application	after application	
		5 days after birth	14 days after birth	28 days after birth
EAC-RUL, 0	C	63.66 ± 0.66	63.6 ± 0.50	63.0 ± 0.31
	D	62.0 ± 0.57	62.2 ± 0.58	61.8 ± 0.37*
3-5	C	28.66 ± 0.88	27.2 ± 1.06	27.4 ± 0.40
	D	30.66 ± 0.66	29.8 ± 0.73	27.6 ± 0.67
6-10	C	5.33 ± 0.33	5.8 ± 0.73	6.0 ± 0.44
	D	5.0 ± 0.57	4.6 ± 0.24	6.4 ± 0.67
M	C	2.33 ± 0.33	3.6 ± 0.50	3.6 ± 0.24
	D	1.66 ± 0.33	3.4 ± 0.24	4.4 ± 0.24*
%	C	36.63 ± 0.66	36.4 ± 0.50	37.0 ± 0.31
	D	37.33 ± 0.33	37.8 ± 0.58	38.2 ± 0.37*

***Note:** EAC-RUL – B lymphocytes, *P < 0.05, **P < 0.01, ***P < 0.001*
***Source:** compiled by the authors*

These data indicate the activating effect of the feed additive factors on the humoral defence factors of the piglet organism in critical periods of postnatal development. The increase in the number of B-lymphocytes in the blood of piglets under the influence of the investigated feed additive at 28 days of age (before weaning) is positive, given that these immunocompetent cells, as noted above, largely provide humoral immunity by synthesising specific antibodies (immunoglobulins), and also affect the activity of some populations of T-lymphocytes in cellular immunity reactions. In general, the research results showed that the use of the EnzActive Mix feed additive in sow feed during pregnancy and lactation, as well as in piglets at an early age, has a positive effect on the immune function of the mother and offspring. This is especially important in sows in the last period of pregnancy under conditions of physiological immunosuppression and the formation of transcolostral protective factors. It is equally important for piglets, especially during critical periods of postnatal development. After all, intensive piglet-rearing technologies that involve early weaning of piglets from sows and exposure to various stress factors lead to the depletion of the body's immune and antioxidant potential and the development of immunodeficiency. It is also known that intensive livestock production technology involves not only the creation of a stable feed base but also the preservation of health and increased productivity of farm animals.

The quality of the raw materials used to make compound feed significantly impacts metabolic processes in sows during pregnancy and lactation. Poor quality grain and protein groups cause an increase in the level of free radicals and peroxide in the body of sows, which subsequently leads to a violation of metabolic homeostasis, reduced productivity and the occurrence of diseases. A significant number of enzymes is used to improve digestion and nutrient absorption of feed. According to A. Maggiolino *et al.* (2023), and T. Pruduys (2023), the use of enzyme additives significantly increases the efficiency of feed nutrient absorption and has a positive effect on piglet growth and viability. The study has demonstrated that enzyme supplements also reduce stress levels in sows during lactation. At the same time, H. Zhai *et al.* (2021) proved that the inclusion of phytase in the diet of sows improves the absorption of minerals such as calcium and phosphorus during the farrowing period. This has a positive effect on the formation of the foetal bone system and contributes to the weight gain of newborn piglets. Reducing the level of inflammation in the intestine and reducing stress levels is due to the action of the enzyme β-glucanase, which breaks down β-glucans in fibre feed. According to Zh. Li *et al.* (2021), this enzymatic action also affects the body's immune and antioxidant potential, probably through better nutrient absorption and intestinal health. An important role in this is played by microorganisms, representatives of the natural microflora of the gastrointestinal tract, which, through their active life, participate in the digestive process, counteract the development of many pathogens, and increase the body's nonspecific resistance. Probiotic preparations are developed and manufactured on their basis.

The results of the current study obtained in this experiment are consistent with the previous study by Ya. Kovalchuk *et al.* (2009), where the effect of 1 and 2% *Saccharomyces cerevisiae* yeast on the state of natural and adaptive immunity in early-age piglets and at weaning, as well as the literature on these issues (literature). The results of these studies indicate a stimulating effect of the supplementation factors on the natural mechanisms of nonspecific resistance of sows and offspring, such as serum lysozyme and bactericidal activity. This can be explained by the additive effect of biologically active substances contained in the supplement. Mannans and D-glucans have been isolated from the cell wall of the yeast *Saccharomices cerevisiae*, which exhibits immunomodulatory, radioprotective, antitumour and other properties. Recent studies demonstrated that the use of yeast as a probiotic in animal feeding has immunomodulatory properties. E. De Marco Castro *et al.* (2021) are convinced that these substances can block the attachment of pathogens to the intestinal mucosa. They may also have a versatile mechanism of action on cytokine synthesis, which makes it possible to influence immunological processes by directing their action in the Th-1 or Th-2 type. The anti-inflammatory effect of probiotics is especially relevant in diseases associated with mucosal integrity disorders, which is important for piglets in the early postnatal period of development.

S. Ogawa *et al.* (2016) demonstrated that in piglets before colostrum intake, serum immunoglobulins are absent, and their content increases dramatically due to intestinal adsorption with maternal colostrum during the first 24-36 hours of life. According to N. Martínez-Boixaderas *et al.* (2022), and D. Masiuk *et al.* (2023), in newborn piglets, cellular immunity factors are more pronounced than humoral ones in the early stages of development. This is evidenced by the appearance of a blast transformation reaction with allogeneic lymphocytes and phytohaemagglutinin, cell transplant rejection, synthesis of class M immunoglobulins, and the phenomenon of spontaneous rosette formation. However, the functional activity of cellular defence factors in this age group is also low. P. Han *et al.* (2024) noted a low level of cellular immunity in the blood of piglets up to 30 days of age, in particular, a significant number of undifferentiated and low-differentiated T-lymphocytes, a small number of T-active lymphocytes, B-lymphocytes and the concentration of certain classes of immunoglobulins, low functional activity of neutrophil granulocytes. In piglets, the differentiation of the T and B immune systems in the peripheral lymphoid organs is mainly completed by day 30 of development. At the same time, T cells bearing receptors characteristic of T helper cells make up almost 60%, and only 12-18% are T suppressors.

C. Velez *et al.* (2024) confirmed that piglets' immunity has several critical aspects, such as before colostrum consumption and from 15 to 28 days of life. During these periods, active immunity is at its lowest levels, and passive immunity is already being lost, which lasts for 4-6 weeks with sufficient colostrum consumption. This is because maternal immunoglobulins derived from colostrum begin to lose their effectiveness, and the production of their immunoglobulins is very low and increases over 7-14 days. Research results and analysis of the scientific literature show that yeast-containing probiotics are effective. This makes it possible to consider them as immunomodulatory drugs, the mechanism of action of which is mainly implemented through the mucous membrane of the digestive tract.

CONCLUSIONS

Feeding sows with the studied feed additive during periods of low immune potential of their body (in the last trimester of pregnancy and lactation), caused a stimulating effect on the activity of natural mechanisms of the humoral link of nonspecific resistance of the body. This is evidenced by the higher bactericidal and lysozyme activity of sow blood serum during pregnancy and lactation ($p < 0.05$-0.001). At the same time, on the 21st day of lactation, a lower content of circulating immune complexes was recorded in the blood of sows of this group ($p < 0.05$), indicating a decrease in the antigenic load on the animal body. In piglets born from these sows under the influence of the specified feed additive, similar changes in natural defence factors were observed but expressed to a lesser extent. A higher BASK ($p < 0.05$) and a lower CIC content ($p < 0.05$) were recorded.

The activating effect of the feed additive on the state of adaptive immunity, in particular cellular defence factors in sows and their piglets, was established. This is indicated by a higher number of T-lymphocytes (total, active and theophylline-resistant) and B-lymphocytes ($p < 0.05$-0.001) and their higher functional activity. These changes in the blood of sows and piglets were due to the redistribution of the receptor apparatus of immunocompetent cells – an increase in the number of T- and B-lymphocytes with low and medium receptor density and a decrease in functionally inactive cells ($p < 0.05$-0.001). Prospects for further research are to study the effect of Saccharomyces cerevisiae and a complex of enzymes on the antioxidant function of sows and their offspring.

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CONFLICT OF INTEREST

The authors declare no conflict of interest in this paper.

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Стан Т- і В-клітинної ланок специфічного імунітету й активність гуморальних факторів природного захисту свиноматок та їх поросят за впливу комплексу дріжджів *Saccharomyces cerevisiae* та ферментів

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Анотація. Незрілість імунної системи новонароджених поросят призводить до значних їх втрат у постнатальний період та повністю залежить від материнського організму, особливо в останній період поросності, що зумовлено посиленням метаболічних процесів і фізіологічною імуносупресією. Мета роботи – визначити активність природних й адаптивних факторів захисту у свиноматок та народжених від них поросят за впливу кормової добавки, що містить дріжджі *Saccharomyces cerevisiae* та ферменти. Результати досліджень показали, що згодовування свиноматкам у період поросності і лактації, а також поросятам у період до відлучення кормової добавки позитивно впливало на імунну функцію організму матері та приплоду. Зокрема за дії вказаних чинників добавки констатовано активуючий вплив на природні механізми гуморальної ланки неспецифічної резистентності організму, особливо у свиноматок. Про що свідчать вища бактерицидна і лізоцимна активність сироватки крові свиноматок у період поросності і лактації ($p < 0{,}05$-$0{,}001$) та менший вміст циркулюючих імунних комплексів ($p < 0{,}05$), що вказує на зменшення антигенного навантаження на організм матері, особливо у період імуносупресії. Подібні зміни, тільки виражені меншою мірою, зафіксовано у поросят, виявлено вищу БАСК ($p < 0{,}05$) та менший вміст ЦІК ($p < 0{,}05$). Згодовування свиноматкам та поросятам дріжджів та ферментів у періоди низького імунного потенціалу їх організму спричинило активуючий вплив на стан адаптивного імунітету, зокрема клітинних факторів специфічного захисту організму. Про що свідчать збільшення у крові кількості Т-лімфоцитів (загальних, активних і теофілін-резистентних) і В-лімфоцитів ($p < 0{,}05$-$0{,}001$) та підвищення їх функціональної активності за рахунок перерозподілу рецепторного апарату імунокомпетентних клітин – збільшення кількості Т- і В-лімфоцитів з низькою і середньою щільністю рецепторів та зменшення недиференційованих у функціональному відношення клітин ($p<0{,}05$-$0{,}001$). Таким чином констатовано активуючий вплив досліджуваних чинників кормової добавки на стан природних і адаптивних факторів захисту в організмі свиноматок та їх приплоду, що позитивно впливає на формування імунної відповіді у періоди низького імунного потенціалу їх організму

Ключові слова: поросята; дріжджі *Saccharomyces cerevisiae*; пробіотики; Т- і В-лімфоцити; імунологічні дослідження

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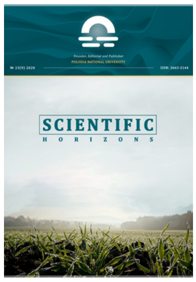

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Utilisation of α-amylase and β-glucanase enzymes to improve the productivity of poultry farms

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Abstract. In modern poultry farming, increasing the efficiency of feed use is a key factor for increasing productivity and reducing production costs. One of the promising methods for improving productivity indicators is the use of enzyme supplements such as α-amylase and β-glucanase, which improve nutrient absorption by improving feed

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Narmuratova, Zh., Suleimenova, Zh., Blieva, R., Akhmetsadykov, N., & Zagritsenko, I. (2025). Utilisation of α-amylase and β-glucanase enzymes to improve the productivity of poultry farms. *Scientific Horizons*, 28(2), 23-32. doi: 10.48077/scihor2.2025.23.

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digestion. The purpose of this study was to evaluate the effect of α-amylase and β-glucanase enzymes in broiler diets on productivity. The study used broilers, which were divided into a control group and an experimental group. Weight gain, feed conversion rate, and nutrient digestibility were measured. Economic indicators were calculated based on feed costs and productivity of birds. The results showed that the addition of the α-amylase and β-glucanase enzymes significantly improved weight gain and FCR. Broilers receiving these enzymes showed improved body weight gain and lower FCR values compared to the control group. In addition, there was an increase in the height of the villi and the depth of the crypts in the tissue of the small intestine, which indicates better intestinal health and the ability to absorb nutrients. The digestibility of proteins and amino acids has also increased significantly. Improved nutrient uptake has led to a reduction in nutrient release into manure, minimising environmental impacts. Economic calculations have shown a reduction in feed costs due to the use of cheaper ingredients and an increase in overall productivity. There was also a decrease in the amount of abdominal fat in birds that were fed diets with enzymes. Prospects for further research are aimed at optimising enzyme dosage and investigating their effects on different poultry species and feed ingredients

Keywords: additives; nutrients; economic efficiency; feed conversion; energy value

INTRODUCTION

Enzymes play an important role in the feed industry and their use has grown dramatically over the past decade. Most dietary ingredients cannot be digested by animals without the help of enzymes, which reduces the efficiency of digestion and causes health problems. Therefore, enzymes of microbial origin such as amylases, xylanases, β-glucanases, proteases, phytases are added to improve digestibility and increase productivity, as stated by G.H. Podrepsek *et al*. (2023) and B.S. Velázquez-De Lucio *et al*. (2021). The use of α-amylase and β-glucanase enzymes in poultry farming has shown a significant increase in productivity due to improved nutrient absorption and feed efficiency. These enzymes promote the breakdown of complex carbohydrates and fibre, which are otherwise not digested by poultry, increasing the overall nutritional value of the feed. For example, the study by A. Aderibigbe *et al*. (2020) showed that the addition of α-amylase to the diet of broiler chickens improved growth rates, digestibility, and activity of digestive enzymes, especially in different growth phases. The study showed that the growth phase affects the response of birds to exogenous α-amylase, making it more effective at the initial stages of development.

The α-amylase is an enzyme that breaks down starch into simpler sugars. Starch, consisting of amylose and amylopectin, requires efficient digestion to ensure the energy status of birds (Ilchuk *et al.*, 2023). Amylose contains α-1,4 bonds, and amylopectin contains α-1,6 bonds, which affects digestion. The study by S. Castro *et al*. (2020) showed that despite the fact that dietary changes did not affect the parameters of the carcass, the enzyme was effective for increasing productivity with reduced metabolised energy in the diet. In addition, M. Alagawany *et al*. (2018), indicated that α-amylase dietary supplement improves body weight gain (BWG) and feed efficiency in broiler chickens, especially when fed with corn-soy meal-based diets. The enzyme increases the apparent digestibility of starch and energy in the ileum, which contributes to a better use of the energy value of the feed. In addition, the intake of α-amylase is associated with an increase in the height of the villi in the tissue of the small intestine, which indicates an improvement in intestinal health. This study also indicated that β-glucanase breaks down β-glucans, which are non-starch polysaccharides (NSP) found in grains such as barley and oats. NSP can increase the viscosity of intestinal contents, preventing the absorption of nutrients

The combined use of α-amylase and β-glucanase provides a synergistic effect, improving the digestibility of both starch and fibre. For example, S. Vieira *et al*. (2015) evaluated the effect of the introduction of the α-amylase-β-glucanase complex from *Bacillus amyloliquefaciens* on growth rates and feed assimilation in broilers receiving corn-soy diets. The results showed that the enzyme complex improved BWG and feed conversion, and reduced the amount of abdominal fat, although it did not affect the yield of carcasses and commercial cuts, demonstrating significant bioequivalence of apparent metabolisable energy (AME) at the level of 40-99 kcal/kg, depending on dosage. In general, the addition of various enzyme complexes to low-calorie diets can significantly improve growth rates and feeding efficiency in broilers. In the study by S. Gilani *et al*. (2021), the addition of a combination of xylanase and β-glucanase to a low-energy diet also led to improved growth and feeding efficiency, bringing the results closer to those of a full-fledged diet and surpassing those of a diet with reduced nutritional value without additives.

The economic benefits of using these enzymes include lower feed costs and increased efficiency, which can significantly reduce overall production costs in poultry farming (Melnyk *et al.*, 2024). Despite the proven effectiveness of α-amylase and β-glucanase enzymes in increasing poultry productivity, there remain unresolved problems associated with optimising their use. It is necessary to study in more detail the optimal dosages and conditions for the use of enzymes in various diets and conditions of maintenance to maximise their positive effect on growth, health, and feed conversion in birds. In addition, further research is needed on the economic and environmental aspects of the application, including the long-term effects on bird health and farm sustainability. The purpose of this study was to evaluate the effect of the addition of α-amylase and β-glucanase enzymes to compound feed on overall productivity. The research is aimed at identifying the optimal conditions for the use of these enzymes to increase the productivity and sustainability of poultry farms.

MATERIALS AND METHODS

Detailed methodological approaches have been developed and used to ensure the accuracy and reliability of the research results. The study was conducted at a poultry farm, where optimal conditions were created for keeping and feeding broilers, including temperature, humidity, and ventilation control. An important aspect of the study was the use of control and experimental groups, which helped to objectively assess the effect of enzyme supplements on various productivity indicators.

For the experiment at the "Astana Kus" poultry farm, 200 one-day-old broiler chickens of the Cobb 500 cross were selected, which were randomly divided into two groups: control and experimental, with 100 birds each. The birds were kept in standard conditions of the poultry house with controlled temperature, humidity, ventilation, and 24-hour access to food and water. The control group received a basic diet based on corn and soy meal without the addition of enzymes. The experimental group received the same diet supplemented with α-amylase and β-glucanase enzymes. Enzyme supplements were introduced into the diet in the amount of 500 units of α-amylase and 1000 units of β-glucanase per kg of feed. The diets were balanced in terms of nutrients in accordance with the recommendations of the National Research Council (Nick, 1994). The study also considered possible interactions between enzymes and other feed components, which provided an integrated approach to assessing their effects. To achieve reliable results and eliminate feeding errors, pre-calibrated dispensers and carefully tested feed mixing methods were used.

The experiment was conducted for 42 days, during which the birds were weighed weekly to determine BWG, and feed intake was recorded to calculate FCR. At the end of the experiment, 10 birds were selected from each group to analyse intestinal morphology. BWG was determined by weekly weighing of all birds, FCR was calculated based on total feed intake and BWG for the entire period of the experiment. To analyse the intestinal morphology, selected birds were euthanized, and samples were taken from their small intestine for histological analysis, while the height of the villi and the depth of the crypts were measured using a microscope and special image analysis software. The assessment of the digestibility of nutrients was carried out by analysing the chemical composition of feed and excrement. The digestibility indices were calculated using standard chemical analysis methods (analysis of protein, fat, fibre, and ash content).

The economic efficiency of using enzymes was estimated based on feed costs, production costs, and productivity indicators. The calculations considered such parameters as the cost of feed ingredients, the cost of enzyme additives, and total production costs. Additional economic parameters were also analysed, including the profitability of production and the economic benefits of improving feeding efficiency. All data has been subjected to a thorough statistical analysis. The differences between the control and experimental groups were evaluated using a t-test for independent samples, which helped to identify statistically significant differences between the groups. The values of $p < 0.05$ were considered statistically significant, which ensured high reliability of the results obtained.

RESULTS

The duration of the experiment was 42 days, with weekly weighing of birds, recording of feed intake, and analysis of intestinal morphology. As a result of the study, data were obtained on BWG, FCR, intestinal health indicators, and economic efficiency. The use of α-amylase and β-glucanase enzymes in poultry diets has been shown to positively affect several key productivity indicators, including weight gain, FCR, and overall productivity. The addition of these enzymes improves BWG in broilers, and birds fed with these enzymes showed weekly improvement in BWG, even when the ME of the diet was reduced. Enzymes help break down complex carbohydrates, improving nutrient absorption and energy use, which directly contributes to improved growth performance. BWG is a key indicator of productivity in poultry farming, as it reflects the rate at which broilers accumulate weight during the growth period. During the study, BWG was evaluated weekly for 42 days to determine the effect of the addition of α-amylase and β-glucanase enzymes on the growth rate of poultry (Table 1).

Table 1. *BWG for broilers*

Week	Control group (g)	Experimental group (g)
1	150	155
2	350	370
3	550	580

Table 1. Continued

Week	Control group (g)	Experimental group (g)
4	750	790
5	950	1,010
6	1,150	1,220

Source: *compiled by the authors*

In the first week of the experiment, the BWG of broilers in the experimental group was 155 g, which was slightly higher compared to the control group, where the increase was 150 g. A slight improvement in the initial stage indicates the positive effect of enzyme supplements on nutrient absorption and feed efficiency. At this early stage, the difference in BWG is associated with faster feed digestibility due to α-amylase and β-glucanase, which contributes to more efficient absorption of energy and nutrients. As the birds grew, the difference in BWG between the groups became more noticeable. At the sixth week, the BWG in the experimental group reached 1220 g, while in the control group it was 1,150 g. Such a significant difference indicates that enzyme supplements have a long-term positive effect on the growth rate of broilers. The increase in growth rates can be explained by improved nutrient uptake, which continued to accumulate as the birds got older.

During the entire period of the experiment, the average BWG in the experimental group was 120 g higher than in the control group. Systematic improvement confirms that α-amylase and β-glucanase enzymes contribute to more efficient digestion of feed and improve the overall condition of birds. A higher BWG in birds with fermented diets indicates a higher level of metabolic activity and better overall growth, which is associated with more optimal use of feed resources and improved nutritional status. The differences in BWG between the groups were statistically significant ($p < 0.05$), which indicates the effect of enzymes on improving growth indicators. Thus, it is confirmed that the α-amylase and β-glucanase enzymes contribute to more efficient broiler growth by improving feed digestion and nutrient absorption, which contributes to faster bird growth. Another significant factor is the addition of α-amylase and β-glucanase, which improves the FCR, reflecting the effectiveness of using poultry feed for weight gain. The coefficient is calculated as the ratio of the total amount of feed consumed by birds to the total BWG for a certain period. A lower FCR value indicates a more efficient use of feed. During the experiment, FCR was evaluated weekly for 42 days to control the effect of enzyme supplements on feeding efficiency (Table 2).

Table 2*. Feed conversion rate*

Week	Control group (g)	Experimental group (g)
1	1.8	1.75
2	1.75	1.7
3	1.72	1.67
4	1.64	1.59
5	1.61	1.56
6	1.57	1.52

Source: *compiled by the authors*

The FCR in the experimental group was expected to be lower compared to the control group throughout the experiment, which indicates a more effective use of feed in birds receiving α-amylase and β-glucanase enzymes. Starting from the first week, the FCR in birds receiving fermented diets was 1.75, which is slightly lower than 1.8 in the control group. This early decrease in FCR indicates an initial improvement in feed digestibility due to more efficient breakdown of complex carbohydrates and improved metabolic activity. Over time, the difference in FCR between the experimental and control groups continued to increase. At the end of the experiment, the FCR in the experimental group reached 1.4. A significant improvement demonstrates that α-amylase and β-glucanase enzymes contributed to more efficient digestion and assimilation of feed, which reduced the amount of feed needed to achieve BWG. In general, throughout the experiment, the average FCR in the experimental group turned out to be 0.05 units lower than in the control group. Based on the data obtained, it can be argued that the addition of enzymes to the diet contributes to more efficient digestion of feed and improved assimilation. Although the main focus of the presented study is on broilers, the principles of improving nutrient digestibility and energy use can also be applied to laying hens.

The next important factor is the morphology of the intestine. Intestinal morphology, including villi height and crypt depth, is an indicator of gut health and functionality in birds (Shuranova *et al.*, 2024). These parameters reflect the ability of the intestine to absorb nutrients and the general state of its structure. In this study, histological analysis of small intestine samples was performed to assess the effect of enzyme additives (α-amylase and β-glucanase) on intestinal morphology in broilers. The results showed that in the experimental group, the villi height averaged 280 microns, which is 30 microns higher than in the control group (250 microns). An increase in the height of the villi is associated with an increase in the surface area for absorption of nutrients, which can help improve their absorption and the general condition of the intestine. Crypt depth was also increased in the experimental group and averaged 100 microns, which is 20 microns less than in the control group (120 microns). The lower depth of the crypts indicates a more efficient cellular metabolism, an improvement in the ability of the intestine to absorb nutrients and maintain its general condition. Thus, the α-amylase and β-glucanase enzyme additives had a positive effect on the intestinal morphology of broilers, improving the height of villi and the depth of crypts, which, in turn, can contribute to more efficient digestion of feed and improve the productivity of birds.

The ratio of villi height to crypt depth in the experimental group was 2.8, which is significantly higher than the indicator of the control group, equal to 2.08. This improvement in the ratio indicates a more favourable intestinal condition and indicates a more efficient absorption of nutrients. In addition, the use of β-glucanase in the experimental group led to a decrease in the viscosity of the intestinal contents, which additionally contributed to improved nutrient absorption and overall intestinal function. Thus, enzyme supplements not only improved the morphological parameters of the intestine, but also contributed to optimising its functionality. The supplements contributed to an improvement in the overall health of birds, which manifested itself in the form of more stable and uniform growth, fewer diseases, and improved overall activity. Histological analysis of intestinal tissues performed at the end of the experiment confirmed an improvement in intestinal morphology, including an increase in the height of the villi and the depth of the crypts, which indicates a better condition of the intestinal surface and improved absorption of nutrients. Improving intestinal health helped the birds better absorb nutrients from the feed, which helped to increase their productivity and reduce energy losses.

Although the use of α-amylase and β-glucanase enzymes did not significantly affect the overall yield of carcasses or commercial cuts, there was a noticeable decrease in the amount of abdominal fat in birds receiving diets with the highest levels of enzyme supplements. In this case, fat reduction indicates more efficient feed processing and improved metabolism of birds, which allows better use of nutrients and energy from feed ingredients. Enzymes contribute to an increase in the content of AME in the diet, which allows birds to use the energy contained in the feed more efficiently. This improvement in energy absorption is directly related to an improvement in growth and FCR. The increase in available energy helps birds to gain body weight more efficiently, which is reflected in improved growth rates and reduced feed requirements to achieve the same BWG.

Positive changes in productivity and bird health are also important for economic efficiency. Improving the FCR and increasing the overall growth of poultry leads to lower feed costs and optimisation of production processes (Szeląg-Sikora *et al.*, 2024). The economic efficiency of using α-amylase and β-glucanase enzymes in broiler diets was evaluated based on an analysis of feed costs, production costs and productivity indicators. The study considered the cost of feed ingredients, the cost of enzyme additives, and total production costs. The assessment was carried out to determine how the introduction of enzymes affects cost reduction and increased profitability of poultry farming (Table 3).

***Table 3**. Economic efficiency*

Parameter	Control group	Experimental group
Total feed costs (USD/1000 birds)	1,500	1,450
Cost of enzyme supplements (USD)	0	500
Total production costs (USD/1000 birds)	1,550	1,950
BWG (kg/1000 birds)	2,000	2,100
FCR	1.5	1.4
Saving on feed (USD/1000 birds)	-	50
Net profit (USD/1000 birds)	1,000	1,150

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

The α-amylase and β-glucanase, the total feed costs in the experimental group were lower, despite the additional costs of enzyme supplements. In particular, the reduction in total feed costs amounted to USD 50 per 1,000 birds compared to the control group. The decrease was due to more efficient use of feed, which reduced the cost of feed ingredients. Cost minimisation is associated with more efficient use of feed due to enzyme additives, which has reduced the cost of feed ingredients. Since the beginning of the experiment, there has been a decrease in feed consumption in the experimental group compared to the control group. In the first week, the feed intake in the experimental group was 110 g per head, which was slightly lower compared to 115 g per head in the control group. This trend continued in the later stages of the study. In the sixth week, the feed intake in the experimental group was 1,850 g per animal, which was 100 g less than in the control group, where the feed intake reached 1,950 g per head. A decrease in feed intake indicates that enzyme supplements have contributed to more efficient feed use, allowing birds to achieve the same growth rates with less feed consumed.

The cost of enzyme supplements was USD 500 per 1000 birds, which increased production costs. However, this increase was offset by lower feed costs and improved FCR. Thus, although the total production costs in the experimental group amounted to USD 1,950 per 1,000 birds compared to USD 1,550 in the control group, the improvement in productivity indicators led to a significant increase in net profit. The net profit in the experimental group reached USD 1,150 per 1,000 birds, which is USD 150 more than in the control group (USD 1,000). This profit increase was made possible by improved FCR and increased BWG, which increased overall production efficiency. The savings on feed in the experimental group amounted to USD 50 per 1,000 birds, which indicates that more efficient use of feed with the addition of enzymes reduced the cost of feed ingredients. Thus, the introduction of α-amylase and β-glucanase enzymes into broiler diets not only increased productivity and improved FCR, but also led to significant savings on feed. The additional costs of enzyme supplements are recouped by increasing net profit and overall economic efficiency. This confirms that the use of enzymes is a profitable solution from both an economic and a productive standpoint.

DISCUSSION

The results obtained during the study and published data on the use of α-amylase and β-glucanase enzymes in poultry diets show similar results and trends. According to M. Marchiori *et al*. (2022), the addition of a multi-enzyme including carbohydrases and proteases to low-calorie diets improved BWG, FCR, and reduced the percentage of abdominal fat. The studies by T. Diana *et al*. (2020), E. Macêdo *et al*. (2022) show the use of a combination of xylanase and β-glucanase in low-energy diets increased BWG and improved feeding efficiency, bringing the results closer to those on a full-fledged diet. In addition, feed enzymes such as phytase, protease, and xylanase are used to improve nutrient absorption and increase growth performance in pigs and broilers. Recent research by S. Sureshkumar *et al*. (2023) show that these enzymes help to break down phytic acid, proteins and β-1,4-xylan, which can positively affect intestinal health and animal microbiota. This study confirmed these findings by showing that adding a mixture of exogenous enzymes to a low-nutrient diet improves the digestibility of feed, and improvement of zootechnical indicators emphasising their practical value in the production of broilers.

An important aspect that should also be considered is the effect of enzymes on intestinal morphology. In the course of the study, a histological analysis of samples from the small intestine was performed, which showed that enzyme additives such as α-amylase and β-glucanase significantly increase the height of the villi and reduce the depth of the crypts. As a result, the height of the villi in the experimental group was 280 microns, which is 30 microns more than in the control group, and the depth of the crypts was reduced to 100 microns compared with 120 microns in the control group. The changes indicate a more efficient absorption of nutrients and an overall improvement in the condition of the intestine. Similar results are confirmed by the data of J. Madigan-Stretton *et al*. (2021), where the use of superdosed multienzymes led to an improvement in the height of villi and the maintenance of microbial diversity, which also contributed to the optimisation of digestion and digestibility of nutrients.

However, the results of these studies contrast with the data of H. Zhou *et al*. (2021) on the effect of exogenous α-(1,4)-amylase on starch utilisation. While this study observed an improvement in the height of the villi and the depth of the crypts, which indicates a more efficient absorption of nutrients and improved intestinal condition, the results of α-(1,4)-amylase show that its excessive introduction can reduce starch digestibility coefficients and worsen growth indicators. One of the reasons for these differences may be the dosage of enzymes: in this study, balanced levels of α-amylase and β-glucanase were used, which contributed to improved digestibility and intestinal morphology. While in the study with α-(1,4)-amylase, a high dose of the enzyme (more than 600 U/kg) led to negative effects, possibly due to inhibition of the glucose transporter and impaired starch metabolism. In addition, there is a difference in the types of enzymes used and their interaction with feed components. In the case of α-amylase and β-glucanase, the combination provided a synergistic effect, improving both nutrient absorption and intestinal health, whereas α-(1,4)-amylase in high doses could disrupt the normal digestion and assimilation of starch with an overabundance of the enzyme. The difference in effects may be due to both the dosage and the combination of enzymes, and specific research conditions such as feed composition and metabolic parameters in broilers.

Turning to the specifics of the effects of β-glucanase, it should be noted that this enzyme plays a key role in the breakdown of β-glucans, which are NSP contained in cereals (Montayeva *et al*., 2023). These polysaccharides, although they have beneficial properties such as supporting the immune system, can also cause digestive problems in birds, especially by increasing the viscosity of intestinal contents and impaired absorption of nutrients, as repeatedly mentioned in the studies by L.K. Edison *et al*. (2022) and M. Vinche *et al*. (2021). The current study has confirmed the effectiveness of β-glucanase in eliminating these problems. The addition of exogenous β-glucanase to animal feed significantly reduced the viscosity of the digestive tract, which helped to improve the digestibility of nutrients and maintain the optimal state of the intestinal microbiota. This is especially important for feeds containing high levels of β-glucan, such as barley and oats, where the enzyme provides significant improvements in digestion and digestion.

Overall, the results are consistent with studies that emphasise the importance of enzyme supplements for improving intestinal functionality and overall productivity of birds. The combination of α-amylase and β-glucanase enzymes also demonstrated improved FCR scores, which is associated with better nutrient absorption, reduced anti-nutritional factors, and overall improved intestinal health. The results are also consistent with the research by A. Karamad *et al*. (2024), who emphasise that the addition of enzymes leads to improved growth and productivity in poultry farms due to the synergistic effect and flexibility in feed formulation. The economic benefits are also correlated: enzymes allow the use of cheaper feed ingredients and reduce feed costs (Montayev *et al*., 2023). The study showed that the addition of α-amylase and β-glucanase to broiler diets reduced feed costs by USD 50 per 1,000 birds, improving feed efficiency and increasing productivity. Similarly, the use of sunflower meal with multiferments as in the study by M.J. Mbukwane *et al*. (2022) also demonstrated cost reduction through improved digestibility and increased economic efficiency. In both cases, enzyme supplements provide significant savings and payback by improving FCR and productivity, reducing dependence on more expensive feed ingredients. Another example is the study by A.O. Sorunke *et al*. (2021), in which it was shown that the addition of enzyme cocktails to the diet of pigs with a high fibre content improves daily weight gain and reduces the cost of feed per kilogramme of gain. In particular, the use of a cocktail of enzymes at a dose of 0.25 g/kg provided the lowest cost of feed per kg of gain. Increased feeding efficiency and improved growth rates lead to overall cost savings in poultry production.

The results show that exogenous enzymes complement the natural production of enzymes by poultry, which is especially useful for young birds or under stressful conditions. The study confirms and complements existing data, demonstrating the significant effect of α-amylase and β-glucanase enzymes on improving productivity, intestinal health, and economic and environmental benefits for poultry farms.

CONCLUSIONS

The results of the study showed that the addition of α-amylase and β-glucanase enzymes to the broiler diet significantly improves productivity and economic efficiency. In particular, the BWG in the experimental group was 8.3% higher compared to the control group, indicating a higher growth rate in birds treated with enzymes. FCR was 2.9% lower in the group with enzyme supplements, which indicates more efficient use of feed and improved digestibility. Enzymes also contribute to reducing the amount of abdominal fat, which indicates a more efficient metabolism and a better distribution of energy. This leads to an improvement in the overall health of birds and an increase in their productivity.

The economic analysis showed that despite the additional costs of enzyme supplements, the total feed costs were USD 50 lower in the experimental group, which allowed compensating for the cost of additives and increase net profit by 15%. The improvement of FCR and the increase in BWG contributed to a significant reduction in costs and increased profitability of production. The α-amylase and β-glucanase enzymes had a significant positive effect on broiler productivity. α-amylase helps to improve the digestibility of starch, increasing the efficiency of energy use from feed and the growth rate of birds. β-glucanase, in turn, helps to break down β-glucans, which reduces the viscosity of intestinal contents and improves the absorption of nutrients. In general, the addition of these enzymes to the broiler diet helps to improve their overall health and improve feeding efficiency. In the long term, the results of the study open up opportunities for further optimisation of dosages and combinations of enzymes to achieve even more pronounced results. Future research may focus on assessing the long-term economic effects, the effect of enzyme supplements on the intestinal microflora, and the immune status of birds, which may contribute to a more comprehensive improvement of feed technologies and increase productivity in poultry farming.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Використання ферментів альфа-амілази та бетта-глюканази для підвищення продуктивності птахівничих господарств

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Анотація. У сучасному птахівництві підвищення ефективності використання кормів є ключовим фактором збільшення продуктивності та зниження собівартості продукції. Одним із перспективних методів покращення показників продуктивності є використання ферментних добавок, таких як α-амілаза та β-глюканаза, які покращують засвоєння поживних речовин за рахунок покращення перетравлення корму. Метою даного дослідження було оцінити вплив ферментів α-амілази та β-глюканази в раціонах бройлерів на продуктивність. У дослідженні використовували бройлерів, які були розділені на контрольну та дослідну групи. Вимірювали приріст ваги, коефіцієнт конверсії корму та перетравність поживних речовин. Економічні показники розраховували на основі витрат на корм та продуктивності птиці. Результати показали, що додавання ферментів α-амілази та β-глюканази значно покращило приріст ваги та конверсію корму. Бройлери, які отримували ці ферменти, показали кращий приріст живої маси та нижчі значення FCR порівняно з контрольною групою. Крім того, спостерігалося збільшення висоти ворсинок і глибини крипт в тканині тонкого кишечника, що свідчить про краще здоров'я кишечника і здатність засвоювати поживні речовини. Засвоюваність білків та амінокислот також значно зросла. Покращене засвоєння поживних речовин призвело до зменшення викидів поживних речовин у гній, мінімізуючи вплив на навколишнє середовище. Економічні розрахунки показали зниження витрат на корми завдяки використанню дешевших інгредієнтів і підвищення загальної продуктивності. Також спостерігалося зменшення кількості абдомінального жиру у птахів, яким згодовували раціони з ензимами. Перспективи подальших досліджень спрямовані на оптимізацію дозування ферментів та вивчення їх впливу на різні види птиці та інгредієнти корму

Ключові слова: добавки; поживні речовини; економічна ефективність; конверсія корму; енергетична цінність

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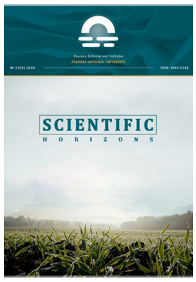

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Protection of seed potatoes against virus infections in the field conditions of Polissia of Ukraine

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Abstract. Viral diseases pose a significant problem for potato seed production, therefore, to ensure high-quality characteristics of seed material, it is necessary to research the development of new methods of their control. The study aimed to determine the effectiveness of the integrated application of elements of the system of protection of basic seed potato plantations from viral diseases using mineral oils, top removal and biological preparations based on nanoparticles in the South of Polissia of Ukraine. The

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study demonstrated that the treatment of potato tubers and spraying of plants during the growing season with a nanopreparation of biological origin increased the yield of seed potatoes of Myroslava variety compared to the control without treatment by 2.7 t/ha or 6.94 %, and Fotyniia variety – by 2.6 t/ha or 6.9 %. The use of potato tops desiccation, treatments and mineral oil provided an increase in the yield of Myroslava by 3.3 t/ha or 9.5%. The use of potato tops desiccation and potato treatments during three growing seasons, according to the results of the visual method of plantation assessment, contributed to a 2.9% reduction in the damage of Myroslava potato variety plants by virus diseases, and 2.6% in Fotyniia variety, while the damage of plants in the control varieties was 4.5% and 4.7%, respectively. The results of the enzyme-linked immunosorbent assay of potatoes in the post-harvest period showed that treatment of vegetative potato plants with the nanopreparation reduced the infection of seed potatoes with *Potato virus Y* (PVY) by 0.5 %, while the infection of plants with PVY virus infection in the control without treatment was 1.0 %. Based on the results of the research, elements of the system of integrated application of a multicomponent nanopreparation of biological origin, spraying of plantations with insecticides and mineral oil and desiccation of potato tops to combat viral diseases of pre-basic, basic and certified seed potatoes were proposed

Keywords: yield; viral diseases; *Potato virus Y* infection; nanoparticle-based preparations; mineral oil

INTRODUCTION

An important problem in potato growing is the high susceptibility of potatoes to viral diseases. Potatoes can be affected by more than 50 viruses. For instance, when potato plants are infected with the PVY virus, the yield reduction can reach up to 80% (Kreuze *et al.,* 2020; Jones, 2021). Studies evaluating the yield of potatoes derived from PVY-infected seed determined that 1% PVY infection in seed resulted in a 0.18 t/ha reduction in yield, marketability, and tuber size (Torrance & Talianksy, 2020). The spread of the PVY virus in the United States has been increasing since 2000 (Mondal *et al.,* 2023). In Ukraine, a significant increase in the spread of potato diseases caused by PVY alone and with pathocomplexes of other viruses has been detected. Measures to limit the spread of PVY in potato plantations include quality control of seed potato lots, selection of resistant varieties, early phytosorting to reduce the amount of harmful inoculum in the field and the destruction of vector vectors (Demchuk *et al.*, 2024).

The results of many studies demonstrate the effectiveness of the use of mineral oils together with other methods of protecting seed potatoes from re-infection with PVY virus infection in the field. G.V. Baliota and C.G. Athanassiou (2023) presented an in-depth analysis of the insecticidal properties of mineral oils. The most effective method was to combine the use of mineral oils with insecticides. Mineral oils are harmless to the environment and do not cause resistance in target insect pests. T.D.B. MacKenzie *et al.* (2022) proved that the use of mineral oils increases the retention of a pyrethroid insecticide in potato leaves for a longer period compared to insecticides that were applied without the addition of mineral oils, which confirms the positive synergistic effect of combined spraying of plantations to reduce the spread of PVY.

Field trials conducted by J.L. Rolot *et al.* (2021) in the Ardennes region of Belgium using insecticide treatments with mineral oil, insecticides and mixtures of insecticides showed that the use of mineral oil is an effective way to protect seed potato crops from the spread of PVY. However, this protection may not be sufficient. The study determined that the use of insecticides was ineffective, especially pyrethroid drugs. Systemic insecticides provided additional protection if applied in a mixture with mineral oil during the period of high activity of winged aphids. Early destruction of the aboveground vegetative mass of plants reduced the presence of PVY infection in the seed tubers. Mulching plantations treated with mineral oil with straw increase the level of protection of potato crops. It can also reduce the number of sprayings required.

A. Bondarchuk *et al.* (2020) also proved that an effective agronomic measure to maintain high-quality characteristics of seed potatoes is the removal of potato tops, which significantly reduces the number of tubers infected with viruses in the current year due to the fact that virus particles do not have time to penetrate the tubers of the new crop. The probability of virus infection of plants is significantly reduced with a decrease in the number of insect vectors and their activity with the use of insecticides and mineral oils. O. Vushnevska *et al.* (2021) revealed the best way to preserve the quality of potato seed material, which reduced the content of viral infection in seed potatoes, which was achieved by using desiccation of potato tops on the 20th day after flowering of potato varieties Myroslava, Predslava and Alliance and the use of Sunspray mineral oil. Biological products with antiviral effects can be an alternative environmental element of the system for combating viral diseases. S.M. Talebi and M. Ghorbanpour (2023) demonstrated that nanopreparations are used as fertilisers and can eliminate the effects of environmental stress on plants. B. Rashwan *et al.* (2023) proved that the treatment of plants with NP Zn resulted in a significant improvement in their growth parameters, yield and nutritional qualities of tubers.

The issues of antiviral properties of a biological multicomponent micronutrient preparation with nanoparticles and NP Ni for the protection of seed potatoes from potato diseases remain poorly understood. The use of mineral oil and insecticide treatments for basic seed potatoes in the southern Polissia zone of Ukraine is also insufficiently studied. Therefore, the study aimed to develop elements of control of potato virus infections using nanopreparations, insecticide treatments in combination with mineral oil and potato tops desiccation.

MATERIALS AND METHODS

The research was conducted in the fields of scientific crop rotation at the Institute of Potato Growing of the National Academy of Agrarian Sciences of Ukraine. In 2021-2023, certified seed potatoes of super-superelite, superelite and elite classes, improved by biotechnology, were planted. The field experiment was conducted following the provisions of A.A. Bondarchuk *et al.* (2019). The scheme of the experiment is shown in Table 1.

Table 1*. Experiment design*

Variant number	Experiment variants
1	Control 1. Treatment of tubers with Celest® Top, 0.7 l/ha.
2	Seed treatment with Avatar-2 Protection, 300 ml/ha; plant treatment* with Avatar-2 Protection, 200 ml/ha
3	Treatment of seed material with Celest® Top, 0.7 l/ha and NP Ni, 20 ml/l of water; treatment of plants* with NP Ni, 20 ml/l of water
4	Control 2. Treatment of seed material with Celest® Top, 0.7 l/ha; destruction of tops with Reglon® Super 150 SL, 2.0 l/ha
5	Treatment of seed material with Avatar-2 Protection, 300 ml/ha; treatment of plants* with Avatar-2 Protection, 200 ml/ha; destruction of tops with Reglon® Super 150 SL, 2.0 l/ha.
6	Treatment of seed material with Celest® Top, 0.7 l/ha, NP Ni; 20 ml/l of water; treatment of plants* with NP Ni, 20 ml/l of water; destruction of tops with Reglon® Super 150 SL, 2.0 l/ha.
7	Control 3. Seed treatment with Celest® Top, 0.7 l/ha; plant treatment* with OLEMIX® 84 k.e. mineral oil, 1.0 l/ha; tops destruction with Reglon® Super 150 SL, 2.0 l/ha.
8	Treatment of seed material with Avatar-2 Protection, 300 ml/ha; treatment of plants* with Avatar-2 Protection, 200 ml/ha; treatment of plants* with OLEMIX® 84 h.e. mineral oil, 1.0 l/ha; destruction of tops with Reglon® Super 150 SL, 2.0 l/ha.
9	Treatment of seed material with Celest® Top, 0.7 l/ha, Ni nanoparticles, 20 ml/l of water; treatment of plants*, 20 ml/l of water; mineral oil OLEMIX® 84 k.e., 1.0 l/ha; destruction of tops with Reglon® Super 150 SL, 2.0 l/ha.

Note: *treatment of plants during the growing season with Avatar-2 Protection, Olemix® 84 k.e. mineral oil, and NP Ni was done during the plant development phase: seedlings (BBCH 1-10) and budding (BBCH 51-59)*
Source: *compiled by the author*

All experimental variants except 1 (control) used drugs as the base model: Engio® 247 SC hp, 0.18 l/ha; Fastak® 100 EC, 0.07-0.10 l/ha; Karate® Zeon 050 EC, 0.1-0.2 l/ha; Metaxyl® ZP, 2.5 kg/h; Shirlan® 500 SC, 0.3 l/ha; Nativo® 75 WG, 0.35 kg/ha. Spraying of potato seed material and spraying of plants was carried out with a manual sprayer, with a water rate of 10 l/t for seed treatment and 170 l/ha for plant treatment. For phenological studies, biometric measurements, and determining the timing of various types of technological operations, including desiccation of potato tops, the international scale of plant growth and development BBSN was used, which defines the following phases: seedlings (BBCH 1-10), budding (BBCH 51-59), flowering (BBCH 60-69), "green berryЭ (BBCH 70-79), technical maturity (BBCH 91-99).

The experiment was replicated four times. The total area of the variant is 22.5 m^2, and the accounting area is 11.25 m^2. The experiment was conducted by the overlapping method during 2021-2023, i.e. the seed material was not changed every subsequent growing season. The method of planting potatoes is 75×20 cm with a plant density of 66.7 thousand units/ha. The cultivation technology is generally accepted for seed potato plantations in the Polissia zone of Ukraine. In the spring, the field was ploughed and cultivated, and ridges were formed at the beginning of potato germination with a milling cultivator. Mineral fertilisers were applied in the form of nitroammophoska at a rate of 500 kg/h in physical weight or active ingredient: $N_{80}P_{80}K_{80}$ in kg/h with the addition of potash fertiliser at a dose of K_{30} kg of active ingredient per 1 ha. Fertilisers were applied locally in the rows during potato planting, and ammonium nitrate – N_{20} kg/h of active ingredient was applied in the phase of growth and development of potato plants – plant sprouts.

The experiment used NP Ni and the Avatar-2 protection preparation. The composition of Avatar-2 protection includes the following chemical elements: S, Cu, I, Al, Ni, Bi and V, Mg, Zn, Fe, Mn, Co, Mo, La, Ti, Se, Ge, Si, B and Ce, produced by nanotechnology and in organic compounds with citric acid. Avatar-2 Protection is registered in Ukraine and certified by Organic Standard LLC. The preparation based on NP Ni contains NP as a dispersed phase and 1.5-2.5% citric acid solution as a dispersion medium. The dose of the preparation based on NP Ni is specified by the manufacturer (Avatar Research and Production Company LLC).

Visual assessment of the symptoms of viral diseases on potato plants was carried out following the Guidelines for field assessment of seed potato plantations (Furdyha *et al*., 2023). Desiccation of the aboveground mass of plants was carried out during the period of maximum formation of seed tubers no more than 28-60 mm in size by the largest transverse diameter of 70-80% of the structure of the entire crop. Potato tops were removed by spraying the plants with Reglon® Super 150 SL with 2 treatments – the first treatment of tops at a dose of 0.8 l/ha, the second – at 1.2 l/ha. Spraying of the plantations with mineral oil OLEMIX® 84 k.e. was performed along with the application of insecticides and fungicides at a dose of 1.0 l/ha per 300 l/ha of water. The yield was determined from each variant and each replication. Before harvesting, the number of healthy and diseased plants was determined, and the places of possible exceptions to sowing were identified.

Statistical processing of the experimental data was done based on a one-factor analysis of the variance of the results of the field experiment (Bondarchuk *et al.,* 2019). The yield increase was calculated relative to the controls following the experimental design (Table 1). The content of virus infection in potato plants was determined by indexing tubers in the post-harvest period according to the method of M.M. Furdyha *et al*. The detection of PVY virus infection in potato tubers was carried out by a solid-phase enzyme-linked immunosorbent assay (ELISA) (double sandwich version, DAS-ELISA) using commercial test systems from LOEWE, Germany. The results of the enzyme-linked immunosorbent assay were read on a Termo Labsystems Opsis MR photometer (USA) with the Dunex Revelation Quicklink software at 405 nm. Statistical processing of the results of optical density in the wells of the polystyrene plate with samples was carried out by descriptive statistics, with the establishment of mean and standard deviations of the data. For each plate, the threshold value of optical density was set separately to determine the positive results of the enzymatic reaction different from the background value according to the recommendations (Technical Information. ELISA Data Analysis). The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

Determination of the effect of the preparation with nanoparticles on the yield of basic seed potatoes showed that on average for 2021-2023 treatment of planting material and plantations according to the scheme: seed treatment with 300 ml/ha + plant treatment with 200 ml/ha during vegetation (variant 2), the yield of seed potatoes of Myroslava variety increased by 2.7 t/ha or 6.94% (at NIR_{05} value of 1.24-1.4 t/ha), and by 2.6 t/ha or 6.9% for Fotyniia variety (at NIR_{05} value of 1.13-1.45 t/ha) (Table 2). Spraying of planting material and vegetative plants with NP Ni did not contribute to the growth of seed potato yields of Myroslava and Fotyniia varieties. The treatment of basic seed potatoes with the product and the use of potato tops desiccation on average for three growing seasons, 2021-2023, increased the yield of Myroslava variety by 2.5 t/ha or 6.5%.

A. Vasylchenko and S. Derevianko (2022) also indicated that the "preparation with nanoparticles" has antioxidant and protective activity and contributes to the growth of crop productivity. The use of the NP Se+I composition had a positive effect on the marketability of tubers and potato yield. W.A. Al-Selwey *et al.* (2023) determined that the use of ZnO and SiO_2 nanoparticles improved the biochemical properties of potato tubers, contributed to increased plant resistance to diseases, improved growth and development, and increased productivity and quality of potatoes under moisture deficit conditions. The use of mineral oil against the background of treatments with preparation with nanoparticles and desiccation of potato tops contributed to an increase in yield by 3.3 (9.5%) t/ha in the Myroslava potato variety (with a NIR_{05} value of 1.94-2.01 t/ha). In the Fotyniia variety, this variant did not show an increase in yield. The use of mineral oil against the background of treatments of planting material and plants during the growing season with NP Ni provided an increase in the yield of potato variety Myroslava in 2023 by 2.0 t/ha, while this effect was not detected in the potato variety Fotyniia.

Table 2*. Effect of the use of plant protection system elements against virus infections of basic seed potatoes on yield, 2021-2023*

Variant number	Experiment variants	2021			2022			2023			2021-2023		
		Yield, t/ha	Increase		Yield, t/ha	Increase		Yield, t/ha	Increase		Yield, t/ha	Increase	
			t/ha	%		t/ha	%		t/ha	%		t/ha	%
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Myroslava variety													
1.	Control 1. Processing with Celeste® Top	41.1	-	-	41.7	-	-	34.1	-	-	38.9	-	-
2.	Processing with Avatar-2 Protection	43.4	2.3	5.6	44.7	3.0	7.2	36.6	2.5	7.3	41.6	2.7	6.94
3.	Ni+ processing with Celeste® Top	41.3	-	-	41.9	-	-	35.0	-	-	39.4	-	-
	HIP_{05}	**-**	**1.24**		**-**	**1.40**		**-**	**1.29**		**-**	**-**	

Table 2. Continued

Variant number	Experiment variants	2021			2022			2023			2021-2023		
		Yield, t/ha	Increase		Yield, t/ha	Increase		Yield, t/ha	Increase		Yield, t/ha	Increase	
			t/ha	%		t/ha	%		t/ha	%		t/ha	%
1	2	3	4	5	6	7	8	9	10	11	12	13	14
	S_x%	-	0.9		-	0.9		-	1.1		-	-	
4.	Control 2. Processing with Celeste® Top alongside desiccation	36.8	-	-	40.4	-	-	30.0	-	-	35.7	-	-
5.	Processing with Avatar-2 Protection alongside desiccation	40.2	3.4	9.2	42.3	-	-	32.0	2.0	6.7	38.2	2.5	6.5
6.	Ni treatment + Celeste Top® alongside desiccation	36.0	-	-	40.1	-	-	28.0	-	-	34.7	-	-
	HIP_{05}	**-**	**1.30**		**-**	**2.55**		**-**	**1.95**		**-**	**-**	
	S_x%	-	1.0		-	1.8		-			-	-	
7.	Control 3. Treatment with Celeste® Top alongside desiccation	36.8	-	-	37.9	-	-	29.1	-	-	34.6	-	-
8.	Processing with Avatar-2 Protection alongside mineral oil and desiccation	40.1	3.3	8.9	40.5	2.6	6.9	33.0	3.9	13.4	37.9	3.3	9.5
9	Ni treatment + Celeste Top® alongside mineral oil and desiccation	36.7	-	-	42.1	4.2	11.1	31.0	1.9	6.5	36.6	2.0	5.8
	HIP_{05}	**-**	**2.01**		**-**	**1.94**		**-**	**1.95**		**-**	**-**	
	S_x%	-	1.5		-	1.4		-	1.9		-	-	
	Variety Photinia												
1.	Control 1. Processing with Celeste® Top	33.3	-	-	40.6	-	-	38.7	-	-	37.5	-	-
2.	Processing with Avatar-2 Protection	36.8	3.5	10.5	43.3	2.7	6.7	40.1	-	-	40.1	2.6	6.9
3.	Ni+ processing with Celeste® Top	33.8	-	-	39.6	-	-	39.5	-	-	37.6	1.4	3.7
	HIP_{05}	**-**	1.13		**-**	1.45		**-**	1.20		**-**	**-**	
	S_x%	-	0.9		-	1.0		-	1.0		-	-	
4.	Control 2. Processing with Celeste® Top alongside desiccation	28.6	-	-	38.3	-	-	28.3	-	-	31.7	-	-
5.	Processing with Avatar-2 Protection alongside desiccation	31.4	2.8	9.8	41.4	2.6	6.8-	27.2	-	-	33.3	1.6	5.0
6.	Ni treatment + Celeste Top® alongside desiccation	28.7	-	-	39.3	-	-	30.2	2.1	7.4	32.7	1.0	3.2
	HIP_{05}	**-**	2.30		**-**	2.07		**-**	1.39		**-**	**-**	
	S_x%	-	2.3		-	1.5		-	1.7		-	-	
7.	Control 3. Treatment with Celeste® Top alongside desiccation	28.6	-	-	42.6	-	-	29.7	-	-	33.6	-	-
8.	Processing with Avatar-2 Protection alongside mineral oil and desiccation	30.6	2.0	7.0	42.1	-	-	29.1	-	-	33.9	0.3	0.9
9	Ni treatment + Celeste Top® alongside mineral oil and desiccation	28.7	-	-	41.7	-	-	28.2	-	-	32.9	-	-
	HIP_{05}	**-**	**2.42**		**-**	**1.13**		**-**	**1.42**		**-**	**-**	
	S_x%	-	2.4		-	0.8		-	1.7		-	-	

Source: compiled by the author

In studies on the action of NP Se+I and preparation with nanoparticles, S. Derevianko and A. Vasylchenko (2020) determined the most effective composition for the control of infectious diseases in potatoes. The study by S. Liu *et al.* (2024) on the antiviral properties of NP of copper oxide (CuONPs) using orange peel extract showed effective control of *tobacco mosaic virus* (TMV) infection both *in vitro* and *in vivo*. L. Cai *et al.* (2020) highlighted antiviral activity against the Tobacco mosaic virus of NP Fe_3O_4. Studies conducted in 2021-2023 determined that the use of the drug and NP Ni for the treatment of planting tubers and plantations reduced the manifestation of symptoms of viral diseases on vegetative potato plants (Table 3).

***Table 3**. Influence of plant protection system elements on the defeat of basic seed potatoes by viral diseases (by symptoms), 2021-2023, %*

Variant number	Experiment variants	Mottling	Mosaic leaf curl	Wrinkled and striped mosaics	Total
1	2	3	4	5	6
	Myroslava variety				
1.	Control of processing with Celeste® Top	3.18	1.17	0.17	4.51
2.	Processing with Avatar-2 Protection	1.26	0.41	0	1.68
3.	Ni+ processing with Celeste® Top	2.12	0.99	0	3.11
4.	Control of processing with Celeste® Top alongside desiccation	2.09	0.53	0	2.62
5.	Treatment with Avatar-2 protection alongside tops removal	1.14	0.26	0	1.4
6.	Ni treatment with Celeste® Top alongside tops removal	1.57	0.42	0	1.99
7.	Control of treatment with Celeste® Top alongside tops removal	0.59	0.33	0	0.93
8.	Treatment with Avatar-2 protection alongside Celeste® Top and mineral oil with tops removal	0.75	0.25	0	1
9.	Ni treatment with Celeste® Top alongside mineral oil and tops removal	0.97	0.3	0	1.27
	HIP_{05}	**0.90**	**0.36**	**0.05**	**1.31**
	S_x%	0.30	0.12	0.02	0.43
	Fotyniia variety				
1.	Control of processing with Celeste® Top	3.18	1.37	0.17	4.71
2.	Processing with Avatar-2 Protection	1.61	0.5	0	2.11
3.	Ni+ processing with Celeste® Top	2.34	0.73	0	3.08
4.	Control of processing with Celeste® Top alongside desiccation	1.67	0.7	0	2.37
5.	Treatment with Avatar-2 protection alongside tops removal	1.14	0.4	0	1.54
6.	Ni treatment with Celeste® Top alongside tops removal	1.41	0.57	0	1.98
7.	Control of treatment with Celeste® Top alongside tops removal	0.56	0.23	0	0.79
8.	Treatment with Avatar-2 protection alongside Celeste® Top and mineral oil with tops removal	0.65	0.27	0	0.92
9.	Ni treatment with Celeste® Top alongside mineral oil and tops removal	0.69	0.23	0	0.92
	HIP_{05}	**0.90**	**0.38**	**0.05**	**1.33**
	S_x%	0.30	0.13	0.02	0.45

***Source:** compiled by the author*

Seed potatoes of the Myroslava variety under treatment of tubers before planting and double spraying of plants with preparation with nanoparticles (variant 2) had a 2.9% reduction in plant damage by viral diseases compared to the control without treatment by visual assessment. In the variety Fotyniia, the reduction of viral diseases was 2.6%, while the damage in the control was 4.7%. Reduction of plant damage by mosaic curl of potato leaves (causative agent – *Potato virus M* (PVM)) in Myroslava variety was 0.7%, in Fotyniia variety – 0.8%, by leaf spot disease (causative agent – *Potato virus S* (PVS)) – by 2.2% and 1.6%, respectively, by varieties. Symptoms of potato plant damage by wrinkled and striped mosaic (causative agent – *Potato virus Y*) were observed in the control variant without treatments – 0.3% of plants in the Myroslava variety and 0.2% of plants in the Fotyniia variety. The use of a product based on Ni NF reduced the manifestation of symptoms of viral diseases by 1.5% in the Myroslava potato variety and by 1.7% in the Fotyniia potato variety; when using potato tops desiccation – by 0.7% and 0.5%, respectively. Desiccation of tops (variant 4) contributed to a 1.7% reduction in potato virus infection in the Myroslava variety and 1.5% in the Fotyniia variety.

The combination of tops desiccation with nanoparticle treatment (variant 5) reduced the damage of the Myroslava variety by virus diseases by 3.1%, the Fotyniia variety – by 3.2%, including mosaic curl by 2.0% and 0.9% respectively, with the disease affecting 1.1% and 1.3% of plants in the control, respectively, by varieties. The use of mineral oil (variant 7) contributed to a decrease in plant damage by viral diseases compared to the control with desiccation of the aboveground mass of plants in the Myroslava variety by 1.8%, and in the Fotyniia variety – by 1.9%. The complex effect of the preparation, tops desiccation, and oil treatment of plants (variant 8) provided a 3.5% reduction in seed potato virus disease damage in Myroslava and 4.0% in Fotyniia. N.I. Helmy *et al.* (2023) determined that NPs are effective in combating plant viruses. The comparison of curcumin (Cur) and curcumin NPs (Cur NPs) as methods of protection against potato virus Y NTN (PVYNTN) infection determined that plants treated with Cur NPs+V (10 mg/ml) had the highest percentage of reduction in severe viral disease (98%), therefore Cu NPs have the potential of a low-cost, highly effective means of controlling potato viruses and are an alternative to traditional PVY control technologies.

The results of ELISA diagnostics of seed potatoes in the post-harvest period in 2023 (Table 4) showed that the treatment of planting material and vegetative potato plants with preparation with nanoparticles contributed to a decrease in the damage to seed potatoes by PVY. The reduction in the level of PVY damage to potato plants relative to the control variant of Myroslava and Fotyniia varieties was 0.5%, while the control indicator was 1.0%. Treatment of plants with the preparation and desiccation of the aboveground part of plants during three growing seasons (variant 6) ensured the absence of infected potato plants with PVY, while in the control variant, 1.0% of diseased plants were found. Research conducted by M.A. Shah *et al.* (2021) found that mineral oils reduce the spread of PVY by more than 50% compared to untreated controls. M. Kamlesh *et al.* (2020) and V. Rakesh *et al.* (2024) also confirmed that mineral oils in combination with insecticidal treatments provided a high level of efficiency (over 50%) in protecting seed potatoes from PVY infection in the field. T.D.B. MacKenzie *et al.* (2020) highlighted the importance of mineral oil treatments of seed potato plantations in maintaining seed quality. The use of mineral oil treatments of seed potato plantations (variant 7, 8, 9) against the background of insecticide treatments ensured that the varieties Myroslava and Fotyniia did not have PVY infection.

Table 4*. Dependence of infection of basic seed potatoes with Potato virus Y on the use of plant protection system elements,%, 2023*

Variant number	Experiment variants	PVY
	Myroslava variety	
1.	Control1 Celeste® Top	1.0
2.	Avatar-2 Protection	0.5
3.	NP Ni + Celeste® Top	1.0
4.	Control 2. Celeste® Top + tops removal	0.5
5.	Avatar-2 Protection + tops removal	0
6.	NP Ni with Celeste® Top alongside tops removal	0.5
7.	Control 3. Celeste® Top alongside mineral oil and tops removal	0
8.	Avatar-2 protection alongside Celeste® Top and mineral oil with tops removal	0
9.	NP N_i treatment with Celeste® Top alongside mineral oil and tops removal	0
	Fotyniia variety	
1.	Control1 Celeste® Top	1.0
2.	Avatar-2 Protection	0.5
3.	NP Ni + Celeste® Top	1.0
4.	Control 2. Celeste® Top + tops removal	0.5
5.	Avatar-2 Protection + tops removal	0
6.	NP Ni with Celeste® Top alongside tops removal	0.5
7.	Control 3. Celeste® Top alongside mineral oil and tops removal	0
8.	Avatar-2 protection alongside Celeste® Top and mineral oil with tops removal	0
9.	NP N_i treatment with Celeste® Top alongside mineral oil and tops removal	0

Source: *compiled by the author*

As a result of the research, methods were developed to reduce the infection of seed potatoes with viral pathogens in the agroecological conditions of the Southern Polissia zone of Ukraine using a nanoparticle-based preparation, Ni NPs, insecticidal plant treatments in combination with "mineral oil" and tops removal.

CONCLUSIONS

The use of early desiccation and preparation with nanoparticles in 2021-2023 reduced the damage to plants of the Myroslava variety by virus diseases by 2.9%, in the Fotyniia variety the reduction of virus disease damage was 2.6%, while the value in the control without treatment was 4.7%. The use of mineral oil reduced the manifestation of symptoms of viral diseases on potato plants compared to the control without desiccation treatment in the Fotyniia variety by 1.9% and in the Miroslava variety by 1.8%. The combined effect of the preparation, top desiccation and oil treatment of plants ensured a 3.5% reduction in the manifestation of symptoms of viral diseases in the Myroslava potato variety and a 4.0% reduction in the Fotyniia variety. Symptoms of potato plants affected by wrinkled and striped mosaics (*Potato virus Y* pathogen) were observed in the control variant without treatments – 0.3% of plants in the Myroslava variety and 0.2% of plants in the Fotyniia variety.

ELISA diagnostics of plants grown from seed potato tubers showed that treatment of vegetative plants with nanoparticle preparation reduced PVY damage in Myroslava and Fotyniia varieties by 0.5%, while the damage in the control plants of both varieties was 1.0%. The treatment of plants with the product, desiccation of tops, and treatment of plants with mineral oil during three growing seasons ensured the absence of infected PVY potato plants, while 1.0% of diseased plants were found in the control variant. Elements of the plant protection system for basic seed potatoes against viral infections were developed using a biological preparation based on Ni nanoparticles, with the application of mineral oil in plantations in combination with insecticides and top removal. The proposed measures had a positive effect on the yield of basic seed potatoes of Myroslava and Fotyniiaa varieties in the South of Polissia of Ukraine. The average yield increase during the research period for the application of the preparation with nanoparticles was 2.7 t/ha for the Myroslava seed potato variety and 2.6 t/ha for the Fotyniia variety. The use of Ni NPs did not contribute to the growth of the yield of potato varieties Miroslava and Fotyniia.

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CONFLICT OF INTEREST

None.

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Захист насіннєвої картоплі від ураження вірусними інфекціями в польових умовах Полісся України

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Анотація. Вірусні хвороби становлять значну проблему для насінництва картоплі, тому для забезпечення високих якісних характеристик насіннєвого матеріалу важливими є дослідження щодо розробки нових методів їх контролю. Мета досліджень полягала у визначенні ефективності комплексного застосування елементів системи захисту насаджень базової насіннєвої картоплі від вірусних хвороб за використання мінеральних олій, видалення бадилля та біологічних препаратів на основі наночастинок в умовах Півдня Полісся України. Встановлено, що обробка садивних бульб картоплі та обприскування рослин під час вегетації нанопрепаратом біологічного походження підвищували рівень урожайності насіннєвої картоплі сорту Мирослава відносно контролю без обробок на 2,7 т/га або 6,94 %, сорту Фотинія – на 2,6 т/га або 6,9 %. Застосування десикації картоплиння, обробок та мінеральної олії забезпечило приріст урожайності сорту Мирослава на 3,3 т/га або на 9,5 %. Використання десикації картоплиння та обробок картоплі впродовж трьох вегетаційних сезонів за результатами візуального методу оцінювання насаджень сприяло зниженню ураження рослин сорту картоплі Мирослава вірусними хворобами на 2,9 %, сорту Фотинія – на 2,6 %, за ураження рослин на контролі відповідно у сортів 4,5 та 4,7 %. Результати імуноферментної діагностики картоплі у післязбиральний період показали, що обробки вегетуючих рослин картоплі нанопрепаратом сприяли зниженню зараження насіннєвої картоплі *Potato virus Y* (PVY) на 0,5 %, за ураження рослин вірусною інфекцією PVY на контролі без обробок 1,0 %. За результатами досліджень запропоновано елементи системи комплексного застосування багатокомпонентного нанопрепарату біологічного походження, обприскувань насаджень інсектицидами та мінеральною олією та десикації картоплиння для боротьби з вірусними хворобами добазової, базової та сертифікованої насіннєвої картоплі

Ключові слова: урожайність; вірусні хвороби; інфекція *Potato virus Y*; препарати на основі наночастинок; мінеральна олія

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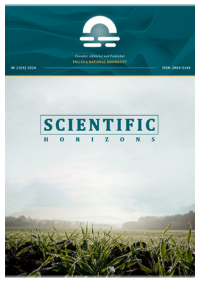

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Organic raspberry cultivation in Lviv region

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Abstract. The purpose of this study was to establish scientifically based approaches to the use of biological methods of raspberry protection to increase both yield and quality in organic farming. The study investigated the effectiveness of biological means of protecting raspberries from the main pests, specifically aphids (*Aphis ruborum*), caterpillars, and raspberry beetle (*Byturus tomentosus*), in the field conditions of Lviv region. Three types of biological agents were used for the experiment: entomophages (ladybugs, trichogramma) and bioinsecticides based on *Bacillus thuringiensis*. The experimental design included a control group without protection, groups with the use

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of individual agents, and a combined group where all methods were used simultaneously. The count of pests and the level of fruit damage were analysed on a decadal basis during the growing season, which lasted from May to August. The findings revealed that the combined use of biological agents was the most effective. The use of ladybugs reduced the count of aphids by 85%, trichogramma reduced fruit damage by caterpillars by 90%, while bioinsecticides reduced yield losses caused by raspberry beetles by 60%. In the combined group, the count of pests decreased by up to 98%, while yield losses were reduced to a minimum. The economic analysis confirmed the feasibility of using biological methods: the combined approach increased the profitability of raspberry cultivation by 35% while ensuring that the products met organic farming standards. The findings of the study demonstrated the high efficiency of biological pest control agents, their economic viability, and environmental safety. The findings are of practical significance for organic farming and can be used as recommendations for farmers

Keywords: agriculture; biological products; pests; biological protection; entomophages

INTRODUCTION

Raspberry cultivation is a significant segment of agriculture in Ukraine, specifically in the Lviv region, which is characterised by favourable climatic and soil conditions for this crop. The relevance of the subject under study lies in the necessity of ensuring effective protection of raspberry plantations from pests, while maintaining environmental safety and compliance with organic standards. The growing demand for raspberries grown according to organic farming principles dictates the requirements for environmentally friendly pest control methods that not only reduce crop losses but also maintain the natural balance in agroecosystems. Despite their effectiveness, traditional chemical pest control products are increasingly being replaced due to the risk of environmental pollution, accumulation of toxic substances in products and negative impact on beneficial insects and biodiversity (Shahini *et al.*, 2024).

One of the key challenges in raspberry cultivation is the vulnerability to major pests such aphids (*Aphis ruborum*), caterpillars, and the raspberry beetle (*Byturus tomentosus*) (Sykalo & Shpak, 2024). These pests cause extensive damage to the crop by damaging leaves, shoots, and fruits, resulting in a 30-50% reduction in yield depending on the level of infestation. Conventional control methods, including the use of chemical pesticides, albeit effective, pose environmental risks, degrade product quality, and contradict organic farming standards (Haleeva *et al.*, 2024). At the same time, inaction in pest control is unacceptable due to possible crop losses and reduced economic stability of farms (Maharramova, 2023). The introduction of biological methods of protection, such as entomophages (ladybugs, trichogramma) and bioinsecticides, is intended to solve this problem, but their effective impact and economic feasibility require in-depth scientific analysis and field research.

The problem of the effects of protection and fertilisation systems on raspberry quality continues to be a key issue in organic farming. M. Balawejder *et al.* (2022) demonstrated that changing the substrate in soilless raspberry cultivation can increase the content of bioactive substances in the fruit. However, the researchers did not investigate the effects of biological plant protection products on quality and yield in the field. R. Anjos *et al.* (2020) confirmed that organic methods of raspberry cultivation contribute to the preservation of the phytochemical composition of berries compared to conventional systems. However, the study did not factor in the effects of entomophages on the biochemical composition of the fruit. S. Murtić *et al.* (2022) compared the quality of raspberry fruit of Meeker variety from organic and conventional cultivation systems, emphasising the advantages of organic systems. However, the study was focused on berry quality, without emphasis on pest management practices.

D. Sangiorgio *et al.* (2021) found that organic farming increases the flavour and biodiversity of beneficial bacteria on raspberries. However, the effects of biological agents on long-term pest control and interaction with microflora were not analysed. M. Kotuła *et al.* (2022) characterised the chemical composition of raspberries from organic, conventional, and wild cultivation. The researchers emphasised the significance of organic systems, but did not consider biosecurity measures. A. Ponder and E. Hallmann (2020) studied the vitamin C content of different raspberry varieties from organic and conventional cultivation systems. The data highlighted the benefits of the organic approach but leave open questions about the influence of biological pest control methods. M. Milinković *et al.* (2021) investigated the chemical composition of the Willamette variety raspberry fruits grown in different systems. The researchers confirmed the environmental benefits of the organic approach, but did not consider the cost-effectiveness of the protection products. M.N. Frías-Moreno *et al.* (2021) focused on the antioxidant activity of raspberries depending on fertiliser. However, the study did not analyse biological pest control agents. A. Estrada-Beltran *et al.* (2020) discovered the effect of organic fertilisers on volatile compounds in raspberry fruit. However, their research did not cover aspects related to pests and control methods. A. Ispiryan *et al.* (2023) emphasised the role of sustainability in raspberry cultivation. The researchers covered a wide range of issues, but did not consider the effects of biological control agents on berry yield and quality.

The analysis of these sources showed that although many studies examined organic raspberry cultivation systems, the use of biological control agents and their effectiveness, economic feasibility, and interaction with other factors are still understudied. The purpose of the present study was to evaluate the effectiveness of biological control agents, such as entomophages (ladybugs, trichogramma) and bioinsecticides based on *Bacillus thuringiensis*, in the control of major raspberry pests (aphids, caterpillars, raspberry beetle) in the Lviv region. The objectives of the study were to determine the effect of entomophages (ladybugs, trichogramma) and bioinsecticides on reducing the count of major raspberry pests and the level of fruit damage, to assess the economic efficiency of individual and combined use of biological protection methods, and to investigate compliance with organic farming standards and the effects on crop quality.

MATERIALS AND METHODS

The study was conducted on raspberry plantations in the Lviv region during the growing season of 2023, from May to August. The region is characterised by a temperate continental climate with an average summer temperature of around +18…+22°C and sufficient rainfall (60-90 mm per month), which creates favourable conditions for raspberry cultivation. The experiment was conducted on the Polana variety of raspberry, which is known for its high yield and popularity among farmers. The study followed the ethical standards set out in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992). The plots selected for the experiment were characterised by loamy soil with good moisture retention capacity, which created favourable conditions for raspberry growth and research.

Three different biological control agents were employed to control the main pests. Ladybugs (*Coccinellidae*) were used to control aphids (*Aphis ruborum*), which is one of the most harmful insects for raspberry plantations. Ladybugs were released on each bush in an amount sufficient to naturally reduce the pest population. To reduce the number of caterpillars damaging the fruit, the study used *Trichogramma spp.* Trichogramma was placed in capsules in areas with caterpillars, providing a long-term control effect. To control the raspberry beetle (*Byturus tomentosus*), which damages both fruit and leaves, bioinsecticides based on *Bacillus thuringiensis* were used. All these products were certified according to organic farming standards, specifically the European Regulations EC 834/2007 (2007) and EC 889/2008 (2008), which regulate the use of biological products for pest control in organic agriculture. These products were applied to the plants in the form of spraying according to the manufacturer's recommendations.

The experimental design included a control group and four experimental groups, with 50 bushes in each group. The control group did not use any protection products, which helped to estimate the natural level of pest abundance and yield losses. The first experimental group received only ladybugs, the second – only trichogramma, while the third – only bioinsecticides. The last group, the combined group, included all three methods of protection at once, which helped to assess the interaction and synergistic effect. The assessment of the effectiveness of the methods was based on counting the count of pests and the level of fruit damage. Several methods of data collection were used for this purpose. Aphid numbers were determined by visual inspection of leaves and shoots, considering the number of individuals per bush. Caterpillars and raspberry beetle were counted using traps and random inspection of plants. The percentage of damaged fruit in each group was also assessed to determine the influence of pests on yield. All data were collected on a daily basis, which helped to identify the dynamics of changes in the count of pests and fruit damage. This helped to assess both the short-term effectiveness of the methods in the first weeks after application and the long-term effects throughout the entire period of active growth, flowering, and ripening of berries.

The study employed bioinsecticides based on *Bacillus thuringiensis* (Bt), which are effective against lepidopteran pests, to control caterpillars. The preparation consisted of a spore-crystal complex of the bacterium, which, when ingested by the pest's digestive system, caused the destruction of the intestinal wall, leading to death. The preparation was applied in the form of a working solution with a concentration of 1.5-2.0 litres per 100 m^2 of raspberry plantations. The treatment was performed three times during the growing season with an interval of 10-14 days, starting from the first signs of caterpillar damage. The solution was applied using a knapsack sprayer, ensuring uniform coverage of all aerial parts of the plants. To preserve the activity of the product, the treatment was performed in the evening to avoid exposure to ultraviolet radiation. This ensured a comprehensive evaluation of each method and helped to develop recommendations for implementing these approaches in practice.

RESULTS

Dynamics of aphid counts. The study was conducted on raspberry plantations in the Lviv region during the growing season of 2023, from May to August on raspberry plantations in the Lviv region and aimed to evaluate the effectiveness of biological methods of plant protection against pests. The region with a temperate continental climate, an average temperature of +18…+22°C during the growing season and monthly precipitation of 60-90 mm creates suitable conditions for growing berry crops. At the same time, these conditions contribute to the active reproduction of aphids (*Aphis ruborum*), which is one of the most harmful insects that causes great damage to raspberry crops. The relevance of the study was confirmed by the need to develop effective environmentally friendly protection methods for organic farming (Shabliy *et al*., 2025).

In the control group, where no protection was applied, the aphid population grew rapidly. The initial 50 individuals per bush reached 300 by the end of the 30-day period. This indicated a six-fold increase in counts caused by favourable conditions for the pest's reproduction. Each new generation considerably increased the pressure on the plants, which could lead to a complete loss of yield. This situation is typical for uncontrolled pest spread in agricultural conditions. The experimental group, where ladybugs (*Coccinellidae*) were used to control aphids, demonstrated a completely different dynamic. In the first 10 days after the release of ladybugs, the count of aphids decreased by 40% – from 50 to 30 specimens per bush. Over the next 10 days, the population decreased by 70%, reaching 15 specimens. By the end of the experiment, the count of pests in this group was only 7 per bush, which corresponds to an overall reduction of 85%. This confirms the high efficiency of ladybugs as a natural method of protection.

The results of comparing the control and experimental groups demonstrated the considerable advantages of the biological approach. On the 10th day of the experiment, the count of aphids in the control group increased to 120 individuals, while in the group with ladybugs it decreased to 30. At the end of the experiment, the difference became even more pronounced: 300 specimens in the control group versus 7 in the experimental group. This is 43 times less, which demonstrates the effectiveness of a natural method of protection that can considerably reduce the count of pests (Medvid, 2021). It is especially significant to note the rapid efficacy of the method. In the first 20 days after the release of ladybugs, the largest decrease in aphid numbers was recorded, which is explained by the active predatory behaviour of ladybugs. This period was key to reducing the pest population to a safe level. The further slowdown in the rate of population decline observed in the final 10 days indicated that the minimum population level was reached, which the ladybugs stably maintained until the end of the experiment.

The data in Table 1 also underline the significance of biological control in organic farming. In the control group, an uncontrolled increase in the aphid population was observed, which could have caused considerable crop losses and negatively affected the economic performance of the farm. The use of ladybugs helped to reduce the count of pests to a minimum, without harming the environment or using chemicals. The biological method of protection is not only environmentally friendly, but also economically justified, as the cost of purchasing and releasing ladybugs was considerably lower than the potential damage from the uncontrolled spread of aphids.

***Table 1**. Dynamics of the counts of aphids*

Observation period	Control group (average count of aphids per 1 bush)	Experimental group (average count of aphids per 1 bush)	Reduction in the counts in the experimental group (%)
Start of the experiment	50	50	0
10 days later	120	30	40
20 days later	200	15	70
30 days later	300	7	85

***Source:** created by the authors*

Thus, the table clearly illustrates the effectiveness of ladybugs in aphid control. The data confirmed that the use of this method can be a successful tool for protecting raspberry plantations, especially in organic farming, where the use of chemical pesticides is limited (Todosiychuk, 2024). The considerable reduction in aphid numbers in the experimental group compared to the control group demonstrates the potential of ladybugs as a key element of an integrated plant protection system.

Dynamics of caterpillar counts. Caterpillars are another major pest of raspberry plantations in the Lviv region. Caterpillar activity leads to fruit damage, which reduces the quality and quantity of the crop. The study evaluated the effectiveness of *Trichogramma spp*. in controlling caterpillar numbers and reducing the impact on yield. *Trichogramma* is a microscopic parasite that lays eggs in caterpillar eggs, stopping development and greatly reducing the damage caused by the pests. In the experimental plots, cardboard capsules with a *Trichogramma* were used, which were placed on every fifth raspberry bush. The control group was left without the use of any protective equipment. The level of fruit damage was performed every 10 days during the entire growing season. Both the level of fruit damage and the total number of caterpillars in the control and experimental plots were assessed. Table 2 shows a clear difference in the fruit damage levels between the control and experimental groups throughout the study, which highlights the effectiveness of *Trichogramma* in caterpillar control. In the control group, where no protection products were applied, the level of fruit damage steadily increased with each observation period. At the beginning of the experiment, about 10% of the fruit was damaged, which can be considered a natural level of damage in the presence of caterpillars without intervention. However, after 30 days, this figure increased to 55%. Such a rapid increase in the level of damage indicates active pest reproduction and a considerable impact on yield.

In the control group, the caterpillars developed freely, causing damage to the fruit. The activity was conditioned by favourable environment, including the absence of natural enemies or protective measures. The caterpillars damaged the fruit, resulting in losses for commercial use and considerably reducing the overall quality of the crop. This increase in damage levels demonstrates how quickly the negative impact of caterpillars can progress if no action is taken to control their numbers. In the experimental group, where the *Trichogramma* was used, the situation was radically different. Within 10 days after the application of the *Trichogramma*, the level of damaged fruit decreased by 40% compared to the control group, amounting to 15% versus 25%. This first reduction was caused by the fact that the *Trichogramma* began to act actively, laying its eggs in the eggs of the caterpillars, which stopped development. Due to this, the caterpillars did not reach the stage at which they could harm the fruit, which explained the rapid effect in the first days after application. Twenty days after the start of the experiment, the effectiveness of the *Trichogramma* became even more evident. The level of damaged fruit in the experimental group decreased to 12%, which corresponded to a 70% reduction in damage compared to the control group. During this period, the *Trichogramma* demonstrated its ability to effectively control the count of caterpillars in a long period. This suggests that the effect of *Trichogramma* is not limited to a brief period after application, but has a long-term effect, maintaining a low level of pest numbers (Vasyliev, 2021; Shahini *et al.*, 2023). 30 days after the start of the *Trichogramma* application, which corresponded to the end of the main stage of the experiment, the level of damaged fruit in the experimental group was only 10%. This suggests the effectiveness of the method during the key raspberry growing season, although the total growing season of the crop lasted from May to August. This figure was eight times lower than in the control group, where the level of damage reached 55%. This difference clearly demonstrates the benefits of using *Trichogramma* as an effective biological control agent (Table 2).

***Table 2**. Dynamics of the counts of caterpillars*

Observation period	Control group (count of caterpillars per 1 m^2)	Experimental group (count of caterpillars per 1 m^2)	Reduction in the counts in the experimental group (%)
Start of the experiment	5	5	0
10 days later	12	8	33
20 days later	20	6	70
30 days later	30	5	83

***Source:** created by the authors*

Notably, *Trichogramma* is a cost-effective means of protection. Its use requires minimal costs compared to the losses that can be caused by the uncontrolled spread of caterpillars (Hablak, 2022). In the control group, where the level of fruit damage reached 55%, farmers could have lost a significant portion of their crop. At the same time, in the *Trichogramma* group, the level of damage stayed minimal, ensuring satisfactory fruit quality and maintaining yields.

Effects of bioinsecticides on reducing crop losses caused by raspberry beetle. The raspberry beetle (*Byturus tomentosus*) is one of the main pests of raspberry plantations, which causes major yield losses due to damage to berries. The study evaluated the effectiveness of a combination of bioinsecticides based on (*Bacillus thuringiensis*) in reducing damage from this pest. The bioinsecticides were applied to the experimental plots, while the control group was left untreated. The study considered the level of crop losses and the counts of raspberry beetles on the bushes.

The data clearly demonstrates the difference between the level of crop losses in the control and experimental groups. In the control group, yield losses increased steadily throughout the study, starting at 10% at the beginning of the experiment and reaching 70% at the end. This indicated that without intervention, the raspberry beetle managed to reproduce freely and cause damage to the crop. At the same time, in the experimental plots where bioinsecticides were used, crop losses were much lower. 10 days after the start of the experiment, losses in the control group increased to 30%, while in the experimental group they stayed at 15%, which indicated a 50% reduction in losses compared to the control plots. After 20 days, crop losses in the control group reached 50%, while in the experimental group they were only 25%, i.e., reduced by half. By the end of the study, after 30 days, the yield losses in the control group reached 70%, while in the experimental group they stayed at 28%. This meant that the combination of bioinsecticides reduced crop losses by 60%.

Analysing these data, it can be concluded that bioinsecticides provided a gradual and stable reduction in the effects of raspberry beetle on yield. The bioinsecticides worked through several mechanisms, including inhibition of the pest's vital functions, which led to a decrease in the counts and, consequently, the level of damage to the berries. Furthermore, the study also showed that the effects of bioinsecticides were long-term. During the entire period of the experiment, the level of crop losses in the experimental group stayed significantly lower than in the control group. This indicated that bioinsecticides had not only a quick but also a long-lasting effect, providing stable protection of plantations. Notably, the use of bioinsecticides did not affect the quality of the fruit in the experimental group. The berries stayed clean and free of pesticide residues, which is significant for organic farming. In the control group, a sizeable proportion of the berries were damaged, resulting in their loss for commercial use (Table 3).

***Table 3**. Effects of bioinsecticides on reducing crop losses caused by raspberry beetle*

Observation period	Control group (yield losses, %)	Experimental group (yield losses, %)	Reduction in the counts in the experimental group (%)
Start of the experiment	10	10	0
10 days later	30	20	33
20 days later	50	25	50
30 days later	70	28	60

***Source:** created by the authors*

Thus, the table demonstrates that the use of a combination of bioinsecticides is an effective solution for raspberry beetle control. The 60% reduction in crop losses confirmed the feasibility of using biological protection products in agriculture, especially in organic production (Tkalenko, 2022; Tanchyk *et al.*, 2024). This method not only minimised the impact of pests on the crop, but also preserved the ecological balance, ensuring the stable production of environmentally friendly products.

Comparison of the effectiveness of protection methods. The analysis of the results of the combined method showed significantly higher efficiency compared to the separate application of each method. The aphids, which in the control group reached 300 specimens in 30 days, were almost completely destroyed in the combined group, where the number decreased to 5 specimens, which corresponded to 98.3% reduction. After 10 days, the number of aphids in the combined group decreased to 20 specimens, demonstrating the high efficiency of ladybugs in combination with other methods. On the 20th day, the number decreased even more – to 10 specimens, which confirmed the stable effects of the combined approach.

The combined method also proved to be extremely effective for caterpillars. In the control group, the level of fruit damage increased from 25% to 55%, while in the combined group it stayed at 5% until the end of the experiment. After 10 days, the losses decreased to 10%, which corresponded to a 60% reduction, while after 20 days, this figure dropped to 8%, providing an 80% reduction in losses. By the end of the experiment, the combined method provided a 90.9% reduction in caterpillar losses, which exceeded the effectiveness of the individual *Trichogramma* application. Raspberry beetle also experienced a considerable reduction under the effects of the combined method. In the control group, crop losses reached 70% by the end of the experiment, while in the combined group this figure stayed at 7%, which corresponded to a 90% reduction in losses. After 10 days, the losses in the combined group decreased to 15%, and after 20 days – to 10%, which demonstrated the stable effectiveness of bioinsecticides in combination with other methods (Table 4).

***Table 4**. Comparison of the effectiveness of protection methods*

Method/Pest	Time (days)	Control group (%)	Combined group (%)	Reduction of losses (%)
Ladybugs (aphids)	10	120	20	83.3
	20	200	10	95
	30	300	5	98.3
Trichogramma (caterpillars)	10	25	10	60
	20	40	8	80
	30	55	5	90.9
Bioinsecticides (raspberry beetle)	10	30	15	50
	20	50	10	80
	30	70	7	90

***Source:** created by the authors*

The combined method also proved to be effective in preserving the crop. Total crop losses in the control groups were significantly higher, while in the combined group, losses stayed minimal for all three pests.

Furthermore, the method ensured environmental safety and met organic farming standards, which is a crucial aspect for farmers (Baker *et al.*, 2019).

Economic analysis of the efficiency of protection methods. Figure 1 illustrates the cost-effectiveness of applied protection methods, clearly demonstrating the benefits of a combined approach. The data confirmed that integrating multiple biological control methods is a cost-effective strategy that helps to reduce yield losses and increases profitability of agricultural production (Concept of development of a biological..., 2023).

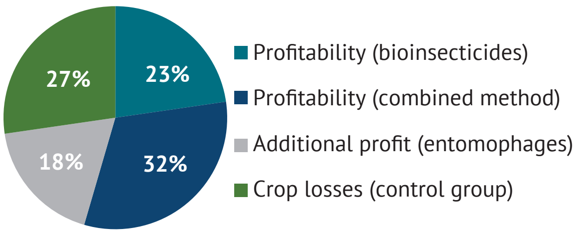

***Figure 1**. Economic analysis of the efficiency of protection methods*
***Source:** created by the authors*

The analysis of the economic efficiency of the applied biological protection methods revealed a substantial difference between the control and experimental groups. In the control group, crop losses amounted to 30%, indicating a severe negative impact of pests on the economic performance of the farm. This level of losses caused extensive financial losses, especially considering the high demand for quality products. The use of entomophages helped to achieve an additional 20% profit. This demonstrated the significant contribution of biological control to cost optimisation and increased agricultural production efficiency (Lee *et al.*, 2024). The method provided a short-term influence but was cost-effective in controlling concrete pest species.

The bioinsecticides used in the study included *Bacillus thuringiensis* (Bt) bacterial preparations, which have proven efficacy against scale pests. The preparation consisted of a spore-crystal complex of the bacterium capable of destroying the intestinal wall of pests, causing death. The dose of the preparation was 1.5-2.0 litres of working solution per 100 m^2 of raspberry plantations, while the treatment was performed three times during the growing season with an interval. The effect of bioinsecticides was less rapid than that of entomophages but stable, which made them suitable for an integrated approach (Basanets, 2024). However, the stability of the product's action ensured a long-term reduction in pest counts and maintained the yield at a stable level. Two weeks after the first treatment, the counts of caterpillars decreased by 50%, and by the end of the experiment – by 70%.

Apart from its effectiveness in reducing pest counts, the use of bioinsecticides positively influenced the farm's economic performance. By reducing crop losses, the profitability of raspberry cultivation increased by 25%. The preparation also showed high compatibility with other protection methods, making it suitable for an integrated approach. The use of bioinsecticides not only reduced the count of pests, but also ensured long-term stable plant protection, which confirmed its efficiency in organic farming. The greatest outcome was demonstrated by the combined method, which provided a 35% increase in profitability. The application combined the benefits of entomophages, bioinsecticides, and *Trichogramma*, creating a synergistic effect. This resulted in a maximum reduction of crop losses and increased economic efficiency.

DISCUSSION

The findings of the study confirmed the high efficiency of biological means of protecting raspberries from major pests, such as aphids (*Aphis ruborum*), caterpillars, and raspberry beetle (*Byturus tomentosus*) in real field conditions. The use of entomophages (ladybugs and *Trichogramma*) and bioinsecticides demonstrated the ability of these methods to reduce pest counts and fruit damage substantially. The best results were obtained with the combined use of these products, which reduced the count of pests by up to 98% and minimise crop losses. Particularly noteworthy was the efficiency of entomophages, which provided a rapid reduction in the count of aphids and other pests in the first weeks after application. Ladybugs showed fast action, while *Trichogramma* demonstrated a stable long-term effect on caterpillars. The bioinsecticides based on *Bacillus thuringiensis* had a slower but sustained effect, especially in the control of raspberry beetles. This combination of various mechanisms of action helped to achieve pronounced efficiency of the combined approach.

M. Kotuła *et al.* (2024) focused on the effects of packaging types on the quality parameters of raspberries during storage. Although the findings of this study emphasised the significance of maintaining berry quality in the post-harvest period, the effects of plant protection methods on the final product were not addressed. The findings of the present study helped to fill this gap, as they proved that the use of biological protection methods, such as entomophages and bioinsecticides, not only mitigates yield losses, but also maintains prominent quality characteristics of the product at the growing stage. The findings of the present study confirmed the effectiveness of biological methods of raspberry protection against pests, which helped to reduce yield losses and increase yield stability. These findings have some similarities with the findings of C. Fuentealba *et al.* (2024), who investigated the quality of raspberries depending on growing conditions. This study indicated that cultivation methods affect the metabolism and quality characteristics of berries. However, C. Fuentealba *et al.* did not analyse plant protection and pest control, which limited the practical relevance of the findings for farmers. The presented findings demonstrated that the integrated use of biological protection methods not only contributes to the preservation of product quality but also ensures a sustainable level of yield in organic farming.

The findings of the present study are also partially consistent with the findings of R. Popa *et al.* (2024), who emphasised the role of raspberry production as a promising area of agribusiness development in a circular economy. The study examined the economic component of raspberry cultivation, focusing on the potential benefits for farmers. The presented findings complement these findings of R. Popa *et al.*, demonstrating that the introduction of biological methods of plant protection can greatly increase the profitability of production by reducing crop losses and minimising the cost of chemicals. Furthermore, the proposed methods are harmoniously integrated into the concept of the circular economy, as they ensure environmental safety and sustainable development of agricultural systems. This integrated approach also contributed to the preservation of fruit quality and economic profitability, which was not analysed in depth in the cited study. R. Anjos *et al.* (2020) compared the effects of organic and conventional raspberry cultivation methods on the phytochemical composition of berries. The researchers noted that organic cultivation methods positively influence the content of biologically active substances in berries, which contributes to the growth in demand for such products among consumers. The present study confirmed this trend, as the use of biological protection methods ensured the preservation of raspberry quality characteristics, such as flavour, texture, and appearance, even with a major reduction in pest counts. However, in contrast to the study by R. Anjos *et al.*, the present findings emphasised the effectiveness of pest control, which is a key factor in ensuring a stable harvest.

The findings obtained are in line with the findings of G. Podedworny *et al.* (2024), who investigated the influence of biodiversity practices on pest and beneficial organism populations in organic raspberry and strawberry cultivation. The researchers emphasised that the use of environmentally friendly practices allows striking a balance between pests and entomophages, which reduces the need for chemical pesticides. The presented findings confirmed this approach, demonstrating that the use of ladybugs, trichogramma, and bioinsecticides can effectively control the count of pests with minimal impact on the ecosystem. However, unlike the study by G. Podedworny *et al.*, the present study paid closer attention to the practical aspects of integrating biological methods into production systems, including assessing profitability and reducing yield losses. The findings are also partially consistent with the findings of M. Ičanović *et al.* (2024), who investigated the effect of humus extract on raspberry quality. The researchers noted that improving soil characteristics contributes to an increase in berry quality. Although the effects of fertilisers were not considered in the present study, the data obtained confirmed that the use of biological protection methods allows maintaining product quality by minimising damage from pests. In contrast to the study by M. Ičanović *et al.*, the present study focused on pest management, emphasising an integrated approach to increasing yields and maintaining ecological balance.

The findings of the present study are partially in line with the findings of M. Drobek *et al.* (2024), who investigated the effects of microbial biostimulants on the antioxidant profile, enzyme activity, and quality of raspberries. The researchers noted that the use of biological agents can greatly improve the quality of fruit by increasing antioxidant activity. Although microbial biostimulants were not used in the present study, the findings confirmed that biological protection methods, such as the use of ladybugs, *Trichogramma*, and bioinsecticides, help to maintain the quality characteristics of berries while minimising damage from pests. This ensures environmental safety of production and high competitiveness of products on the market. The findings also correlate with those presented by M. Kuboń *et al.* (2024), who analysed the use of eco-friendly technologies, specifically the modification of coconut fibres to increase sustainability in dessert raspberry production. Their study focused on the environmental friendliness of production processes that help reduce environmental impact. The findings confirmed the significance of ecological approaches, showing that the use of biological protection methods, such as entomophages and bioinsecticides, can effectively control pests without harming the ecosystem. In contrast to the study by M. Kuboń *et al.*, the present study focused more on the practical aspects of pest control, including an assessment of the economic efficiency of such methods.

The findings of the study partially coincide with the findings of G. Ilhan (2024), who investigated the ecotypes of wild raspberries in northeastern Turkey. The researchers focused on the ecological adaptation of wild varieties and the potential for use in organic production. Although the present study used the Polana variety, the findings confirmed that biological control methods such as entomophages and bioinsecticides can be effectively applied to both cultivated and wild raspberry varieties to ensure sustainable production. The distinctive feature of the present study lies in the detailed analysis of the effectiveness of concrete pest control agents, which makes it more oriented towards practical implementation. G. Velicevici *et al.* (2024) focused on the evaluation of the characteristics of different raspberry varieties grown in Timis county, Romania. The researchers analysed the effects of cultivar on berry yield and quality. Although the analysis made a valuable contribution to the understanding of raspberry varietal characteristics, the issue of plant protection against pests stayed outside the scope of the study. The findings presented in the current study complemented these findings, demonstrating that the use of biological control methods can ensure stable yields and berry quality regardless of varietal characteristics, creating a universal solution for organic farming.

The discussion results confirmed that the use of biological control agents, especially in a combined approach, is a highly effective solution for raspberry pest control. The integration of entomophages and bioinsecticides provided a substantial reduction in pest counts, minimised yield losses, and met environmental standards. This study not only highlighted the advantages of biological methods compared to chemical methods but also demonstrated the practical feasibility for farmers focused on organic farming.

CONCLUSIONS

The conducted study helped to assess the effectiveness of biological methods of raspberry protection in organic farming. The key focus was placed on investigating the impact of entomophages, bioinsecticides, and their combined use on pest counts and yield losses. The findings confirmed the promising potential of biological agents in raspberry pest control, specifically in providing effective control of aphids, caterpillars, and raspberry beetles.

The experimental design, which included control and experimental groups, helped to systematically compare the effects of each method individually and in combination. The use of entomophages proved to be particularly effective in rapidly reducing the counts of pests in the early stages of the growing season. *Trichogramma* showed a prominent level of long-term control of caterpillar counts, preventing extensive fruit damage. Bioinsecticides, albeit acting more slowly, had a stable effect at the level of the total raspberry beetle population. The data obtained showed the value of a combined approach that provided the greatest level of protection for the plantations. The synergy of methods contributed to a substantial reduction in the level of harmful effects of insects, as well as maintaining high quality of the crop. This confirmed the feasibility of integrating various biological products into plant protection systems. Apart from the direct effect on yields, the study confirmed that the applied agents followed organic farming standards. The absence of chemical residues in fruits, environmental safety, and biodiversity conservation are major advantages of using biological methods compared to conventional chemical pesticides. The economic assessment also revealed significant advantages of biological control methods. The combined approach minimised yield losses, which increased the profitability of raspberry cultivation. This aspect is crucial for farmers focused on environmentally friendly production and meeting the growing demand for organic products.

Overall, the study confirmed the effectiveness and feasibility of using biological protection products for raspberry cultivation. The findings obtained can be applied to develop recommendations for integrated plant protection systems aimed at increasing yields, economic profitability, and environmental sustainability. The study was limited to the conditions of Lviv region, a single raspberry variety (Polana) and did not factor in the interaction of biological methods with other agronomic practices. Further research could focus on expanding the range of biological agents and investigating their effectiveness in varying climatic conditions.

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CONFLICT OF INTEREST

None.

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Органічне вирощування малини у Львівській області

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Анотація. Метою дослідження було встановлення науково обґрунтованих підходів до використання біологічних методів захисту малини для підвищення і врожайності та якості в умовах органічного землеробства. У статті досліджено ефективність біологічних засобів захисту малини від основних шкідників, зокрема попелиці (*Aphis ruborum*), гусениць та малинового жука (*Byturus tomentosus*), у польових умовах Львівської області. Для проведення експерименту використовували три типи біологічних засобів: ентомофагів (сонечка, трихограма) та біоінсектициди на основі *Bacillus thuringiensis*. Експериментальний дизайн включав контрольну групу без захисту, групи із застосуванням окремих засобів та комбіновану групу, де використовували всі методи одночасно. Чисельність шкідників і рівень пошкоджень плодів аналізували щодекадно протягом вегетаційного періоду, що тривав із травня до серпня. Отримані результати продемонстрували, що комбіноване використання біологічних засобів було найефективнішим. Застосування сонечок зменшило чисельність попелиці на 85%, трихограма забезпечила зниження рівня пошкодження плодів гусеницями на 90%, а біоінсектициди зменшили втрати врожаю через малинову жуку на 60%. У комбінованій групі чисельність шкідників знижувалася до 98%, а втрати врожаю скоротилися до мінімуму. Економічний аналіз підтвердив доцільність застосування біологічних методів: комбінований підхід дозволив підвищити рентабельність вирощування малини на 35%, забезпечуючи водночас відповідність продукції стандартам органічного землеробства. Висновки дослідження свідчать про високу ефективність біологічних засобів захисту для контролю шкідників, економічну вигідність і екологічну безпечність. Результати мають практичне значення для органічного землеробства та можуть бути використані як рекомендації для фермерських господарств

Ключові слова: землеробство; біопрепарати; шкідники; біологічний захист; ентомофаги

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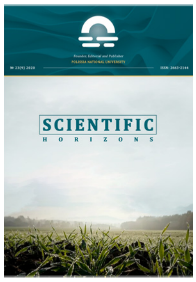

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Formation of sowing qualities of oil radish seeds depending on the nutrition system in the Western Forest-Steppe

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Abstract. The reasons for the limited distribution of oil radish include the lack of seeds caused by the imperfection of the elements of cultivation technology, which requires additional research. The purpose of this study was to improve the technology of growing oil radish varieties through the plant nutrition system. Methodological research was based on general scientific and special methods. The study was conducted at the experimental base of the Department of Seed Production and Seed Science of the

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Institute of Agriculture of the Carpathian Region of the National Academy of Agrarian Sciences of Ukraine. Based on the results obtained in 2022-2024, it was substantiated that the low natural fertility of grey forest surface-gleyed soils of the Western Forest-Steppe and the insufficient supply of microelements in them cause low yields and seed quality of the crop under study. This problem can be solved by developing a balanced nutrition system for oil radish based on innovative macro- and microelements. Under effective pre-sowing seed treatment with microfertilisers in combination with insecticidal and fungicidal seed treatment with Modesto preparation, 48% FC (12.5 l/t) and against the background of mineral fertilisers in the norm of $N_{30}P_{90}K_{100}$ with nitrogen fertilisation + N_{50} (main growth stage and developmental stages – BBCH 14-16) + N_{30} (BBCH 52-53), the statistically significant yield increases were 0.23-0.36 t/ha. Balanced plant nutrition contributed to the improvement of sowing qualities of seeds, specifically, the thousand-kernel-weight, germination energy, and laboratory germination. The improved nutrition system for oil radish, considering the introduction of mineral fertilisers and chelated micronutrients into the cultivation technology, can be used by agricultural enterprises and farms engaged in growing the crop for seeds, which will increase the production of seed material to expand the sown areas in the region

Keywords: oil radish; variety; seeds; mineral fertilisers; micronutrient fertilisers; yield; sowing qualities

INTRODUCTION

Currently, agribusiness is focused on growing marketable, high-yielding oilseeds. Among the biological range and agrotechnical possibilities, oil radish plays a significant role. This previously well-known crop can be used as a fodder crop in the context of climate change, and its spring post-mowing and post-harvest sowings are a valuable source of green fodder in the conveyor production system. It can be grown in monoculture and in grass mixtures. During a short growing season (40-50 days), it produces 30-70 t/ha of leaf mass with an optimum content of digestible protein. Its great value lies in restoring the fertility of depleted soils, as well as in its use as a substitute for organic fertilisers when ploughing biomass. According to H.S. Hereshko *et al.* (2021), the significant agrotechnical value of this crop resides in the fact that the plant cleanses the soil from nematodes, wireworms, pathogens, enriching it with a complex of useful substances (organic matter, nitrogen, phosphorus, potassium, trace elements), prevents root rot, and is antagonistic to malicious wheatgrass.

Producers of this crop are offered different varieties for cultivation, created in distinct soil and climatic zones, with differences in morphological characteristics and economic qualities. However, S.V. Nrigorenko (2019) and Ya. Tsytsyura (2020) noted that the technological spread of the crop itself is conditioned by the limited varietal resources, with an urgent problem of using it for feed and seed purposes. From both theoretical and practical standpoints, it is vital to investigate the reaction of the variety to concrete growing conditions and the proposed elements of technology, which allows selecting the most environmentally friendly and plastic ones for different zones, subzones, and levels of management (Karamushka & Moroz, 2018).

In recent years, climate change has become evident, affecting vital functions under unfavourable environmental conditions, and therefore obtaining high and stable yields and qualities of oil radish seeds depends on the resistance of plants during the growing season, according to Bilonizhka (2023). It is with a balanced macro- and microelements nutrition system that their negative impact can be levelled. Kh.V. Bilonizhka (2024) reported that optimum nutrition of oil radish varieties conditioned by the application of mineral fertilisers and micronutrient fertilisers contributes to an increase in the morphological parameters of plants, namely: plant height, number of stems per plant, pods, seeds in the pod and per plant, increases the weight of seeds per plant, and the thousand-kernel-weight, which affects their productivity.

According to A.V. Yunyk and I.V. Trifonov (2020), to form 1 tonne of dry matter, oil radish consumes 35-40 kg of nitrogen, 12-19 kg of phosphorus, 48-50 kg of potassium, and 16-20 kg of calcium. The soils of the Carpathian region are characterised by a low supply of available forms of macro- and microelements and therefore obtaining high yields and sowing qualities of oil radish seeds is somewhat problematic and requires scientific substantiation. Scientific publications on the technology of growing this crop are limited and do not fully cover the innovative elements of today.

The purpose of the present study was to improve the plant nutrition system of oil radish varieties through the main application of mineral fertilisers and pre-sowing seed treatment with microfertilisers for the formation of yield and sowing characteristics in the Western Forest-Steppe zone.

MATERIALS AND METHODS

Experimental research was conducted at the Department of Seed Production and Seed Science of the Institute of Agriculture of the Carpathian Region of the National Academy of Agrarian Sciences (49°47′07″ N, 23°52′07″ E, 314 m above sea level) in 2022, 2023, and 2024. Varieties (factor B) of oil radish were used for the research: Zhuravka – originated by the Carpathian State Agricultural Research Station of the Institute of Agriculture of the Carpathian Region of NAAS, and

Fakel – Institute of Oilseeds of NAAS. The grey forest, surface-gleyed, light loamy soil of the experimental plots was characterised by a very low supply of nitrogen and potassium, medium supply of phosphorus, and a slightly acidic reaction of the soil solution (pH_{salt} – 5.4). The content of trace elements was as follows: boron (B) – 0.67 mg/kg soil (average supply), manganese (Mg) – 21.99, cobalt (Co) – 0.56, copper (Cu) – 1.68 (low), and high in zinc (Zn) – 0.59 mg/kg soil.

In all variants of the experiment, seeds were treated with insecticidal-fungicidal seed preparation Modesto, 48% FC (12.5 l/t). The experimental scheme included microfertilisers (factor A): 1. Without microfertilisers – control, 2. Oracle seed (1.0 l/t), 3. YaraVita Brasitrel Pro (1.0 l/t), 4. Vitazim (1.0 l/t). The level of mineral nutrition was $N_{30}P_{60}K_{70}$ + N_{40} (BBCH 14-16) + N_{20} (BBCH 52-53). The study was conducted using the methodology by S. Tkachyk (2016). The field experiments were set up and conducted according to the generally accepted methodology of research work – statistical analysis of the results was performed using the analysis of variance according to the method of V.O. Ushkarenko *et al.* (2014). The correlation between yield and seed quality was determined considering: from 0 to 0.33 – weak, from 0.33 to 0.66 – medium, from 0.66 to 1.00 – strong, 1.00 – complete, both for direct and inverse correlation (r), with reliability at the 5% statistical significance level. Sowing qualities of seeds were determined in the laboratory according to the thousand-kernel-weight, germination energy, and laboratory germination according to the methods of DSTU 4138-2002 (2004).

According to the standard, the thousand-kernel-weight was determined by two weights of 500 kernels each, after which it was converted to the thousand-kernel-weight and the average weight was calculated to the nearest 0.1 g. If the deviation of the weight of two samples from the average thousand-kernel-weight exceeded 0.5 %, a third sample was deducted and weighed. The calculated average thousand-kernel-weight was adjusted to a standard moisture content of 8% using the following formula:

$$W = \frac{W1x(100-m)}{100-Sm}, \quad (1)$$

where W_1 is the thousand-kernel-weight, g; *m* is the moisture content, %; *Sm* is the standard moisture content, 14%.

The germination energy and laboratory germination of seeds were determined in a certified laboratory of agrochemistry and analytical research of the Institute of Agriculture of the Carpathian region of NAAS by germinating each variety in Petri dishes on filter paper under optimum conditions of 25°C in a dry-air thermostat TS-80. The ratio of seeds that germinated to the total number (100 pcs.) was used to determine the germination energy on Day 3, and the laboratory germination of seeds on Day 6. The seed yield was determined by continuous threshing with a Sampo-130 combine harvester from each plot, after which the seeds were weighed and recalculated to a standard moisture content of 8%.

The weather conditions during the years of research were characterised by higher monthly air temperatures and slightly lower precipitation compared to the long-term average. Figure 1 shows the hydrothermal coefficient (HTC), i.e., the moisture availability of the territory during the growing season of oil radish varieties. For the Western Forest-Steppe of Ukraine, the norm is 1.1-1.6; in 2022, the HTC was insufficient on average (0.87), in 2023 – excessive (1.66), and in 2024 – optimum (1.16).

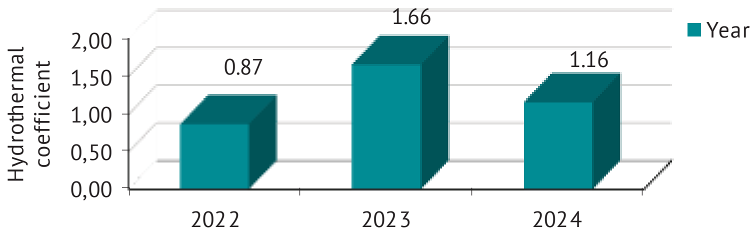

***Figure 1**. Moisture level (2022-2024)*
***Source:** compiled by the authors of this study*

The total area of the experimental plot was 60 m², and the accounting area was 50 m². The variants were placed systematically, with three replications: Zhuravka, Fakel is generally accepted in this zone. Soil cultivation includes primary tillage to a depth of 10-12 cm and ploughing to a depth of 20-22 cm. The previous crop was winter wheat. Sowing was performed in the third decade of April. The seeding rate of oil radish (*Raphanus sativum d. var. oleifera* Metrg.) varieties was 2.0 million germinating seeds per hectare. The seeds were treated with Modesto seed preparation, 48% FC (insecticidal-fungicidal action, 12.5 l/t). The seeding depth was 2-4 cm, and the sowing method was conventional row seeding (15 cm). Herbicides: Roundup, 48% AS (2-3 weeks before ploughing), Butyzan, 40% SC (1.75-2.50 l/ha); insecticides against pests – Calypso, 48% SC (0.25-0.40 l/ha). The study followed the standards of the Convention on Biological Diversity (1992) and the Convention on Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

Against the background of mineral nutrition of plants with $N_{30}P_{60}K_{70}$ + N_{50} (4-6 leaves) + N_{20} (peduncle of the main shoot) and pre-sowing treatment of seeds of Zhuravka and Fakel varieties with microfertilisers, the average yield of oil radish ranged from 3.33 t/ha in the control variant (without microfertilisers) to 3.69 t/ha when applying YaraVita Brasitrel Pro (1.0 l/t), which provided an increase of 0.36 t/ha. A slightly lower result, 3.62 t/ha, was obtained with the Vitazim microfertiliser (1.0 l/t), and the lowest result, 3.56 t/ha, was obtained with the Oracle Seeds (1.0 l/t) (Fig. 2). At $LSD_{0.05}$ = 0.10 t/ha, there was no significant difference between these variants. According to the statistical processing of the data, the greatest influence on the yield of oil radish seeds was as follows: 35% (A) – microfertilisers, 24 – variety (B), 8 – their interaction (AB), 33% – weather conditions (residual) (Fig. 3).

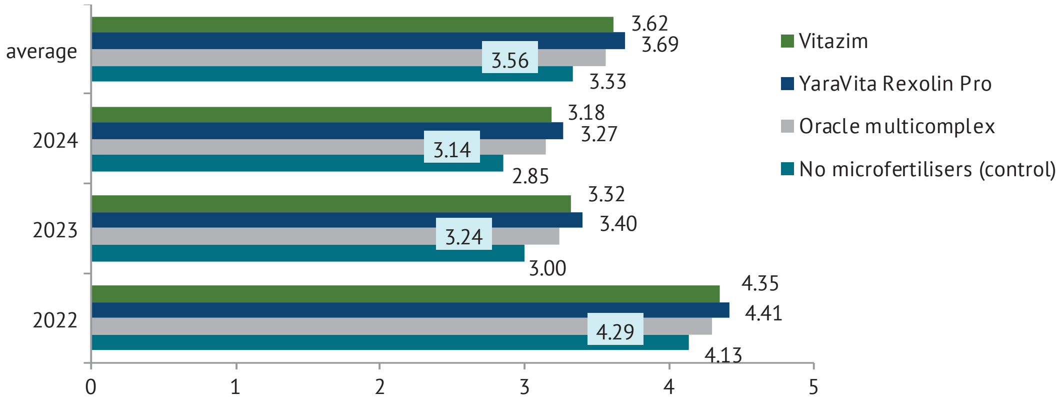

Figure 2*. Average seed yield of oil radish varieties depending on pre-sowing treatment with microfertilisers (2022-2024), t/ha*

Source: *compiled by the authors of this study*

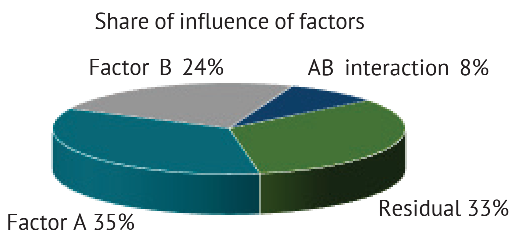

Figure 3*. Share of influence of factors on the yield of oil radish seed varieties (2022-2024), %*

Source: *compiled by the authors of this study*

Microfertilisers contributed to the formation of seeds with high sowing qualities, specifically, the thousand-kernel-weight (Table 1). The average indicators for the years of research suggest an increase in this indicator by 0.19 g compared to the control (without microfertilisers) when using Oracle Seeds (1.0 l/t), and the best effect was observed when using Vitazim (1.0 l/t) and YaraVita Brasitrel Pro (1.0 l/t), with increases of 0.27 g and 0.35 g, respectively. The highest thousand-kernel-weight (9.50-9.93 g) was provided by favourable weather conditions in 2022.

Table 1*. Effect of pre-sowing seed treatment with microfertilisers on the thousand-kernel-weight of oil radish varieties (2022-2024), g*

Pre-sowing treatment of seeds with microfertilisers	Application rate, l/t	Year			Average	± to control	
		2022	2023	2024			
No microfertiliser (control)	–	9.50	9.20	8.90	9.20	–	–
Oracle Seed	1.0	9.71	9.33	9.12	9.39	0.19	–
YaraVita Brasitrel Pro	1.0	9.93	9.52	9.21	9.55	0.35	0.16
Vitazim	1.0	9.84	9.41	9.15	9.47	0.27	0.08
*$LSD_{0.05}$		0.11	0.08	0.09			

Note: **LSD – least significant difference*

Source: *compiled by the authors of this study*

A direct strong correlation between the thousand-kernel-weight and yield was found (Table 2). In the control (without microfertilisers), this indicator was 0.816 and increased with their application to 0.943-0.963.

***Table 2**. Correlation (r) between the thousand-kernel-weight and the yield of oil radish depending on pre-sowing treatment with microfertilisers (2022-2024)*

Seed treatment with microfertilisers before sowing	Microfertiliser application rate, l/ha	Thousand-kernel-weight, g	Seed yield, t/ha	r
No microfertiliser (control)	-	9.20	3.33	0.816
Oracle Seed	1.0	9.39	3.56	0.943
YaraVita Brasitrel Pro	1.0	9.55	3.69	0.961
Vitazim	1.0	9.47	3.62	0.963

***Source:** compiled by the authors of this study*

The formed thousand-kernel-weight under the influence of optimum plant nutrition in favourable weather conditions provided a high percentage of germination energy of the collected seeds (Fig. 4). If in the control (without microfertilisers) it was 90.6%, then under their influence it increased by 0.6-1.7%. It was the highest in 2022 – 91.8-93.5%, and the lowest in 2024 – 89.5-91.4%. The rate of laboratory germination of harvested oil radish seeds in all years was high in 2022 – 95.2-96.8%, in 2023 – 94.5-95.9%, in 2024 – 93.8-94.8% (Fig. 5).

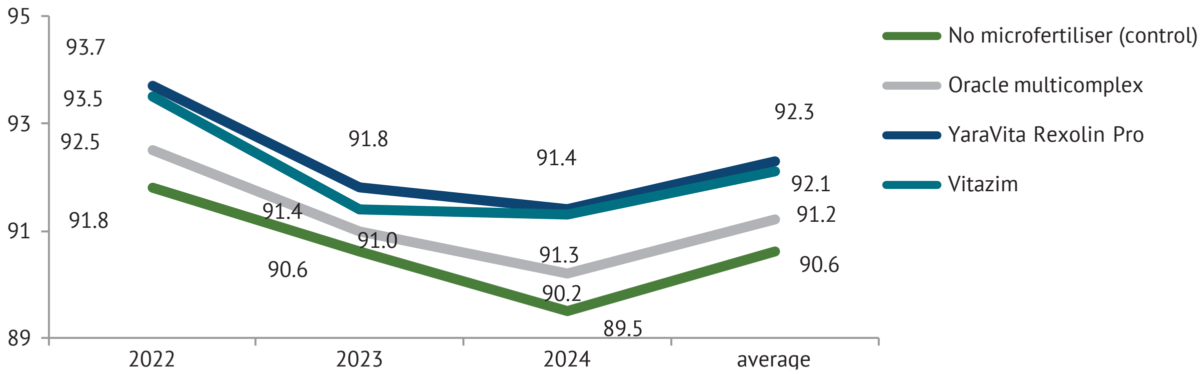

***Figure 4**. Influence of pre-sowing seed treatment with microfertilisers on the germination energy of oil radish varieties (2022-2024), %*
***Source:** compiled by the authors of this study*

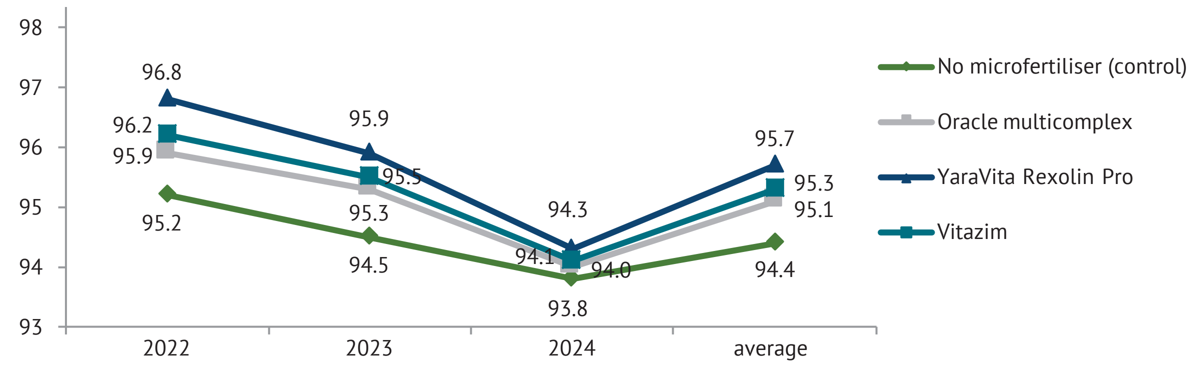

***Figure 5**. Average laboratory germination rate of oil radish seeds depending on pre-sowing treatment with microfertilisers (2022-2024), %*
***Source:** compiled by the authors of this study*

The effect of the studied microfertilisers was estimated at 0.6-1.2% compared to the control variant (without microfertilisers). The greatest influence on the formation of yield, thousand-kernel-weight, germination energy, and laboratory germination was observed during pre-sowing treatment with YaraVita Brasitrel Pro microfertiliser.

S. Verma *et al.* (2022) noted that the average yield of oil radish seeds in Ukraine is lower than in the leading EU countries due to insufficient fulfilment of the genetic potential of the crop varieties. To increase the yield by 40% or more, the reaction of the variety to the plant nutrition system is of great significance, meeting the nutrient needs of plants not only at the initial stages but throughout the entire plant life cycle. In this regard, R. Mondal *et al.* (2020) emphasised the expediency of using microfertilisers, which allows quickly eliminating nutrient deficiencies and compensating for the effects of abiotic and biotic stresses. To increase the efficiency of fertiliser use in advanced oilseed cultivation technologies, it is advisable to apply nitrogen in stages (Mishchenko *et al.,* 2020; Lövgren, 2022).

P. Banerjee *et al.* (2019) emphasised the significance of finding ways to increase the yield of mustard seeds through foliar feeding with macro- and microfertilisers with a harmonious combination of different types, which will help to solve the problem of crop competitiveness and its attractiveness for production. The effectiveness of microfertilisers in pre-sowing seed treatment against mineral fertilisers has been pointed out by many scientists. V.V. Gamayunova and R.V. Zadyrko (2024) found that pre-sowing seed treatment with Bast Complex (0.5 l/t) and treatment of crops in the 'herringbone' phase with microelements – Boron (1 l/ha), Organic D-2M (2 l/ha), Bast Complex (1.5 l/ha) against the background of the main application of mineral fertilisers in the norm of $N_{15}P_{15}K_{15}$ contributed to an increase in the yield of oil flax seeds by 0.51-0.58 t/ha, which is 49.5-56.3%.

Y.G. Tsytsyura and Yu.O. Kovalchuk (2019) pointed to the recommended micronutrient fertilisers for the group of cruciferous crops containing boron, manganese, and zinc – NutriVant Plus Oilseed, Granubor Natur, Ecolist Micro RB, Ecolist Monobor, Rostok Oilseed, etc., which are reliable sources of trace elements that help maintain the balance of growth processes and ensure the qualitative differentiation of plant parts in a harmonious combination. V.M. Sendetsky (2018) substantiated the sunflower yield of 3.6 t/ha and oil yield of 2.03 t/ha under the condition of combined use of pre-sowing seed treatment and double spraying of plants during the growing season with Vermiodis at 4 l/ha.

M.Yu. Voloshchuk (2024) pointed out that providing white mustard plants with the necessary nutrients during the growing season is significant, and therefore the fertilisation system should be based on knowledge of the biological characteristics of the variety and the soil and climatic conditions of the growing zone. The largest increase in seed yield compared to the control (without fertiliser) – 2.46 t/ha – was achieved at the rate of mineral fertiliser application $N_{30}P_{90}K_{100}$ + N_{50} (BBCH 14-16) + N_{30} (BBCH 52-53), due to a 1.85 g greater thousand-kernel-weight. S.O. Butenko and J. PeiPei (2022) found that in the conditions of the northeastern Forest-Steppe of Ukraine, it is advisable to use a complex of growth regulators Bioforge and Fast Start to obtain seeds of white mustard of the White Princess variety with high quality indicators, which allows obtaining more than 2.2 t/ha of seeds and 0.6 t/ha of oil. For the Felicia grey mustard variety, the most effective is the use of growth regulators Anti-Stress, Agrinos, and Regoplan, which ensured the highest seed yield (1.86-1.89 t/ha) and oil yield (0.73-0.74 t/ha). Scientists say that with an optimum plant nutrition system that promotes the productivity of varieties, high economic performance can be achieved.

Thus, the research findings obtained by scientists allow the manufacturer to identify the most effective elements of oil radish cultivation technology that will not only increase yields but also ensure high sowing quality of the grown seeds of different generations. The nutrition system of an agronomically valuable crop, considering the latest innovative fertiliser developments, is narrow and insufficiently covered in scientific papers, which prompted this comprehensive research.

CONCLUSIONS

On grey forest surface-gleyed soils of the Western Forest-Steppe zone of Ukraine, on the background of $N_{30}P_{90}K_{100}$ with nitrogen fertilisation with N_{50} (BBCH 14-16) + N_{30} (BBCH 52-53), pre-sowing seed treatment with microfertilisers in combination with insecticidal-fungicidal preparation Modesto, 48% FC (12.5 l/t) was an effective agricultural measure in the technology of oil radish cultivation. The trace elements in the studied microfertilisers were in a chelated form available to plants, which, when they got into the seed, contributed to the activation of enzymes, improved its viability, as well as increased germination energy, and development intensity. This helped to increase the resistance of oil radish plants to adverse environmental conditions. Thanks to the humic substances contained in the micronutrient fertiliser, the plants intensified root formation, increased water and nutrient supply, which led to an increase in leaf surface area and increased net photosynthetic productivity. A balanced system of nutrition with mineral fertilisers at the rate of $N_{30}P_{90}K_{100}$ + nitrogen fertilisation + N_{50} (BBCH 14-16) + N_{30} (BBCH 52-53) and pre-sowing seed treatment with microfertilisers provided higher plant structure indicators, which contributed to yield increases. In 2022, the seed yield of oil radish varieties was 4.13-4.41 t/ha, in 2023 – 3.00-3.40, and in 2024 – 2.85-3.18 t/ha. The most effective microfertiliser was YaraVita Brasitrel Pro (1.0 l/t), which significantly exceeded Oracle Multicomplex (1.0 l/t) by 0.13 t/ha and insignificantly exceeded Vitazim (1.0 l/t) by 0.04 t/ha in terms of seed yield.

Favourable weather conditions during the years of research and optimum supply of varieties: Zhuravka, Fakel oil radish with nutrients, due to the rate of mineral fertilisers $N_{30}P_{90}K_{100}$ with additional fertilisation with nitrogen fertilisers N_{50} (BBCH 14-16) + N_{30} (BBCH

52-53) and pre-sowing treatment with microfertilisers together with insecticidal-fungicidal treating agent Modesto, 48% FC (12.5 l/t) contributed to the formation of harvested seeds of high sowing qualities, specifically, greater by 0.19-0.35 g – thousand-kernel-weight, 0.6-1.7% – germination energy and 0.6-1.2% – laboratory germination. Research on the effects of new forms of microfertilisers in pre-sowing seed treatment is particularly relevant for growing oil radish varieties on poor and acidic soils with natural fertility.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Формування посівних якостей насіння редьки олійної залежно від системи живлення в умовах Західного Лісостепу

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Анотація. Причинами обмеженого розповсюдження редьки олійної є недостатня кількість насіння через недосконалість елементів технології вирощування, що потребує додаткових наукових досліджень. Мета досліджень було вдосконалення технології вирощування сортів редьки олійної за рахунок системи живлення рослин. Методологічні дослідження базувалися на загальнонаукових і спеціальних методах. Дослідження здійснювали на експериментальній базі відділу насінництва та насіннєзнавства Інституту сільського господарства Карпатського регіону Національної академії аграрних наук України. За результатами отриманих у 2022-2024 рр. обґрунтовано, що низька природня родючість сірих лісових поверхнево-оглеєних ґрунтів Західного Лісостепу та недостатня забезпеченість у них форм мікроелементів зумовлюють низьку врожайність та якість насіння досліджуваної культури. Цю проблему можна вирішити, розробивши збалансовану систему живлення редьки олійної на основі інноваційних макро- і мікроелементів. За ефективної передпосівної обробки насіння мікродобривами сумісно з інсектицидно-фунгіцидною обробкою насіння протруйником Модесто, 48 % т. к. с. (12,5 л/т) та фоні внесення мінеральних добрив у нормі $N_{30}P_{90}K_{100}$ з підживленням азотними + N_{50} (основні стадія росту та фази розвитку – ВВСН 14-16) + N_{30} (ВВСН 52-53) достовірні прирости врожайності становили 0,23-0,36 т/га. Збалансоване живлення рослин сприяло поліпшенню посівних якостей насіння, зокрема маси 1000 насінин, енергії проростання та лабораторної схожості. Удосконалена система живлення редьки олійної з урахуванням внесення в технологію вирощування мінеральних добрив і хелатних мікродобрив може бути використана сільськогосподарськими підприємствами та фермерськими господарствами, які займаються вирощуванням культури на насіння, що дозволить збільшити виробництво насіннєвого матеріалу для розширення посівних площ у регіоні

Ключові слова: редька олійна; сорт; насіння; мінеральні добрива; мікродобрива; урожайність; посівні якості

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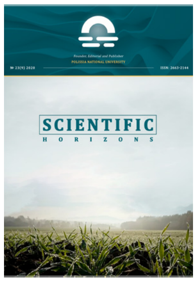

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Mycorrhization as a tool for regulating the stress tolerance of sweet cherry in sustainable agriculture

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Abstract. Encouraging the implementation of sustainable agriculture practices is a crucial strategy for plant health, biodiversity conservation, and addressing food security challenges. One of the key sustainable solutions involves the use of arbuscular mycorrhizal fungi to establish mycorrhizal associations. This study aimed to determine the impact of mycorrhization on the intensity of root colonisation by endomycorrhiza and the response of sweet cherry to the adoption of sustainable practices. The study investigated the effectiveness of root inoculation in sweet cherry using a formulation

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containing propagules of four fungal species: *Glomus intraradices*, *Glomus mosseae*, *Glomus agregatum*, and *Glomus etunicatum*. The research was conducted in the Southern Steppe of Ukraine. The experiment employed field, microscopic, biochemical, and statistical methods. The degree of root colonisation by arbuscular mycorrhizal fungi under mycorrhization was assessed. The ability of *Glomus* fungi to establish an effective mycorrhizal symbiosis with sweet cherry roots has been confirmed, as indicated by an increase in both the frequency of detection and the intensity of mycorrhizal infection. The impact of endomycorrhizal root inoculation on tree growth parameters was investigated. A tendency towards an increase in the annual stem diameter increment, total annual shoot growth, and leaf area was observed. Leaves of inoculated trees with AMF contained higher moisture levels and exhibited greater water retention capacity. The total chlorophyll (*a* + *b*) content and their ratio in leaf tissues of inoculated trees were significantly higher than in the control. A substantial increase in ascorbate and phenolic compounds was recorded in the leaves of mycorrhized trees. Root inoculation with arbuscular mycorrhizal fungi enhanced the activity of antioxidant enzymes while reducing the content of malondialdehyde. These findings may support the promotion and implementation of organic sweet cherry cultivation technologies in line with the Sustainable Development Goals and the European Green Deal initiatives

Keywords: *Prunus avium* L.; arbuscular mycorrhizal fungi; trees; symbiosis; sustainable practices; adaptability; biopreparation

INTRODUCTION

Sustainable fruit production plays a pivotal role in addressing a nation's food security challenges, as fruits are an essential component of a healthy diet. Supporting agriculture in achieving sustainable development goals is paramount, as the health of a population directly influences both their well-being and the resilience of ecosystems. Strategic goals in transforming food systems involve finding solutions that embody the core principles of sustainable agriculture and introduce innovative approaches to balanced nutrition. The role of fruits within food systems is interconnected with numerous United Nations Sustainable Development Goals. Among the most valued fruits and a leading crop in many countries is the sweet cherry (*Prunus avium* L.). The current surge in sweet cherry consumption has driven increased production. It is imperative to reassess agricultural practices, aligning them with the principles of the European Green Deal. This necessitates a search for best practices in transitioning to organic cultivation methods.

Consumers worldwide appreciate sweet cherries for their delicious taste and numerous health benefits, including both preventive and therapeutic properties. According to research by M. Faienza *et al.* (2020), sweet cherries are rich in natural antioxidants, which have a positive impact on human health by neutralising harmful radicals and reducing the risk of certain diseases. These fruits are characterised by high levels of monosaccharides and low caloric content (Gerasko *et al.*, 2022a). As noted by A. Nunes *et al.* (2021), the nutritional and dietary value of sweet cherries is enhanced by the presence of vitamins, organic acids, minerals, and biologically active substances.

The quality of fruit, particularly sweet cherries, is a subject of extensive scientific discussion. Organic sweet cherries are considered to be the most beneficial for human health. However, a common challenge in organic horticulture is reduced yields due to the exclusion of mineral fertilisers, chemical pesticides, and genetically modified organisms, as reported by F. Giampieri *et al.* (2022). Mycorrhization presents a promising avenue for developing new environmentally friendly innovations in agriculture. This could facilitate the broader application of biotechnology in agriculture, a key priority of the European Green Deal to ensure environmental and economic sustainability. As R. Kalamulla *et al.* (2022) highlight, arbuscular mycorrhizal fungi (AMF) play a crucial role in plant vitality, stimulating growth and development, and increasing yields by mitigating various plant stresses. Mycorrhizal symbiosis can alleviate both biotic (e.g., plant pathogens, weeds) and abiotic (e.g., salinity, drought, extreme temperatures, soil pH, heavy metals) stresses by altering a plant's physiological state.

Mycorrhization of fruit tree roots offers a sustainable solution for improving organic sweet cherry cultivation. As reported by G. Dar and P. Dunge (2020), mycorrhizal fungi can stimulate photosynthesis in fruit trees. Their research in Bulgaria highlighted the positive impact on the growth of sweet cherry trees, with increased trunk diameter and average annual shoot length. Mycorrhizal colonisation enhances the resistance of many plant species to diseases caused by soil pathogens. According to T. Gerasko *et al.* (2023), mycorrhizal associations can strengthen a plant's defence mechanisms or induce resistance by creating a less favourable environment for various pathogens. Thus, the use of AMF offers an alternative approach to disease control through induced resistance. M. Delaeter *et al.* (2024) suggest that inoculating plants with mycorrhizal fungi can become a sustainable agricultural practice to reduce the use of synthetic pesticides, considering AMF as an ecosystem service.

Research by R. Dhalaria *et al.* (2020) corroborates the ability of AMF to stimulate plant defence responses against various stressors. Scientists emphasise that the utilisation of arbuscular mycorrhiza is a promising strategy for mitigating the negative impacts of heavy metals on plants. Leveraging the symbiotic properties of AMF is an effective approach to enhancing the resilience of fruit crops to adverse environmental conditions. As noted by B. Dowarah *et al*. (2022), this effect is attributable to changes in plant physiology. AMF facilitate improved uptake of essential nutrients, particularly phosphorus, from the soil, especially under drought stress conditions. However, as cautioned by M. Wang *et al*. (2023), under conditions of insufficient mineral nutrition, drought, and heat, negative effects can occur where mycorrhizal fungi, instead of being symbiotic, become parasitic. Thus, it can be concluded that the influence of root mycorrhization on the physiological parameters of fruit trees, particularly sweet cherry trees, remains incompletely understood, as mycorrhization is rarely applied to this specific fruit crop.

A review of the literature highlights the need to explore ways to reduce agriculture's environmental impact through the use of mycorrhization. This practice promotes more sustainable agricultural technologies, enhancing crop resilience to stress and reducing the reliance on synthetic fertilisers and pesticides. In the context of the European Green Deal, mycorrhization exemplifies how agriculture can become more environmentally sustainable. The application of AMF for plant inoculation helps to reduce the use of chemical fertilisers, improve soil health, enhance plant resilience to climate change, and even contribute to biodiversity conservation. Consequently, mycorrhization is a crucial tool for achieving the Green Deal's objectives, from climate neutrality to the sustainable use of natural resources, assisting the agricultural sector in adapting to new demands and challenges in the face of climate change and environmental transformation.

This study aimed to investigate the impact of inoculating sweet cherry tree roots with mycorrhizal fungi on tree growth, leaf physiological parameters, and the enhancement of the crop's tolerance to drought conditions in the Southern Steppe of Ukraine.

MATERIALS AND METHODS

Experiments were conducted in Heorhiivske Village, Vilyansk District, Zaporizhzhia Region (47°59′13″ N, 35°16′28″ E), located in the Southern Steppe zone of Ukraine. The agrochemical characteristics of the soil at the experimental site are presented in Table 1.

***Table 1**. Agrochemical characteristics of the soil at the experimental plot*

Indicator		Method of determination	Actual value	Reference value
pH (saline)		–	6.5	–
Bulk density, g/cm^3		–	1.1	–
Humus content, %		Tyurin method	3.7	6.0
Nutrient content, mg/kg soil	N	Kornfield method	84	225
	P_2O_5	Chirikov method	103	200
	K_2O	Chirikov method	121	200

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

Analysis of the soil's agrochemical characteristics revealed that the soil solution had a near-neutral pH, and the soil density was optimal. The experimental plots were characterised by insufficient levels of humus and essential nutrients (N, P_2O_5, and K_2O). However, the soil in the experimental plots was entirely suitable for sweet cherry cultivation. The climate of the region where the research was conducted is very warm and very dry, with the sum of temperatures above 10°C ranging from 4,150 to 4,239°C (according to the Meteo Farm weather service). The amount of precipitation during the growing season is 210-230 mm, and the annual average precipitation is 443 mm, with uneven distribution and low relative humidity. It can be concluded that the climatic conditions are favourable for sweet cherry cultivation provided that irrigation is applied.

The experiment was conducted using a sweet cherry orchard (*Prunus avium* L.) of the Kazka cultivar grafted onto *Prunus mahaleb* rootstock. The trees were planted in 2015 according to a 7×5 m spacing pattern. The cold-hardy Kazka cultivar, characterised by early ripening, was created by crossing the cultivars Valeriy Chkalov and Drogana Zhovta. The Kazka cultivar has a pyramidal crown, pomegranate-red spherical slightly elongated fruits weighing up to 12 g with a small stone. The fruits are characterised by firm and uniform flesh and a sweet taste with a hint of honey. Active fruiting of this cultivar begins at the age of five, with up to 5 kg of fruit harvested from one tree. The average yield in the southern regions of Ukraine is about 30 kg. The experiment was designed as follows: 1. Control (no mycorrhization); 2. Mycorrhization of sweet cherry tree roots with the endomycorrhizal biopreparation MycoApply SuperConcentrate 10. This biopreparation consists of propagules of four species (AMF) of the genus *Glomus* – *G. intraradices* (*Rhizophagus intraradices*), *G. mosseae*, *G. etunicatum*, and *G. agregatum*. One gram of the preparation contains 22,000 propagules of *Glomus* fungi.

The total area of the experimental plot was 2 hectares. There were four replicates, and each variant included four model trees. The experimental variants were separated by buffer zones consisting of three rows of trees.

In autumn 2020, sweet cherry tree roots were mycorrhized with AMF according to the manufacturer's instructions. An aqueous suspension of the biopreparation was applied to five points around the base of each tree, within a radius smaller than the tree's canopy projection. The solution was introduced into predrilled holes at a depth of 10 cm at a 45-degree angle. The sweet cherry trees were cultivated using organic methods, which involved the use of only organic fertilisers and biopreparations. The soil in the inter-rows and tree circles was maintained under a cover crop of natural grasses (living mulch), which was mowed at a height of 10 cm and left on the soil surface as mulch. Throughout the growing season, the sweet cherry trees were irrigated 6-8 times, with 40 litres of water applied to each tree.

The intensity of mycorrhization of sweet cherry tree roots was determined in early June 2021 using a microscopic method. The first step of the study involved the collection and preparation of sweet cherry roots. Fourth and fifth-order roots with a total length of 15 cm were excavated from each tree and washed free of soil. Following the experimental period, roots were prepared for microscopic analysis. The roots were boiled in test tubes containing a 15% KOH solution for one hour in a water bath. Subsequently, they were rinsed with tap water and treated with a 1% HCl solution. In the third step, the roots were stained with 0.05% trypan blue in a lactic acidglycerinwater mixture (14:1:1). The stained roots were divided into 1 cm fragments and placed on a microscope slide, sequentially immersed in drops of glycerin (3 groups of 5 fragments). Microscopic examination was conducted at a magnification of 150 times. Five fields of view were examined on each 1 cm root segment, totalling 75 fields of view per slide. The frequency of mycorrhizal infection was calculated as a percentage, determined by the ratio of infected to uninfected root system sections. The intensity of root mycorrhization was visually assessed on a scale of 0 to 3: 0 – no infection; 1 – sporadic infections; 2 – moderately infected roots; 3 – heavily infected roots.

Standard methods were used to measure the biometric parameters of the sweet cherry trees. To calculate annual trunk increment, the diameter was measured at a height of 0.3 m above the graft union using callipers in October 2020 and 2021. The total annual shoot growth was estimated by multiplying the number of new shoots on a tree by their average length in October 2021. For phytochemical analysis, sweet cherry leaves were collected in June 2021 during the fruit ripening stage. Ten leaves were collected from each tree. These leaves were sampled from the middle of one-year-old shoots on the south side of the crown. A 1 cm^2 section was punched out of each leaf and weighed. Leaf area was calculated using the following formula (1):

$$S = \frac{M \times n \times S_1}{M_1}, \tag{1}$$

where M is the mass of leaves in the sample, g; n is the number of punched fragments; S_1 is the area of one punched fragment, cm^2; M_1 is the mass of punched fragments in the sample, g.

Specific leaf area was determined by dividing leaf mass by leaf area. The total moisture content in the leaves was determined by weighing before and after drying at 105°C to a constant mass. Water-holding capacity was calculated as the ratio of water lost (after 24 hours of wilting) to total moisture content (Gerasko *et al.,* 2023). The content of chlorophylls *a* and *b* (mg m^{-2}) in sweet cherry leaves was determined spectrophotometrically based on the light absorption of an acetone extract of the leaf tissue. The intensity of lipid peroxidation was determined by the content of malondialdehyde (MDA), which at 95°C in an acidic environment reacts with thiobarbituric acid to form a pink-coloured trimethyl complex with a maximum absorption at 535 nm. The results were expressed as nmol MDA per gram of plant material (Gerasko *et al.,* 2022b). Catalase activity (CAT, EC 1.11.1.6) was determined spectrophotometrically by the remaining undecomposed hydrogen peroxide. The results were expressed as µmol H_2O_2/g·min. Ascorbate peroxidase activity (APX, EC 1.11.1.11) was determined by the remaining unoxidised ascorbic acid by titration with a 0.001 N solution of Tillmans reagent (2,6-dichlorophenolindophenol). The results were expressed as mg of oxidised ascorbate per gram of fresh weight. Polyphenol oxidase activity (PPO, EC 1.10.3.1) was determined by measuring the optical density (at 420 nm) of the products of pyrogallol oxidation. The results were expressed in arbitrary units per gram of fresh tissue per minute.

Peroxidase activity (PO, EC 1.11.1.7) was determined spectrophotometrically by measuring the oxidation of indigo carmine (at a wavelength of 610 nm against distilled water). The decomposition of hydrogen peroxide by peroxidase releases oxygen, which oxidises indigo carmine, resulting in a colour change from blue-green to yellow-pink. The results were expressed as mkat/g of plant material. Sugar content (%) in leaves was determined spectrophotometrically by the reduction of picric acid (2,4,6-trinitrophenol) to picramic acid. Titratable acidity (%) was determined by titration with NaOH. Phenolic compound content was determined using the FolinCiocalteu reagent spectrophotometrically at 765 nm, corresponding to the concentration of phenolic substances expressed as gallic acid (GA) and expressed as mg GA per 100 g of fresh weight (Yaman, 2022). The content of ascorbic acid and glutathione was determined based on their reducing properties and expressed as mg/100 g of fresh weight.

Laboratory analyses were performed in three biological replicates. The results were statistically analysed using analysis of variance. Significant differences were determined at $P < 0.05$: a) using the least significant difference for biometric parameters of sweet cherry trees; b) using Student's t-test for the frequency and intensity of mycorrhizal infection, and for physiological and phytochemical parameters of leaves. All data were analysed using Microsoft Excel 2010. 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

Evaluation of the treated plants revealed a positive impact of the biopreparation on the development of a symbiotic association between mycorrhizal fungi and sweet cherry tree roots (Table 2).

***Table 2**. Frequency of detection and intensity of mycorrhizal infection in sweet cherry tree roots, $\bar{M} \pm m$*

Variant	Frequency of detection, %	Intensity, score
Control (without mycorrhization)	14.0 ± 0.49	1.3 ± 0.02
Mycorrhization with AMF	98.5 ± 0.06*	2.5 ± 0.02*

Note: ** – difference is significant at $P \leqslant 0.05$*
Source: *developed by the authors*

On the control variant (without root mycorrhization), native mycorrhizal fungi were detected. Inoculation of roots with the endomycorrhizal biopreparation MycoApply Superconcentrate 10 increased the frequency of mycorrhizal infection by 7 times. This led to almost complete colonisation of the roots by endomycorrhizal fungi. The frequency of mycorrhizal infection was as high as 98.5%. AMF colonisation of sweet cherry tree roots using MycoApply Superconcentrate 10 increased the intensity of mycorrhizal infection by 1.9 times compared to the control trees (without inoculation). This indicates successful mycorrhization of all trees in the experimental variant using AMF inoculation. The use of AMF positively influenced the growth and development of the aboveground system of sweet cherry trees inoculated with the MycoApply Superconcentrate 10 biopreparation (Table 3). Mycorrhization of sweet cherry tree roots led to a trend towards increased annual diameter increment of the trunk by 9% compared to control trees (without inoculation). Similarly, the use of the endomycorrhizal biopreparation MycoApply Superconcentrate 10 promoted a 10% increase in total annual shoot growth compared to the control. However, these differences were not statistically significant. Mycorrhization of sweet cherry tree roots with AMF resulted in the maximum leaf area growth, reaching 67.8 m^2/tree. This value is significantly higher by 8% compared to the control trees. This confirms the positive effect of endomycorrhiza on the growth parameters of sweet cherry trees. Research has shown a positive impact of mycorrhization of sweet cherry tree roots with the endomycorrhizal biopreparation MycoApply Superconcentrate 10 on the total moisture content and water-holding capacity of leaves (Table 4).

***Table 3**. Growth parameters of sweet cherry trees with root mycorrhization with AMF*

Variant	**Annual trunk diameter growth, cm**	**Total annual shoot growth, m/tree**	**Total leaf area, m^2/tree**
Control (without mycorrhization)	1.1	45.4	62.5
Mycorrhization with AMF	1.2	50.1	67.8
LSD_{05}	0.52	4.91	5.29

Source: *developed by the authors*

***Table 4**. Physiological parameters of sweet cherry leaves under root mycorrhization with AMF, $\bar{M} \pm m$*

Variant	**Total moisture content, %**	**Water-holding capacity, %**	**Specific leaf mass, g/m^{-2}**
Control (without mycorrhization)	54.9 ± 0.46	87.2 ± 0.75	82.4 ± 4.25
Mycorrhization with AMF	57.9 ± 0.49*	94.5 ± 0.81*	75.2 ± 4.43

Note: ** – difference is significant at $P \leqslant 0.05$*
Source: *developed by the authors*

Inoculation of sweet cherry tree roots with AMF resulted in a significantly higher total moisture content (by 5%) compared to control trees without endomycorrhizal inoculation. Under the influence of the endomycorrhizal biopreparation MycoApply Superconcentrate 10, the waterholding capacity of leaves increased significantly to 94.5%. This is 8% higher compared to the control trees. The water-holding capacity of sweet cherry leaf tissues indicates the content of free water within them. The increased water-holding capacity of leaves following AMF inoculation contributes to the adaptation of sweet cherry trees to drought stress. Specific leaf area in the experimental trees with root mycorrhization using the MycoApply Superconcentrate 10 biopreparation decreased significantly by 9% compared to the control variant. In sweet cherry leaves, an increase in the accumulation of chlorophylls *a* and *b* was observed following root mycorrhization with the MycoApply Superconcentrate 10 biopreparation (Table 5).

***Table 5**. Chlorophyll content and ratio in sweet cherry leaves under root mycorrhization with AMF, $\bar{M} \pm m$*

Variant	Chlorophyll content (*a* + *b*) per leaf area, mg/m^{-2}	Chlorophyll *a/b* ratio
Control (without mycorrhization)	278.5 ± 19.52	1.7 ± 0.04
Mycorrhization with AMF	325.2 ± 22.13*	1.8 ± 0.04*

***Note:** * – difference is significant at $P \leqslant 0.05$*
***Source:** developed by the authors*

Mycorrhization of sweet cherry tree roots led to a 17% increase in the content of chlorophylls *a* and *b* in sweet cherry leaves compared to the non-inoculated control. Inoculation with endomycorrhizal fungi also resulted in a 6% increase in the chlorophyll *a/b* ratio in sweet cherry leaves compared to the control. Based on these findings, it can be concluded that inoculating sweet cherry tree roots with AMF induced an adaptive reorganisation of the photosynthetic apparatus to mitigate the effects of stress factors. The increase in the chlorophyll *a/b* ratio as a result of mycorrhization can be attributed to hormonal stimulation by AMF. Mycorrhizal fungi stimulate the efficiency of the photosynthesis process. Mycorrhization of sweet cherry tree roots had a significant impact on the phytochemical composition of sweet cherry leaves (Table 6).

***Table 6**. Phytochemical composition of sweet cherry leaves under root mycorrhization with AMF, $\bar{M} \pm m$*

Variant	Sugars, %	Titrated acids, %	Phenolic compounds, mg GA/100 g	Ascorbate, mg/100 g	Glutathione, mg/100 g
Control (without mycorrhization)	2.8 ± 0.22	1.3 ± 0.08	45.1 ± 3.55	10.2 ± 0.77	34.6 ± 2.29
Mycorrhization with AMF	3.0 ± 0.23	1.4 ± 0.08	52.5 ± 3.80*	12.5 ± 0.63*	36.5 ± 2.34

***Note:** * – difference is significant at $P \leqslant 0.05$*
***Source:** developed by the authors*

In sweet cherry leaves treated with the endomycorrhizal biopreparation MycoApply Superconcentrate 10, the content of phenolic compounds and ascorbic acid increased significantly by 16% and 23%, respectively. Mycorrhization of sweet cherry roots also showed a trend towards increased content of glutathione, sugars, and titratable acids (by 6%, 7%, and 8%, respectively). However, this increase was not statistically significant. Analysis of the obtained data revealed that mycorrhization of roots with endomycorrhiza significantly reduced the damage from lipid peroxidation in sweet cherry leaves, as the MDA content decreased by 29% (Table 7).

***Table 7**. MDA content and antioxidant enzyme activity in sweet cherry leaves under root mycorrhization with AMF, $\bar{M} \pm m$*

Variant	MDA, nmol/g	CAT, µmol H_2O_2/g·min	APX, mg oxidised ascorbate/g	PPO, a.u./g·min	PO, mkat/g
Control (without mycorrhization)	64.5 ± 4.65	7.3 ± 0.15	5.8 ± 0.18	11.3 ± 0.45	6.9 ± 0.43
Mycorrhization with AMF	45.9 ± 4.29*	7.7 ± 0.17*	6.6 ± 0.25*	15.1 ± 0.53*	12.3 ± 0.37*

***Note:** * – difference is significant at $P \leqslant 0.05$*
***Source:** developed by the authors*

In sweet cherry leaves treated with the endomycorrhizal biopreparation MycoApply Superconcentrate 10, the activity of antioxidant enzymes increased significantly. The most significant increase was observed in peroxidase activity, which was 78% higher compared to the control. Mycorrhization of tree roots with endomycorrhiza resulted in increased activity of catalase, ascorbate peroxidase, and polyphenol oxidase by 5%, 14%, and 34%, respectively, compared to the control variants. Thus, the use of root mycorrhization significantly increases the adaptability and tolerance of sweet cherry trees to abiotic stress conditions. Therefore, mycorrhization can become an important tool for achieving the goals of the European Green Deal, contributing to the preservation of ecosystems, reducing the impact of agriculture on the environment, and increasing the resilience of crops to climate change.

DISCUSSION

In this study, sweet cherry trees were grown in association with natural vegetation, as the orchard soil was maintained under grassing down (living mulch). As reported by A. Trinchera *et al.* (2019), mycorrhizal fungi more readily establish symbioses with wild grasses than with cultivated plants. This co-existence with a living mulch and mycorrhizal fungi brings both positive outcomes (the roots of "living mulch" always maintain a "reserve" of mycorrhizal fungi and other beneficial microbes) and risks. Under stressful conditions (drought, nutrient deficiency), mycorrhizal fungi may colonise grasses at the expense of trees, reducing nutrient content and chlorophyll levels in leaves. However, under optimal moisture and fertilisation conditions (irrigation, organic fertilisation), mycorrhization of sweet cherry tree roots with *Glomus* species can have a positive impact on both tree growth and leaf physiology. This is supported by the results obtained in the study by J. Ilic (2023).

The significant increase in the frequency and intensity of mycorrhizal infection in sweet cherry tree roots indicates the viability of the mycorrhizal fungi strains within the MycoApply Superconcentrate 10 preparation, their adaptability to the arid conditions of the Southern Steppe of Ukraine (including overwintering), and their competitiveness against the local mycoflora (14% of roots were already infected). This also confirms the ability of sweet cherry trees to establish symbiosis with endomycorrhizal fungi, as supported by the research of scientists S. Afonso *et al.* (2022). The study observed a trend towards improved growth parameters in sweet cherry trees as a result of the mycorrhizal symbiosis, confirming previously published data on the mycorrhization of fruit trees. Scientists V. Petrova and S. Krumov (2023) have investigated that the application of AMF positively influenced the growth characteristics of 16 new sweet cherry cultivars. Treated trees showed an increase in trunk diameter and average annual shoot length. Research by Y. Shao *et al.* (2023) established an increase (by 24%) in the cross-sectional area of the trunk of three apple cultivars (Topaz, Odra, and Chopin) and a promising clone (U 8869) after four years of mycorrhization in combination with growthstimulating bacteria.

According to the researchers in the current study, the stimulatory effect of mycorrhizal fungi on their plant partners is linked to the synthesis and supply of biologically active compounds to the plant via the mycorrhizal network. The observed increase in leaf moisture content and waterholding capacity following root mycorrhization aligns with the findings of other researchers. In the studies of T.A. Madouh and A.M. Quoreshi (2023), AMF colonisation enhanced plant tolerance to drought stress through complex physiological changes, including increased photosynthesis, antioxidant enzyme activity, and reduced malondialdehyde levels. The improved water supply to plants following root mycorrhization is attributed to the increased absorptive surface area of the roots of mycorrhizal plants, as described in the scientific article of M. Chandrasekaran (2022).

The observed decrease in specific leaf area following root mycorrhization suggests that mycorrhizal plants were less affected by abiotic stresses (heat, drought). It has been reported that an increase in specific leaf area is an adaptive response of plants to heat, drought, and excessive insolation, as leaves with a higher specific mass have lower concentrations of cytoplasmic compounds and higher concentrations of cell wall compounds (especially lignin). Furthermore, it is a known physiological phenomenon in sweet cherry leaves that as their area increases, their specific mass decreases (Bondarenko, 2019). The significant increase in chlorophyll ($a + b$) content and the chlorophyll a/b ratio in the leaves of mycorrhizal trees indicates the stimulation of photosynthetic activity by mycorrhizal fungi. Similar effects have been reported in the studies of other scientists (Bi *et al.,* 2021). The increase in chlorophyll content and ratio also indicates the successful overcoming of abiotic stresses by plants (Sharma *et al.,* 2023). Significant positive correlations between AMF colonisation and chlorophyll (a and b) and carotenoids were found in research by W. Chen *et al.* (2020). This confirms the beneficial role of mycorrhizal fungi in the formation of photosynthetic pigments. The increase in chlorophyll content may be related to increased P and Mg uptake under the influence of mycorrhizal fungi. The elevated chlorophyll parameters indicate that AMF increase photosynthetic C fixation, which contributes to the progression of photosynthesis.

In studies conducted by A. Villani *et al.* (2021) and A. Wahab *et al.* (2023), increases in ascorbic acid and phenolic compound content, significant decreases in malondialdehyde content, and increases in antioxidant enzyme activity were observed in sweet cherry leaf tissues following root mycorrhization. This supports the hypothesis that mycorrhizal fungi play a protective role against various abiotic stresses by stimulating the production of tissue antioxidants in plants and increasing the activity of antioxidant enzymes. Based on the quantitative data obtained in these studies regarding phenolic compound and ascorbic acid content, sweet cherry leaves may compete with the fruit in terms of antioxidant capacity, as previously highlighted in research by K. Dziadek *et al.* (2019). Thanks to a better understanding of the applications and benefits of AMF, there is a real possibility of using them to promote sustainable agricultural production. Therefore, the results of this research indicate a significant positive impact of mycorrhizal fungi on the growth, physiological state, and resistance of sweet cherry trees to abiotic and biotic stresses. Due to the ability of mycorrhiza to improve nutrient uptake, enhance photosynthetic activity, and activate antioxidant defence in plants, its application can become an important ecological tool for increasing the efficiency of organic horticulture.

CONCLUSIONS

The roots of the control trees in this study were partially colonised by native mycorrhizal fungi (14%). Inoculation with the biopreparation MycoApply Superconcentrate 10 significantly increased both the frequency and intensity of mycorrhizal infection in sweet cherry tree roots. This confirms the successful mycorrhization of tree roots using AMF. Inoculated trees exhibited an increased annual trunk diameter increment (by 9%) and total annual shoot growth (by 10%) compared to the control (without AMF inoculation). Root mycorrhization resulted in a significant increase in the leaf area of sweet cherry trees (by 8%). Moreover, the mycorrhization of roots with AMF led to a significant increase in total leaf moisture content (by 5%) and water-holding capacity (by 8%) compared to the control trees. This, in turn, enhances the plant's adaptation to drought conditions when soil moisture is limited. A significant decrease in specific leaf area (by 9%) was observed in mycorrhizal trees.

Inoculation of sweet cherry tree roots with endomycorrhizal fungi resulted in a significant increase in both chlorophyll *a* and *b* content (by 17%) and their ratio (by 6%) in leaves. This confirms the stimulatory effect of mycorrhizal fungi on photosynthetic processes in sweet cherry leaves. Furthermore, a significant increase in phenolic compounds (by 16%) and ascorbic acid (by 23%) was observed following root inoculation with MycoApply Superconcentrate 10. While there was a trend towards increased levels of glutathione, sugars, and titratable acids in sweet cherry leaves inoculated with AMF, these differences were not statistically significant. A notable decrease in MDA content (by 29%) was observed in sweet cherry leaves following root inoculation with endomycorrhiza, indicating reduced lipid peroxidation damage. Mycorrhization significantly increased the content of phenolic compounds and ascorbic acid in leaves, suggesting enhanced antioxidant capacity. Although the content of sugars, titratable acids, and glutathione showed a trend towards increase, these differences were not statistically significant. The activity of antioxidant enzymes, including catalase (increased by 5%), ascorbate peroxidase (increased by 14%), and polyphenol oxidase (increased by 34%), was significantly higher in sweet cherry leaves inoculated with MycoApply Superconcentrate 10. The most significant increase was observed in peroxidase activity (by 78%), which likely contributed to the decreased MDA content in leaf tissues. These findings demonstrate the potential of root inoculation with AMF to establish a robust mycorrhizal symbiosis and enhance sweet cherry tree adaptation to drought stress. This supports the promising future study of AMF efficacy for forming effective mycorrhizal associations on sweet cherry tree roots and enhancing plant stress resistance to abiotic and biotic factors in sustainable agriculture.

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CONFLICT OF INTEREST

None.

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Мікоризація як інструмент регуляції стресостійкості черешні у зеленому сільському господарстві

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Анотація. Стимулювання імплементації сталих практик в сільському господарстві є важливим рішенням для здоров'я рослин, збереження біорізноманіття і вирішення проблем продовольчої безпеки. Одним із важливих сталих рішень є використання арбускулярних мікоризних грибів для функціонування мікоризних асоціацій. Метою роботи було з'ясувати вплив мікоризації на інтенсивність заселення коренів ендомікоризою та реакцію черешні для впровадження сталих практик. У роботі вивчали ефективність інокуляції коренів черешні препаратом, що містить пропагули 4-х видів грибів *Glomus intraradices*, *Glomus mosseae*, *Glomus agregatum* і *Glomus etunicatum*. Дослідження проводили в умовах Південного Степу України. У процесі експерименті було використано такі наукові методи – польовий, мікроскопічний, біохімічний і статистичний. Оцінено ступінь заселення коренів черешні АМГ за дії мікоризації. Доведено здатність грибів роду *Glomus* розвивати ефективний мікоризний симбіоз з коренями черешні, оскільки збільшилася частота виявлення і інтенсивність мікоризної інфекції. Досліджено вплив інокуляції коренів черешні ендомікоризою на ростові показники дерев. Спостерігали тенденцію до збільшення річного приросту діаметру штамбу, сумарного річного приросту пагонів і площі листків. Листки інокульованих дерев АМГ містили більше вологи і мали більшу водоутримувальну здатність. Сума хлорофілів *a* і *b* та їх співвідношення у тканинах листків інокульованих дерев були істотно вищими порівняно з контролем. У листках мікоризованих дерев істотно збільшився вміст аскорбату і фенольних речовин. Інокуляція коренів АМГ спричинила збільшення активності антиоксидантних ферментів і зменшення умісту малонового діальдегіду. Ці результати можуть сприяти просуванню і впровадженню органічних технологій вирощування черешні для досягнення Цілей сталого розвитку та ініціатив Європейського зеленого курсу

Ключові слова: *Prunus avium* L.; арбускулярні мікоризні гриби; дерева; симбіоз; сталі практики; адаптивність; біопрепарат

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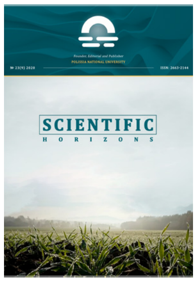

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The role of restoring degraded soils in ensuring food security in the agro-industrial sector

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Abstract. The study was devoted to the analysis of the state of degraded soils in Ukraine, their impact on agricultural productivity and identification of effective approaches to land restoration to ensure food security. The study used a comprehensive approach, including analysis of scientific and official sources, cartographic assessment of the spatial distribution of degraded land, economic assessment of yield losses using

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equations, and research on innovative methods of soil restoration, such as biochar, mulching, and microbiological fertilisers. The results were modelled in Excel, which allowed assessing the impact of innovations on the productivity and profitability of farms. The results showed that more than 40% of arable land in Ukraine is in a state of degradation: water erosion affects 25-30% of the area, most of all in the northern and western regions, wind erosion covers 10-15% in the steppe zone, and humus losses are recorded on 35% of the land, especially in the central part. Heavy metal contamination in industrial regions makes some soils unusable. The economic consequences of degradation include a decrease in wheat, corn, and sunflower yields by 20-30%, an increase in fertiliser costs to UAH 1,800 per hectare, and total losses reaching UAH 15 billion annually. Innovative approaches to restoration, such as biochar, mulching, green manure, and microbiological fertilisers, have shown high efficiency, providing an increase in yields by 15-25% in the first five years, reducing the use of chemical fertilisers by 15-30%, and significantly improving the ecological state of the land. The use of biochar in areas of organic matter deficiency allowed increasing humus by up to 12%, while mulching reduced moisture loss by 20%, making irrigation more efficient. Microbiological fertilisers have significantly reduced the level of soil pollution. The results obtained confirm that the introduction of regionally adapted recovery methods helps to reduce degradation processes and stabilise agroecosystems. This creates the basis for ensuring food security in Ukraine. The study also focused on the need to improve monitoring systems for rapid detection of degraded areas and the development of long-term soil resource management strategies

Keywords: land resources; humus; fertile layer; agricultural production; green manure; mulching

INTRODUCTION

The problem of soil degradation has become one of the most acute environmental and economic challenges for Ukraine, especially given the importance of agricultural production for the national economy. As a result of long-term intensive use of arable land without proper restoration, including erosion processes, humus loss, salinisation, and heavy metal pollution, a significant part of the soil has lost its fertility. During 2014-2024, the area of degraded land was steadily growing, which posed a threat to ensuring food security of the state. The significance of this problem was emphasised by A.O. Gorgots (2023), who analysed the structural components of land use restoration systems in Ukraine. The researcher pointed out the critical need to introduce effective soil restoration mechanisms to support the sustainable development of the agro-industrial complex. A similar emphasis was placed in the study by O.V. Voitseshchuk (2024), who highlighted the scientific and methodological foundations for the rational use of agricultural land, noting that the decline in soil fertility, combined with erosion processes, is becoming a major obstacle to the economic growth of the agricultural sector. One of the key problems in this area remains the loss of humus. A decrease in the natural supply of humus leads to a reduction in the biological productivity of land, which creates additional challenges for farmers and deepens the environmental problems of the regions (Melnychenko, 2024). The critical condition of Ukrainian soils was also the subject of monitoring studies conducted by S.V. Vitvitskyi *et al.* (2019). Monitoring revealed regional features of soil degradation: the most serious were erosion processes in the areas of Donbas and in the strip along the border of the Forest-Steppe with the Northern Steppe. The researchers emphasised the importance of integrated approaches to soil quality monitoring, which should be the basis for management decisions.

Research by V.F. Petrychenko *et al.* (1970) detailed the causal relationships between soil degradation and desertification. They identified several key factors: climate change, organic carbon scarcity, and anthropogenic pressure. The researchers emphasised the need to implement specialised programmes to combat desertification, which should be based on advanced scientific achievements. E. Berezhniak *et al.* (2022) noted that soil degradation is one of the most serious environmental problems in Ukraine, covering more than 40% of arable land that is subject to water erosion, humus loss, salinisation, and chemical pollution. The consequences of this process affect not only agricultural productivity, but also the state of the environment, disrupting the ecosystem balance and reducing the quality of water and soil resources. C.S. Ferreira *et al.* (2022) focused on soil degradation in the Mediterranean regions of Europe, where erosion and loss of organic matter significantly limit agricultural potential. The researchers emphasised that for successful recovery, it is necessary to consider regional climatic and socio-economic features. Their studies are also relevant for Ukraine, as its steppe regions are similar in characteristics to the Mediterranean zones and also suffer from droughts and wind erosion.

Analysis of current approaches to soil restoration conducted by J. Wang *et al.* (2023), demonstrated that remote sensing technologies can effectively detect critical degradation zones, creating the basis for implementing point-based measures. The research emphasised the importance of regular monitoring using satellites, which allows observing the dynamics of changes and quickly assessing the effectiveness of the implemented methods. Another important aspect is the relationship between soil degradation and food security. The study by P.M. Kopittke *et al*. (2019) examined increasing agricultural intensity in the face of growing food demand: the researchers emphasised that without a balanced approach, intensification can lead to irreparable soil degradation, reduced fertility, and reduced access to agricultural land for future generations. At the European level, research by P. Pereira *et al*. (2023) detailed the impact of agricultural practices on soil health, noting that poor resource management accelerates desertification and humus loss. They emphasised the need to review traditional land use methods and introduce innovative solutions adapted to local conditions.

Although there is a significant body of research on this topic, gaps remain in the economic rationale for soil restoration measures and the long-term impact of their implementation on food security. Research mainly focused on individual aspects of degradation (structural, chemical, environmental), but there was no comprehensive approach that would consider the regional specifics of the problem, financial costs, and potential productivity gains in the implementation of innovative technologies. The purpose of the study was to determine the economic feasibility and environmental effectiveness of modern methods of restoring degraded soils in the context of strengthening food security in Ukraine. Special attention was paid to the assessment of regional differences and the integration of innovative solutions that can increase the efficiency of agricultural production and contribute to environmental stability.

MATERIALS AND METHODS

The study was based on the analysis of scientific papers, government programmes, regulatory documents, and statistical data. The sample data included an assessment of soil conditions in agricultural regions of Ukraine that had a high level of degradation. The review included official data from the State Statistics Service of Ukraine, the Food and Agriculture Organisation (FAO) database (2025). Data from regional reports of agricultural farms and recommendations of agronomic centres were also analysed (Gusarova, 2024; Ukrainian development for…, 2024). The research process was based on an integrated approach to analysing the spatial distribution of degraded land. The main tool was the analysis of maps of degraded soils, namely, their territorial distribution (Soil erosion in Ukraine, 2025). This helped to identify critical areas and assess the scale of the problem. A qualitative assessment of each of the degradation zones was carried out based on cartographic models. This helped to identify critical zones that have the greatest impact on the productivity of the agro-industrial complex. Special attention was paid to areas with high intensity of water erosion (northern part of Kyiv Oblast and western part of Cherkasy Oblast), and zones with a lack of organic matter due to long-term agricultural turnover (Forest-Steppe and Steppe zones).

The economic aspects of soil degradation were estimated by calculating losses caused by reduced yields of major agricultural crops such as wheat, corn, and sunflower for the period 2021-2024. The methodology was based on comparing the average yield indicators on degraded land plots with similar indicators for land in proper agroecological condition. For this purpose, official statistics of the State Statistics Service (Statistics Ukraine "Plant Growing in Ukraine", 2022) were used. Key indicators of food security were analysed to assess the impact of soil degradation on ecosystems, agriculture, and populations. Key indicators included food availability, public accessibility, food quality, and supply stability. Food availability is an estimate of the output of major agricultural crops, such as wheat, corn, and sunflower. Accessibility to the population was determined by analysing the impact of changes in yields on food prices in regions experiencing soil degradation. The stability of supply was also evaluated – the dynamics of yield and its fluctuations under the influence of degradation factors, such as erosion, salinisation, and loss of humus.

The economic analysis of losses caused by soil degradation was carried out based on comparing the yields of major agricultural crops, such as wheat, corn and sunflower, on degraded land and land in proper agroecological condition. Land in proper condition was determined according to the following criteria: humus content of more than 3%, stable water retention capacity, no signs of erosion, salinity, or chemical contamination. Data on soil yield and quality characteristics were collected from official sources, such as statistical collections (Statistics Ukraine "Plant Growing in Ukraine", 2022), and regional reports of agricultural enterprises and databases of the State Statistics Service (Ukrainian development for…, 2024; The State Statistics Service summed up…, 2024). The calculation of losses was carried out in two key stages: determining the loss in yield and monetising these losses. The yield loss was calculated using the equation (1):

$$\Delta Y = Y_s - Y_d, \tag{1}$$

where Y_s – average yield on healthy land for 2021-2024 (t/ha); Y_d – yield on degraded land (t/ha); ΔY – difference between them.

The second stage involved monetisation of losses. Economic losses (L) were calculated using the equation (2):

$$L = \Delta Y \times P_c \times A, \tag{2}$$

where P_c – average market price for products (UAH/tonne); A – area of degraded land (ha). Purchase prices are based on the average annual performance of "Nibulon" for the period 2021-2024. This company was chosen as a source for price indicators due to its leadership in the grain market in Ukraine, which guarantees the representativeness of the data obtained. The company also occupies a leading position in the production and export of agricultural products, and its purchase prices are used as indicator prices in the market (Purchase prices, 2025). For greater accuracy, the monetisation process (Equation 2) also considered indirect costs caused by increased costs for nitrogen and potash fertilisers, soil preparation and irrigation, which become necessary due to the loss of humus and deterioration of the physical and chemical properties of the soil.

Land in proper agroecological condition was characterised by the following indicators: humus content of more than 3% and the absence of physical signs of erosion; optimal chemical parameters: soil pH in the range of 5.5-7.5; stable yield over the past three years, which had a deviation of 10% from the average annual level. The humus content and pH of the soil are indicated as reference parameters for chernozems of the Forest-Steppe and Steppe zones. For other soil types, these indicators can be adjusted depending on the natural conditions of the region and soil and agrochemical characteristics. The approach based on the application of equations (1) and (2) allowed conducting a detailed analysis of losses for each crop separately and obtaining an overall picture of degradation risks, which will contribute to the development of effective regional strategies for soil restoration.

In the process of analysing innovative approaches, several technologies were considered, in particular biochar (carbon-containing material produced by pyrolysis of organic waste); green manure (plants that are grown to improve the soil and increase its organic mass); mulching (a method that consists in covering the soil surface with a protective layer of plant material or special organic coatings); microbiological fertilisers (a complex of beneficial bacteria that stimulate plant growth and improve the absorption of nutrients from the soil). The effectiveness of each method was evaluated using a comparative cost-benefit analysis.

The efficiency assessment methodology was based on a comparison of regions where the main degradation factors clearly correspond to certain innovative methods (Poltava, Vinnytsia, Kherson, Dnipropetrovsk oblasts). This helped to determine the most economically substantiated solutions for implementation in degraded territories, considering their regional characteristics. The method of predicting the increase in soil yields based on the analysis of the results of the application of such technologies as biochar, green manure, mulching, and microbiological fertilisers was also used. The data of current studies were extrapolated and yield growth was predicted in the form of expected changes in productivity indicators for 3-5 years based on the results obtained considering the applied innovative approaches to soil restoration. To determine the impact of recovery methods on farm productivity, modelling was performed using Excel software suite. The results were based on the integration of a systematic approach to data selection, and qualitative analysis of modern technologies. Thus, the study creates a theoretical platform for further implementation of innovative approaches in the practice of the Ukrainian agro-industrial complex.

RESULTS

The link between soil degradation and food security is important, as soil degradation has a direct impact on agricultural productivity and the availability of basic food products for the population. Reduced soil fertility due to erosion, pollution, or depletion of natural resources leads to reduced crop yields. This creates not only economic difficulties for farmers, but also contributes to higher food prices. As a result, especially in the face of climate change and unstable weather conditions, countries facing soil degradation are becoming less able to meet domestic food demand, increasing their dependence on food imports, increasing food security risks. In addition, soil degradation not only reduces yields, but also increases the cost of agrotechnical measures. Due to the loss of land fertility, farmers are forced to use additional fertilisers and irrigation systems to support production, which, in turn, increases the cost of production. This increase in spending may make food less accessible to the general population, especially in countries where agriculture is the main sector of the economy. Moreover, additional economic pressures can lead to a decrease in the financial availability of agricultural products, which significantly complicates the situation with food security and health of the population, because worse economic opportunities force some of the population to choose cheaper, often low-quality products.

Thus, the relationship between soil degradation and food security not only highlights the need for government initiatives to combat soil degradation, but also serves as an important guideline for soil resource recovery strategies. Restoring soil fertility through the use of environmentally sustainable agricultural production methods is one of the key factors for ensuring food security in the context of global economic instability. It can also help reduce dependence on food imports, which, in turn, will ensure the stability of food production and availability in the domestic market, and increase the resilience of rural communities to climate change and extreme weather events.

Assessment of the level of soil degradation in Ukraine. The study showed that soil degradation is a critical environmental problem for the agricultural complex of Ukraine. Analysis of data from various sources, including the State Statistics Service of Ukraine and the FAO database (2025), shows that more than 40% of arable land is in a state of degradation, including erosion, humus depletion, salinisation, and pollution. Water erosion is one of the key problems of degraded land in Ukraine, especially common in the western, northern, and central regions (Pichura *et al.*, 2024). This problem primarily affects the western and northern regions (Polissia and Forest-Steppe zones), and the central part of the country. According to available data, water erosion in Ukraine covers 13.4 million hectares of land, of which 10.6 million hectares are arable land. Among them, 4.5 million hectares suffered moderate or severe degradation, and 68 thousand hectares completely lost the humus horizon. These consequences arose from the long-term environmentally unjustified exploitation of land resources and excessive ploughing of soils (Berezhniak *et al.*, 2022). Wind erosion accounts for 10-15% of all affected areas (Gusarova, 2024). The main cause of wind erosion is the lack of forest belts and intensive tillage. It is most common in the Southern Steppe regions, including Kherson and Mykolaiv oblasts, where wind storms annually carry up to 30 tonnes of soil per hectare. Humus loss is a problem about a third of soils, especially in the central and southern regions, are characterised by a low content of organic matter. In many areas, the humus content has dropped to below 2%, which critically affects soil fertility. The greatest losses of humus are observed in regions with long-term intensive agricultural use, such as the Kirovohrad Oblast.

Soil salinity is observed in steppe regions where irrigation systems are used without proper drainage. This causes the accumulation of salts on the soil surface, reducing its productivity and increasing degradation processes. Along with physical degradation, industrial regions such as Donetsk and Dnipropetrovsk oblasts experience soil contamination with heavy metals, radionuclides, and chemicals. These problems exacerbate the environmental situation and limit the suitability of soils for agricultural production. FAO (2025) data confirm that Kherson, Mykolaiv, and Kirovohrad oblasts are among the areas with the highest level of land degradation in Ukraine, where complex degradation is felt due to humus loss, water erosion, and drought. Cherkasy Oblast has a high level of water erosion due to its location in watersheds and clay soil structure. In the western regions of Ukraine, karst processes and intensive agriculture cause the loss of fertile layers (Table 1).

***Table 1**. Types of soil degradation in Ukraine and their share as of 2024*

Type of soil degradation	% of arable land area (32 million hectares)
Loss of humus and nutrients	43%
Over-compaction	39%
Siltation and crusting	38%
Surface water erosion	17%
Acidification	14%
Waterlogging	14%
Radionuclide contamination	11.1%
Wind erosion, loss of topsoil	11%
Contamination with pesticides and other organic substances	9.3%
Heavy metal contamination	8%
Salinisation, alkalinisation	4.1%
Water erosion, ravine formation	3%
Side effect of water erosion (siltation of water bodies, etc.)	3%
Reduction of the level of daytime surface	0.35%
Deformation of the earth's surface by wind	0.35%
Operation of drained peatlands	0.30%
Aridisation	0.21%

***Source:** created by the authors based on A. Gusarova (2024)*

During the study, it was found that soil degradation not only reduces fertility, but also leads to a deterioration in the quality of water resources due to soil flushing into river basins. Another important consequence of degradation is a decrease in biodiversity due to the loss of natural habitat, and an increase in the vulnerability of agricultural systems to climate change, such as droughts and heavy rains. Analysis of available cartographic materials and data from open sources helped to assess the current state of soil degradation in different regions of Ukraine. The study included thematic maps (Soil erosion in Ukraine, 2025), and reports from international organisations such as FAO (2025).

Water erosion is the main problem of the northern part of the Kyiv Oblast, in particular, the territories adjacent to the Dybynets reservoir. These areas are characterised by a complex terrain with numerous water breaks and slopes, where a significant part of the upper soil layer is washed away due to intense downpours. This reduces the productivity of arable land and creates additional risks for aquatic ecosystems where washed-out soil enters (Environmental passport of the Kyiv region, 2022). On arable land in the central regions, such as the Poltava and Kirovohrad oblasts, there is a decrease in humus content. In these regions, its level has decreased to values that are lower than optimal for ensuring stable yields by 1.5-2%. The main reasons for this degradation are the intensive use of soils in agriculture without proper use of organic fertilisers and green manure. Existing maps and reports indicate that the soils most affected by pollution are located in the industrial regions of Dnipropetrovsk, Zaporizhzhia, Luhansk and Donetsk oblasts (Gusarova, 2024). Exceeding the maximum permissible concentrations of heavy metals (lead, cadmium, mercury) in these zones is caused by the activities of metallurgical plants, mines, and chemical enterprises. This makes these soils unsuitable for agricultural use without special remediation measures. Soil degradation in Ukraine has a pronounced regional specificity due to both natural factors and anthropogenic impact (Fig. 1).

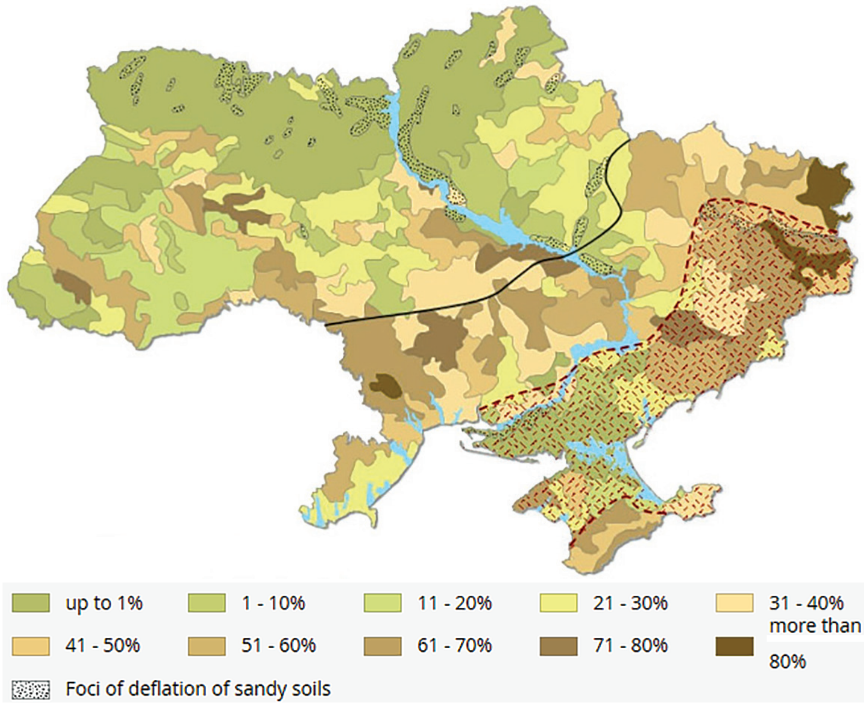

***Figure 1**. Degree of soil erosion in Ukraine*
***Source:** created by the authors based on Soil erosion in Ukraine (2025)*

This heterogeneity requires the development of individual soil restoration strategies that consider the local characteristics of each region, which directly affects food security. Special attention should be paid to integrated approaches that simultaneously reduce erosion, increase the content of organic substances in soils and reduce the level of pollution, which, in turn, ensures stable and sustainable agricultural production. This approach is important for maintaining soil fertility and contributes to crop growth, which directly affects the provision of food security of the population.

Economic consequences of soil degradation. Due to the gradual depletion of fertile land, the productivity of the main crops, such as wheat, corn, and sunflower, decreases in the range of 20-30%. This decrease in yield is primarily conditioned by the deterioration of the quality composition of soils, in particular, due to the loss of humus, increased erosion processes, and pollution. In addition to directly affecting productivity, soil degradation provokes an increase in production costs, which increase by an average of 15-20%. The cost of fertilisers, especially nitrogen and potash fertilisers, increases significantly, as the natural ability of the soil to provide crops with nutrients decreases (Zymaroieva *et al.,* 2021). It also becomes necessary to introduce special agrotechnical measures, such as deep tillage or covering with organic materials, to improve the structure of the land. Reducing the water retention capacity of the soil creates additional irrigation costs, which significantly increases the cost of growing crops in the arid regions of Southern Ukraine (Mykolaiv, Kherson, Zaporizhzhia oblasts) (FAO Soils Portal, 2025).

The study found that wheat suffers the greatest losses due to the high dependence of its yield on soil conditions. The crop is characterised by a 25% decrease in productivity in regions with degraded soils, accompanied by a 20% increase in growing costs, the total losses for which are estimated at UAH 4 billion. Similar trends are observed for corn and sunflower, with total losses reaching UAH 3 and 2.5 billion, respectively.

Calculations using equation (1) showed yield losses for the main agricultural crops on degraded land compared to land in proper agroecological condition (Table 2). According to the calculations of equation (2), the economic losses for each crop were determined by the average market prices and areas of degraded land.

***Table 2**. Calculation of yield losses and monetisation of losses (2021-2024)*

Crop	Yield on healthy land (t/ha)	Yield on degraded land (t/ha)	Yield loss (ΔY) (t/ha)	Average market price (UAH/ tonne)	Area of degraded land (ha)	Economic losses (UAH)
Wheat	4.5	3.2	1.3	6,500	1,000	8,450,000
Corn	6.8	4.9	1.9	5,200	1,500	14,820,000

***Source:** created by the authors based on Statistics Ukraine "Plant Growing in Ukraine" (2022), The State Statistics Service summed up the results of the 2023 harvest (2024), Purchase prices (2025)*

During the monetisation process, the costs of improving the physical and chemical properties of the soil were also considered. This includes costs (fertilisers, irrigation, soil preparation) for wheat, corn, and sunflower. The increase in the cost of nitrogen and potash fertilisers accounts for approximately 30% of total production costs, considering the loss of soil fertility. In particular, additional costs for fertilisers for corn amount to 20,000 UAH/ha, thus, for corn on degraded lands, additional costs amount to:

$$1500 \text{ ha} \times 20\,000 \text{ UAH/ha} = 30\,000\,000 \text{ UAH}.$$

In general, considering both direct and indirect costs, the total economic losses due to soil degradation for the regions can reach UAH 61,950,000. Thus, soil degradation leads to significant economic losses, which reduces the economic efficiency of agricultural production. Calculations show that only due to the loss of yield and increased costs for agrotechnical measures, the region can lose up to UAH 62 million annually. Such data are the basis for developing effective measures to restore soils and improve agronomic practices in regions affected by degradation. Economic losses from soil degradation in Ukraine are estimated under the condition of stable prices for agricultural crops and the absence of changes in agrotechnical practices. It was considered that soil degradation occurs at a standard rate, without significant changes in land cultivation technologies or investments in renewable methods. However, if the latest agronomic technologies are implemented in the future and the level of investment in soil restoration increases, economic losses may significantly decrease. The model does not consider the impact of inflation, changes in energy prices, or global climate changes that may have a significant impact on the situation in the future.

In addition, based on calculations (Table 2), economic losses from soil degradation amount to up to UAH 15 billion per year. However, these calculations assume that there are no significant changes in current agronomic practices and the effectiveness of state measures to restore degraded land. Considering possible unexpected factors, such as catastrophic climate change or potentially new methods of soil regeneration, these losses can both decrease and increase depending on further changes in the economy and agrotechnological sphere of Ukraine. Soil degradation also has larger economic consequences. Reducing the profitability of agricultural enterprises increases the cost of production, reducing the competitiveness of Ukrainian exports on world markets. A long-term decline in productivity threatens a significant decline in export volumes, which make up a significant share of the national economy. The social consequences are manifested in a decrease in employment in the agricultural sector and a decrease in the income of the rural population, which increases the vulnerability of certain groups of the population. Soil degradation leads to significant economic losses, which can threaten Ukraine's food security without timely intervention.

Effectiveness of innovative methods of soil restoration. The results of the study show that innovative methods adapted to the specifics of regions and types of soil degradation demonstrate high efficiency in restoring soil fertility and increasing their productivity. Several approaches applied in different natural and climatic zones of Ukraine are evaluated. The use of biochar in the regions under study significantly improved soil quality, especially in areas with a lack of organic substances, such as Forest-Steppe and parts of the Steppe. This method has shown high efficiency in regions where erosion has led to a loss of humus and a decrease in the water retention capacity of the soil. Three years after the introduction of biochar, the humus content increased to 12%, which became the basis for an increase in yield by 15-20% (Gorgots, 2023). Due to the reduction in the need for mineral fertilisers by 10%, the cost per hectare decreased by about UAH 800, which made this method economically profitable. Biochar showed the best results in the zone of the Poltava Oblast, where soil degradation is caused by intensive land use.

Sideration as a method of soil refinement proved to be effective in Forest-Steppe zones, where the level of organic matter is reduced due to long-term agricultural use (Zorin, 2024). Sowing green manure, especially legumes such as lupine and clover, increased the organic layer, improved soil structure and increased yields by 10% after two years. The use of green manure has reduced the use of nitrogen fertilisers by 30%, which has had a positive impact on the production economy and the ecological state of the region (Gorgots, 2023). The technique showed the greatest effectiveness in the Vinnytsia Oblast, where water erosion and humus losses are particularly common.

Mulching has proven effective in arid regions of Southern Ukraine, such as the Kherson Oblast, where wind erosion significantly complicates agriculture. Applying mulch to the soil surface reduced moisture loss due to evaporation by 20%, making irrigation more efficient and yields increased by 8-12% at no additional cost. Mulching also helped to reduce erosion processes by creating a protective layer that prevented soil loss (Onopriienko *et al.*, 2023). The method is well adapted for areas with low levels of organic matter, where other technologies have proven less effective. In regions with high heavy metal contamination, such as Dnipropetrovsk Oblast, the use of microbiological fertilisers has helped to activate phytoremediation processes and improve soil structure, reduce erosion, and maintain fertility. The introduction of biologics allowed increasing the yield by up to 25%, while reducing the use of chemical fertilisers by 15-20% (Ukrainian development for..., 2024). This method helps to increase natural soil fertility and reduce ecosystem pollution. Official data of the State Statistics Service of Ukraine and the FAO database for 2021-2024 were used to analyse the effectiveness of implementing innovative methods in soil restoration. The information covers generalised yield statistics, dynamics of degradation processes on arable land, and economic indicators such as additional income, cost reduction, and net profit (Table 3).

***Table 3**. Successful implementation of innovative methods of soil restoration (2021-2024)*

Method	Area	Year	Moisture loss (%)	Increase in yield (%)	Additional income (UAH/ha)	Cost reduction (UAH/ha)	Net profit (UAH/ha)
Biochar	Poltava	2021	-	+10	3,000	500	3,500
		2022	-	+12	3,600	600	4,200
		2023	-	+15	4,500	750	5,250
		2024	-	+18	5,400	900	6,300
Green manure	Vinnytsia	2020	-	+8	2,400	400	2,800
		2021	-	+10	3,000	500	3,500
		2022	-	+12	3,600	600	4,200
		2023	-	+14	4,200	700	4,900
		2024	-	+15	4,500	750	5,250
Mulching	Kherson	2020	-15	+5	1,500	300	1,800
		2021	-18	+7	2,100	420	2,520
		2022	-20	+9	2,700	540	3,240
		2023	-22	+10	3,000	600	3,600
		2024	-25	+12	3,600	720	4,320
Microbiological fertilisers	Dnipropetrovsk	2021	-	+12	3,600	600	4,200
		2022	-	+15	4,500	750	5,250
		2023	-	+18	5,400	900	6,300
		2024	-	+20	6,000	1,000	7,000

***Source:** created by the authors based on FAO Soils Portal (2025)*

The areas shown in Table 3 were selected to evaluate the effectiveness of innovative methods due to their representativeness and different types of degradation problems. Each area is characterised by certain problems associated with soil degradation, which corresponds to the conditions for applying the appropriate method. The Poltava Oblast was chosen because of the decrease in humus content in soils, which is characteristic of intensive land use. The use of biochar has significantly improved productivity indicators: already in 2021, the yield increased by 10%, reaching 18% in 2024. Net profit increased to UAH 6,300/ha due to lower fertiliser costs and increased yields. Sideration is used to increase the organic mass and reduce the impact of erosion common in the Forest-Steppe zone (Vinnytsia Oblast). The results showed an increase in yield from 8% in 2020 to 15% in 2024, which provided a net profit of UAH 5,250/ha. Reducing the cost of nitrogen fertilisers (by 30%) has made the method economically attractive for long-term implementation.

The southern regions of Ukraine, in particular, the Kherson Oblast, are characterised by wind erosion and high moisture losses. Mulching showed a steady reduction in moisture loss by up to 25% and a 12% increase in yield in 2024. Net profit increased to UAH 4,320/ha due to optimisation of irrigation and reduction of irrigation costs. Dnipropetrovsk Oblast was chosen because of the high level of heavy metal pollution, where microbiological fertilisers effectively restore the structure of soils and enhance their fertility. From 2021 to 2024, the yield increase reached 20%, and net profit increased to UAH 7,000/ha. Regional results showed that in the arid zones of the southern region (Kherson and Mykolaiv oblasts), mulching and biochar helped to compensate for losses due to erosion processes, and maintain productivity even in adverse weather conditions. In the Polissia area, where water erosion is the main threat, significant results have been achieved due to the introduction of anti-erosion technologies. The use of water management technologies, such as the design of terraces and irrigation systems, has improved soil moisture retention by 18-25% in regions with reduced precipitation.

According to the forecasts made based on extrapolation of the above data, the use of biochar, sideration, mulching, and microbiological fertilisers will contribute to increasing yields in different regions of Ukraine over the next 3-5 years (Fig. 2). It is expected that the introduction of these technologies will provide significant improvements in soil productivity, in particular, reducing erosion and increasing moisture retention, which will have a positive impact on the economic results of the agricultural sector.

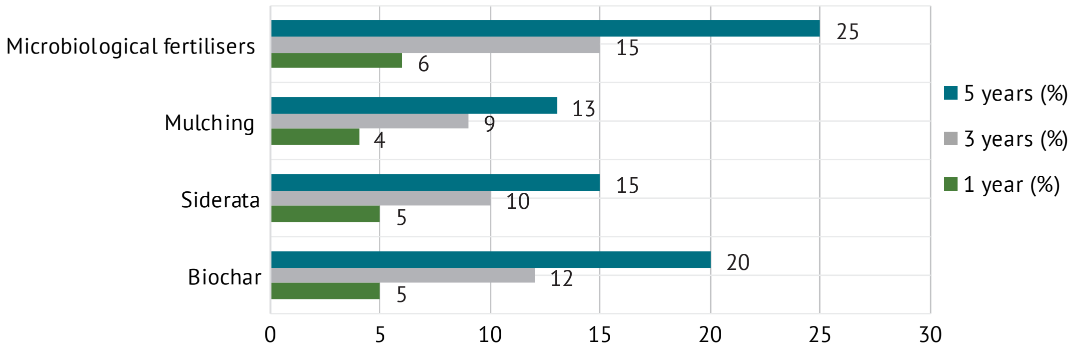

***Figure 2**. Potential yield growth depending on recovery methods*
***Note:** as a percentage of yield growth relative to degraded land*
***Source:** created by the authors*

The graph shows that the highest yield increase is predicted when using microbiological fertilisers, while the use of biochar implies a stable long-term increase in productivity. Green manure and mulching will provide gradual and even growth in the longer term. The data confirm that the choice of soil restoration method depends on the specific type of degradation, which highlights the importance of a differentiated approach to each situation to preserve food security. Biochar is optimal in regions with a low humus content, which helps to maintain soil fertility and increase agricultural production. Green manure is effective in areas with structural disorders of the soil, where its use helps to restore the physical characteristics of soils and ensures the stability of yields. Mulching is effectively applied in the face of wind erosion, reducing water loss and increasing crop resistance to drought, which is key to ensuring sustainable food production. Microbiological preparations are used in areas with chemical contamination, helping to clean soils of toxic compounds and restore their natural fertility. These innovative methods of soil restoration not only increase the productivity of the agricultural sector, but also reduce environmental risks, thereby making a significant contribution to stable food supplies, which is an important aspect of Ukraine's food security.

Comprehensive assessment of the impact of soil restoration on food security. The analysis of the conducted research shows that the introduction of innovative measures to restore degraded soils not only reduces yield losses, but also significantly improves the economic and environmental indicators of agricultural production. The most significant increase is the yield, which varies between 15-25% within the first 3-5 years after the start of using innovative methods. This is ensured by restoring the humus balance, improving water retention capacity, and activating biological processes in the soil. An additional advantage is to reduce dependence on chemical fertilisers by increasing the natural fertility of the soil. This trend significantly contributes to the ecological balance in regions where intensive agriculture has led to pollution of water bodies and increased soil acidity. Reducing fertiliser costs has a direct impact on reducing the cost of growing major crops such as wheat, corn, and sunflower. According to the results of the study, cutting the use of nitrogen fertilisers by 25-30% reduces the cost of each hectare of arable land from UAH 1,500 to 1,800, depending on the crop, soil conditions and region. In regions where the organic matter of soils was restored due to the use of green manure and biochar (Poltava and Vinnytsia oblasts), farmers observed a decrease in the cost of mineral fertilisers by almost a third without reducing yields.

The combination of cost reduction with an increase in yield, which reaches 15-25% in the first three years after the introduction of innovative methods, provides a significant increase in the net profit of farms. For example, if the average annual wheat yield in regions using biochar increases from 3.5 to 4.5 t/ha, and the average grain price is 6,000 UAH/t, this adds 6,000 UAH/ha to the total income while maintaining costs at a minimum level. The study confirms that technologies such as mulching help to reduce moisture evaporation by 20%, which is especially important for the southern and arid regions of Ukraine, in particular, for the Kherson Oblast. This reduces the volume of water used for irrigation, and reduces the cost of electricity or fuel for the operation of irrigation systems. Estimates show that this optimisation reduces irrigation costs to 800 UAH/ha during the growing season. On the scale of a farm, this can mean saving tens of thousands of UAH, especially in large agricultural enterprises.

Technologies for restoring the soil structure through the introduction of biochar and mulching can reduce the need for deep ploughing and loosening. These measures usually require significant costs for fuel and maintenance of equipment. The use of biochar helps to improve the water retention capacity of the soil, which minimises the cost of repeated agrotechnical works, reducing the cost of land cultivation by about 100-200 UAH/ha, depending on the chosen technology. In general, the combined use of innovative methods can reduce production costs by 20-30% in regions with a high level of soil degradation. This contributes to a significant increase in the profitability of farms and increases their economic stability. Reducing direct costs for fertilisers, irrigation, and agrotechnical measures, together with increasing yields, lays the foundation for stable economic development of the agro-industrial sector.

Successful implementation and scaling of innovative approaches to the restoration of degraded soils requires a systematic approach that considers regional characteristics, technical availability, and cost-effectiveness of methods. Large-scale introduction of microbiological fertilisers is recommended in Forest-Steppe and Steppe regions where there is a critically low humus content (1.5-2%). These preparations can effectively activate the biological activity of soils and reduce dependence on mineral fertilisers by 15-20%. Due to the increase in natural fertility, the use of microbiological fertilisers can provide an additional increase in yield at the level of 10-25% after three years of use. In areas with frequent droughts, such as the Kherson and Mykolaiv oblasts, the introduction of mulching should be a priority. By reducing moisture evaporation by 20% and stabilising soil moisture, mulching allows maintaining crop productivity even in adverse climatic conditions. This approach reduces irrigation costs and reduces the need for water resources, which is critical for regions with significant water scarcity. In regions with high erosion activity, such as Vinnytsia and Cherkasy oblasts, large-scale use of green manure is recommended. Sowing legumes such as lupine and clover helps to enrich the soil with organic matter and reduce the risk of erosion. Sowing green manure can improve the soil structure, and their use in crop rotation allows reducing the volume of mineral fertilisers by up to 30%, which reduces agricultural production costs.

Policy measures and state support for innovative methods of restoring degraded soils in Ukraine. For the effective implementation of innovative approaches to the restoration of degraded soils in these regions, state support is needed through the provision of subsidies for the purchase of microbiological fertilisers, green manure and mulching products, and tax incentives for farmers who implement these methods. To reduce the financial burden, it is recommended to introduce co-financing at the level of 30-50% of the cost of technical means and materials necessary for the use of the latest technologies. In addition, the creation of grant programmes can allow farmers to receive irrevocable funds for the introduction of environmentally sustainable practices, such as mulching and the use of green manure.

Conducting pilot programmes in each of the main agricultural regions of Ukraine will allow adapting innovative approaches to local conditions. For example, the USAID Agriculture Resilience Initiative (AGRI) was one of the largest projects that provided funding to support innovations in the agricultural sector of Ukraine. The programme was aimed at increasing agricultural production, in particular, in the context of climate change, through the introduction of the latest technologies and agrotechnical methods. Under the programme, farmers and farmers can receive sub-grants that allow them to invest in innovative equipment, new biologics, and the integration of high-tech methods of soil treatment and irrigation. The programme was being implemented in many regions of the country, especially in areas where soils are experiencing degradation due to a lack of organic matter or unstable access to water resources. Another important step in adapting agricultural land to extreme climatic conditions is the Drought Management Plan in Ukraine, developed to combat the effects of climate change. This plan includes the use of efficient irrigation methods, the use of technologies such as mulching, and the optimisation of water use. In particular, mulching can reduce moisture evaporation by 20% and maintain soil moisture levels even in conditions of prolonged droughts. The introduction of such approaches in the southern regions of Ukraine, in particular in the Kherson, Mykolaiv, and Zaporizhzhia oblasts, can significantly reduce irrigation costs and maintain the sustainability of agricultural land. In addition, the programme provides funding for the implementation of such events, in particular, at the expense of subgrants for farmers, which allows attracting partial state support for such projects.

Special attention in the restoration of degraded land is paid to phytoremediation, which includes the use of specialised biologics for cleaning soils from heavy metals. This technology is an effective way to restore land affected by industrial pollution or contaminated with heavy metals after military operations. For soil cleaning, special plants are often used that absorb toxic substances, enriching the soil with organic materials, and promoting their structural stability. Such programmes are already being implemented in Ukraine in areas where the level of heavy metal pollution is critical, for example, in the Dnipropetrovsk and Kryvyi Rih industrial regions. Expanding these practices will improve the ecological state of contaminated areas and reduce the cost of mechanical or chemical soil cleaning, which is much more profitable in conditions of limited budget resources.

A systematic approach to innovation also implies political support. This may include subsidies for the purchase of environmental fertilisers, funding for agricultural research, and organising training programmes for farmers on innovative soil management techniques. An example of such a program is life HelpSoil, a project funded under the LIFE Programme of the European Union and aimed at supporting sustainable soil management, in particular, through the development and implementation of new strategies to increase soil fertility, improve their physical and chemical properties and, as a result, increase the environmental sustainability of agricultural systems. The project covers many aspects of soil management, such as preserving organic matter in the soil, improving water retention capacity, reducing erosion, and using bioinnovation technologies to improve agricultural efficiency in the face of climate change. An important area is the integration of environmental measures that reduce the burden on the environment, while contributing to economic benefits for farmers, such as reducing the cost of mineral fertilisers through the use of organic and biological soil stimulants.

It is possible to adapt the LIFE HelpSoil programme for Ukraine by implementing similar strategies in the main agricultural regions suffering from soil degradation, such as the Steppe, Forest-Steppe, and southern regions of the country. Ukraine, with its large agricultural territories and agrarian orientation of the economy, could integrate the principles of the programme into its state policy by financing soil restoration projects through subsidy programmes and grants for farmers. For example, support for the use of technologies for restoring organic soil content, such as mulching, the introduction of green manure or organic fertilisers, and the use of biologics to improve soil fertility and reduce the use of chemical fertilisers. There are opportunities to adapt already proven methods to specific conditions in Ukraine, such as reducing the negative impact of droughts and erosion, and increasing the resilience of agricultural farms to climate change.

The development of a national soil restoration programme should become one of the priorities of state policy. This programme should include targeted financial incentives for regions with the highest levels of degradation, such as the southern regions affected by drought and industrial regions exposed to heavy pollution. The programme should provide flexible arrangements for the allocation of funds, considering the specific needs of each region. Consequently, the introduction of innovations contributes to long-term food security, reducing the risks of food shortages and ensuring the stability of agro-industrial production. This was made possible by simultaneously increasing the sustainability of agricultural systems and increasing production volumes that meet the domestic and export needs of Ukraine. It is important to develop long-term plans for natural resource management, including periodic monitoring of soil conditions and the introduction of tools for assessing degradation risks.

DISCUSSION

The results confirm that innovative methods have a significant impact on soil restoration and strengthening food security. Increasing yields, reducing fertiliser costs, and improving the ecological state contribute to the economic stability of the agricultural sector. These approaches also lay a solid foundation for the ecological and social development of regions, creating more sustainable and productive agricultural systems. An assessment of the state of land in Ukraine found that more than 40% of arable areas suffer from various types of degradation, such as erosion, humus loss, salinisation, and pollution. Similar trends were recorded by H. Eswaran *et al.* (2019), who described soil degradation as a global problem that significantly affects land productivity and biological value. Water erosion, which covers 25-30% of the territories, was identified as the main type of degradation in Ukraine. These results are supported by A. Hossain *et al.* (2020), who emphasised that erosion is one of the key causes of fertility loss due to intensive land use and climate change

The decrease in humus content to critical levels (1.5-2%) in the central regions of Ukraine coincides with the conclusions of K. Lorenz *et al.* (2019), who identified organic carbon as a key indicator of soil fertility. The loss of humus in the regions under study correlates with the results of other countries, which confirms the global nature of the problem. K. Lorenz *et al.* also noted that low levels of humus are an obstacle to achieving the sustainable development goals, which focuses on the environmental component of the study. Economic losses caused by soil degradation, in particular, a decrease in yields by 20-30% and an increase in fertiliser costs, reflect the strong negative impact of this process on the agricultural economy. Similar conclusions were drawn by E. Midler (2022), who noted that degradation significantly increases the cost of agricultural production due to rising resource costs. The data obtained in the study on an increase in the cost of nitrogen and potash fertilisers to UAH 1,500-1,800 per hectare confirm this trend.

Innovative restoration methods, including biochar, mulching, and green manure, have been shown to be highly effective in improving land productivity and reducing fertiliser costs. An increase in yield of up to 25% when using microbiological fertilisers correlates with data by M. Baude *et al*. (2019), who proved that ecological approaches can significantly improve land productivity even in adverse conditions. The high efficiency of mulching in drought zones in Ukraine confirms the data obtained by other researchers for arid regions of the world. These studies confirmed that a significant part of the land in Ukraine, in particular, in the steppe regions, is subject to salinity due to incorrect irrigation management. Similar problems were described in detail by I. Kramer and Y. Mau (2020), who applied the SOTE model to assess degradation risks due to salinity in different countries. Their analysis showed that areas affected by salinity reduce soil productivity by more than 25%, which is also confirmed for Ukrainian regions. The identified problem of reducing the level of organic carbon in the soils of Ukraine confirms the trends described by Q. Jin *et al*. (2022). In their research conducted in rice fields in China, it was found that soil degradation leads to a loss of organic carbon and limits the ability of the soil to retain nitrogen and phosphorus. Similar trends in the loss of humus and nutrients were recorded in the Steppe and Forest-Steppe zones of Ukraine, which leads to the need to introduce stabilisation technologies, such as biochar and green manure.

The economic aspects of degradation identified in the study are consistent with the findings of O. Popovych *et al*. (2023), who considered losses from reduced yields in the context of agricultural production. Their calculations show that each reduction in yield by 1% leads to losses of an average of 1.2% of farm profit, which coincides with the established losses of profitability for the main crops in Ukraine due to degradation. The effectiveness of innovative recovery methods reflects the key findings of D. Jinger *et al*. (2023), who emphasised the feasibility of using agroforestry to restore degraded land. It was noted that agroforestry reduces erosion processes and contributes to the preservation of humus. The approach is confirmed for the conditions of Ukraine, where mulching and cover crops reduce the intensity of wind erosion by 20% in the southern regions. The comparison of the effectiveness of different soil restoration methods also coincides with the H. El-Ramady *et al*. (2022), who investigated the role of macroflora and macrofungia in the stabilisation of soil systems. The use of biologically active components facilitates not only soil restoration, but also contributes to the transition to sustainable management, which correlates with the proposed solutions in the Ukrainian context, such as the use of microbiological fertilisers (Drobitko & Alakbarov, 2023).

A significant contribution to the discussion was made by O. Olshanska *et al*. (2022), who examined the impact of soil restoration in the context of food security and bioeconomics development. Their analysis confirms the importance of restoring soil fertility as the main factor for ensuring stable agricultural production. Considering the Ukrainian study, the introduction of renewable technologies, such as biochar and mulching, allowed to increase productivity by 15-25%, which underlines their long-term economic effect. Results of the study by R.S. Guedes *et al*. (2021), who addressed the problems of soil restoration at iron mining sites, confirm the importance of adapting recovery methods to local conditions that include physical, chemical, and biological factors. According to the results obtained, the specifics of soil degradation in Ukraine, such as erosion and reduction of humus content, require the use of complex and localised measures. This approach is consistent with the researchers' findings about the need for differentiated strategies to combat soil degradation.

The study by J. Frouz (2021), which focused on soil recovery after mining, pointed out the importance of using vegetation to cover soils and restore microbiological activity. This is consistent with the results of the current study, which also highlights the role of vegetation and organic matter recovery using techniques such as biochar and mulching. Therefore, it was confirmed that a combination of technological and environmental solutions is an effective way to restore degraded soils. Conclusion of S. Kumar and K. Murugesan (2022) on the use of geothermal systems for soil restoration, which demonstrates the importance of technological approaches in the recovery process, has analogies with the results of the current study, which also states that technologies can be an important element in combating soil degradation, but they must be supplemented by environmental approaches. The study by Y. Xue *et al*. (2022), which examined the environmental risks of soil and water loss due to industrial processes, points to the complex relationship between industrial activity and soil degradation. The results of the study confirmed the importance of comprehensive assessments of environmental and anthropogenic factors for managing recovery processes.

An important aspect was the study by J. Mendoza-Vega *et al*. (2020), who focused on soil restoration by planting native trees in tropical mountain forests, points out the importance of vegetation restoration to improve soil quality. This was also supported by the results of the current study, which recommends the use of suitable vegetation and sustainable agricultural practices to restore degraded soils. One of the most important aspects of the study is the process of soil restoration after intensive use of organic fertilisers, in particular manure. Such approaches have been investigated by S.P. Indraratne *et al*. (2009), who drew attention to the rate of soil recovery after the cessation of long-term manure application in agriculture. The authors of the study found that soil restoration lasts for several years, considering the decrease in the content of organic compounds and the establishment of biological activity in the soil. The results of the current study are consistent with this, as it highlights the importance of giving soil systems time to recover from heavy fertiliser use. They confirm that gradual compensation for reduced humus content and microbiological activity is crucial for long-term soil recovery.

Comparison of results with the study by N. Goutal *et al*. (2012), who analysed the natural recovery of soil volume after compaction of forest soils, provided another important area. The researchers emphasised that recovery after compaction depends on natural processes, such as pore formation and increased biological activity in soils. According to the results of the current study, soil recovery after degradation also requires a comprehensive approach that includes not only physical methods, such as aeration, but also the use of natural processes, such as biological activity, which was confirmed by the study of natural soil systems in different ecosystems. Research by J.D. Bolling and L.R. Walker (2000), who investigated the restoration of vegetation and soil on abandoned roads in arid regions, demonstrated the importance of vegetation's ability to recover from disturbances in preserving soil structure. In this paper, it was demonstrated that successful soil restoration depends on the type of vegetation that can quickly restore the soil structure. This approach is reflected in the current project, which highlights the importance of selecting suitable vegetation to improve soil conditions. In particular, it is important to investigate the interaction between plants and soil for effective restoration of degraded land. The results of the current study, based on which it is possible to recommend the use of natural processes and approaches for soil restoration, are consistent with the conclusions of other researchers. The importance of finding integrated recovery methods that combine technical and natural aspects is a common trend in modern scientific developments, which can become the basis for further research in this area.

CONCLUSIONS

The study confirmed that soil degradation in Ukraine is a multifaceted problem with pronounced environmental, economic, and social consequences. It is estimated that more than 40% of arable land in Ukraine is subject to various forms of degradation, in particular, water and wind erosion. The most affected areas are in Polissia, Forest-Steppe, and in the southern regions of the country, where soil erosion reaches a large scale. In addition, there are problems of humus loss, in particular, in the central and southern regions, where the content of organic substances in many fields is at critical levels, which negatively affects soil fertility. Salinisation and soil pollution due to industrial pollution are also a problem in many agricultural areas.

Analysis of the economic consequences of soil degradation shows that a decrease in the yield of major agricultural crops, such as wheat, corn, and sunflower, leads to significant losses for agricultural enterprises. This is complemented by increased costs for fertilisers and other agrotechnical measures, which creates an additional burden on the budget of farmers, especially in regions with serious degradation problems. Analysis of the effectiveness of innovative methods of soil restoration has shown that these technologies have a positive impact on soil fertility and economic indicators of agricultural production. The use of biochar in the Poltava Oblast led to a significant increase in yields and a reduction in fertiliser costs, which had a positive impact on profitability. Green manure used in the Vinnytsia Oblast showed effectiveness in increasing yields and reducing the use of nitrogen fertilisers, which helped to decrease costs. Mulching in the arid regions of Southern Ukraine has reduced moisture loss and increased yields, which is especially important in conditions of water scarcity. The use of microbiological fertilisers in the Dnipropetrovsk Oblast also contributed to higher yields while reducing fertiliser costs, which provides significant economic benefits. These results confirm the feasibility of implementing such approaches for different types of soil degradation, depending on the specifics of the regions. Further research may focus on integrating remote sensing technologies and creating digital models of soils for operational analysis of their condition. An important area is also the assessment of the long-term impact of innovative methods on the stability of agroecosystems and the economic stability of agricultural production.

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CONFLICT OF INTEREST

None.

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Роль відновлення деградованих ґрунтів у забезпеченні продовольчої безпеки в агропромисловому комплексі

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Анотація. Дослідження присвячено аналізу стану деградованих ґрунтів в Україні, їхньому впливу на продуктивність сільського господарства та визначенню ефективних підходів до відновлення земель для забезпечення продовольчої безпеки. У роботі використано комплексний підхід, включаючи аналіз наукових і офіційних джерел, картографічну оцінку просторового розподілу деградованих земель, економічну оцінку втрат врожайності з використанням формул, а також дослідження інноваційних методів відновлення ґрунтів, таких як біочар, мульчування та мікробіологічні добрива. Результати моделювалися у програмі Excel, що дозволило оцінити вплив інновацій на продуктивність і рентабельність фермерських господарств. Результати показали, що понад 40 % орних земель України перебувають у стані деградації: водна ерозія вражає 25-30 % площ, найбільше у північних і західних регіонах, вітрова ерозія охоплює 10-15 % у степовій зоні, а втрати гумусу зафіксовано на 35 % земель, особливо в центральній частині. Забруднення важкими металами в промислових регіонах робить частину ґрунтів непридатною для використання. Економічні наслідки деградації включають зниження врожайності пшениці, кукурудзи та соняшника на 20-30 %, збільшення витрат на добрива до 1800 гривень на гектар і загальні втрати, що досягають 15 мільярдів гривень щорічно. Інноваційні підходи до відновлення, такі як біочар, мульчування, сидерати й мікробіологічні добрива, показали високу ефективність, забезпечуючи підвищення врожайності на 15-25 % у перші п’ять років, зменшення застосування хімічних добрив на 15-30 % і значне поліпшення екологічного стану земель. Застосування біочару в зонах дефіциту органічних речовин дозволило збільшити гумус до 12 %, тоді як мульчування скоротило втрати вологи на 20 %, зробивши поливи більш ефективними. Мікробіологічні добрива дали змогу значно знизити рівень забруднення ґрунтів. Отримані результати підтверджують, що впровадження регіонально адаптованих методик відновлення сприяє зниженню деградаційних процесів і стабілізації агроекосистем. Це створює основу для забезпечення продовольчої безпеки України. Дослідження також акцентує увагу на необхідності вдосконалення моніторингових систем для оперативного виявлення деградованих територій і розробки довгострокових стратегій управління ґрунтовими ресурсами

Ключові слова: земельні ресурси; гумус; родючий шар; сільськогосподарське виробництво; сидерація; мульчування

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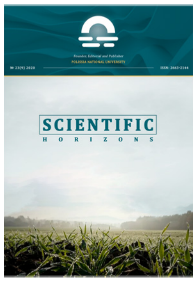

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Economic efficiency of sustainable food production

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Abstract. The purpose of this study was to analyse the effects of implementing the principles of sustainable food production on aspects of agro-industrial enterprises. Using the example of the Ukrainian company Myronivsky Hliboproduct and the Uzbek company Toshkentvino Kombinati, the study found that the rational use of resources can substantially reduce the loss of raw materials, reduce waste, and increase the level of material reuse. The use of energy-efficient technologies helps to reduce energy costs, which ensures the growth of financial performance and increases

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the competitiveness of enterprises. Implementation of practices to limit the use of pesticides and chemical fertilisers positively influences the product quality and reduces the environmental impact. Social initiatives, such as supporting local farmers, developing regional communities, and creating fair labour conditions, not only strengthen the reputation of companies but also contribute to the long-term development of local economies. The study also highlighted the significance of international standards such as ISO 14001, ISO 22000, and Global Good Agricultural Practices in implementing sustainable approaches in the food industry, which ensure the unification of processes and increase trust from partners and consumers. The examples of the companies selected for the study demonstrated how the implementation of sustainable practices affects the improvement of financial performance, environmental responsibility, and social image of enterprises. The findings obtained can be employed by managers and specialists of agro-industrial companies to adapt production processes to the principles of sustainable development. Furthermore, the developed recommendations will be useful for public authorities regulating the agricultural sector, as well as for NGOs working in the field of environmental and social responsibility of business

Keywords: environmental responsibility; innovation; energy saving; international standards; organic production

INTRODUCTION

Sustainable development is becoming a key area of modern economic and environmental thinking due to the limited natural resources and growing global environmental challenges. The food industry, as one of the largest and most significant sectors of the economy, plays a crucial role in resource consumption and waste generation, which underscores the relevance of implementing sustainable practices. Growing demand for food, the need to preserve ecosystems and ensure social justice require a review of conventional approaches to production. The introduction of energy-efficient technologies, rational use of resources, and environmental innovations can not only minimise environmental impacts but also increase economic efficiency, making sustainable development an important task for the industry and society overall. The significance of investigating the economic efficiency of sustainable food production is driven by the need to find the best ways to harmonise economic and environmental interests. It is through a sound analysis and generalisation of best practices that sustainable principles can be promoted among producers, which will be a step towards building a sustainable global economy.

There are many studies in the scientific literature that highlight the cost-effectiveness of sustainable production in the food industry. P.A. Østergaard *et al.* (2020) showed that enterprises that started implementing sustainable technologies in the early stages of their operations managed to reduce energy and water costs substantially, which positively affected their competitiveness in the industry. S.M. Didukh and A.K. Korikova (2020) emphasised that the introduction of sustainable development principles in agricultural production allows not only to minimise environmental damage but also to open new business opportunities through the development of organic production and the growing demand for environmentally friendly products. K. Uktamov *et al.* (2024) found that the active use of the circular economy concept allows businesses to considerably reduce the amount of production waste and increase resource efficiency. R. Singh and G.S. Singh (2017) emphasised that a sustainable approach to food production can become a major driver of economic growth due to the increased demand for environmentally friendly products in international markets. K. Liczmańska-Kopcewicz *et al.* (2020) emphasised that investments in sustainable technologies, specifically in the implementation of energy-efficient solutions, allow enterprises to reduce energy costs substantially, which positively affects profitability.

S. Momot (2022) highlighted the role of corporate social responsibility in sustainable development, noting that companies that integrate environmental and social standards into their operations not only gain financial benefits, but also strengthen consumer confidence and build stable partnerships. A. Hamidov *et al.* (2024) showed that enterprises that actively implement measures to reduce water and energy consumption not only achieve cost savings but also improve their reputation among consumers and partners. O. Kravchenko *et al.* (2020) focused on the effects of sustainable practices in agriculture on international trade, indicating that countries that support these practices greatly increase their export potential and gain competitive advantages in trade with developed countries. R. Hashmi (2023) examined the effects of government support on promoting sustainable development in the manufacturing sector, emphasising that policies that provide subsidies and tax breaks promote the active implementation of sustainable production methods, especially among small and medium-sized enterprises. Finally, N. Arabov *et al.* (2024) demonstrated that companies that integrate sustainability strategies achieve not only economic benefits but also substantial social benefits, specifically through improved working conditions and interaction with local communities.

Research confirms that a sustainable approach to food production not only positively affects the environment, but is also economically beneficial for businesses, contributing to their long-term competitiveness and financial stability. Although there is a large body of research covering certain aspects of sustainable production in the food industry, many significant topics are still understudied. One of them is the lack of research on the economic aspects of implementing sustainable practices in small and medium-sized enterprises, which often have limited resources for large investments. There is also little research on the effects of sustainable technologies on the long-term competitiveness of enterprises in different regions.

The purpose of this study was to assess the cost-effectiveness of implementing sustainable production practices in the food industry and their effects on the competitiveness of enterprises. The objectives of the study were to assess the effects of sustainable production practices on the economic performance of food industry enterprises, as well as to investigate the influence of sustainable technologies on the competitiveness of food enterprises in a transition economy.

MATERIALS AND METHODS

The study conducted a comprehensive analysis of the principles of sustainable production, focusing on the agro-industrial sector, specifically the food industry. The analysis was conducted considering the specifics of the implementation of these principles at enterprises in Ukraine and Uzbekistan, with an emphasis on their unique economic, social, and climatic features. The study employed a qualitative analysis to assess the principles of sustainable development in the agricultural sector, particularly in the food industry. Specifically, the study examined aspects of rational use of resources, including energy efficiency, waste reduction, and the introduction of a circular economy, which involves recycling and reuse of materials in production. Special attention was paid to reducing the use of pesticides and chemical fertilisers, which is a significant part of environmentally responsible production. To assess sustainable practices in the surveyed enterprises, international standards such as ISO 14001 (2004) for environmental management and ISO 22000 (2018) for food safety management systems were considered. Furthermore, the study analysed certifications confirming the companies' compliance with sustainability standards, including Global Good Agricultural Practices (GlobalG.A.P.) (2024) for agri-food products and Roundtable on Sustainable Palm Oil (2024), which regulates the sustainable development of palm oil, and Fair Trade International (2024), which guarantees fair labour conditions.

A detailed analysis of available data was performed, including statistical reports, official documents, and annual reports of companies. For this, the study employed data from the State Statistics Service of Ukraine (Economic indicators of..., 2024), Statistics agency under the President of the Republic of Uzbekistan (2024). The financial reports of leading companies such as Myronivskyi Hliboprodukt (MHP) (2023) and Joint-Stock Company Tashkentvino Kombinati with foreign investment (2023) were also considered. The companies were selected for the study due to their role as leaders in their respective industries – food and wine. The collected data helped to assess quantitative indicators of the industry's development, including the dynamics of production volumes, the structure of resource use, economic results, and the level of implementation of environmentally friendly practices. For instance, for Myronivskyi Hliboprodukt, the study examined the use of modern energy saving technologies, specifically biogas units, and for Toshkentvino Kombinati, the study examined the introduction of environmentally friendly methods of processing production residues. The analysis methods included data systematisation, trending, and interpretation. Graphs were built, such as the volume of food production in 2014-2024 in the two countries, to illustrate changes and identify patterns in the development of the sector.

The study also included an analysis of the effectiveness of implementing sustainable practices using leading companies as examples. For example, MHP examined the use of biogas plants for organic waste disposal. The energy efficiency of technologies, such as automated climate control systems for poultry farms, was assessed. The experience of Toshkentvino Kombinati in using winery residues to produce natural fertilisers was also analysed. The social aspects of sustainable production were investigated through the lens of job creation, support for local communities, and cooperation with small farmers. This included an analysis of initiatives to improve labour conditions and access to international markets through certification of products according to organic production standards. The methodology also included a comparative analysis of the two countries' approaches to sustainable production, considering climatic, economic, and social conditions. Particular attention was paid to the assessment of innovative technologies such as drip irrigation and renewable energy sources, specifically the use of solar panels in Uzbekistan.

RESULTS

In a world where resources are limited and environmental challenges are becoming increasingly significant, the food industry faces two major challenges: ensuring food security and reducing adverse environmental impact. In this context, the concept of sustainable production becomes particularly relevant. It is an approach that seeks to combine economic benefit, environmental responsibility, and social justice in the process of creating foods. Sustainable production is based on the rational use of resources. In the food industry, this means reducing the loss of raw materials, reducing waste, and reusing resources wherever possible (Garcia *et al.,* 2020). For instance, the introduction of circular models, where organic waste is converted into fertiliser or animal feed, can reduce environmental impact. Such approaches also have an economic effect, reducing the cost of disposal and procurement of new resources.

Another significant component of sustainable production is energy efficiency. The food industry consumes large amounts of energy at all stages – from growing raw materials to transporting finished products. Using energy-saving equipment, switching to renewable energy sources, and optimising logistics processes help to reduce the carbon footprint of companies. This not only reduces costs but also improves the environmental image of companies, which is an essential factor in the modern competitive environment (Salah & Mustafa, 2021). Another prominent aspect is the reduction in the use of pesticides and chemical fertilisers in the production of agricultural raw materials. Excessive use of these substances not only harms the environment but can also negatively affect consumer health. The transition to organic farming and biotechnology opens new opportunities for creating better products and new markets (Srivastav, 2020).

Sustainable production in the food industry also encompasses social aspects, such as ensuring fair labour conditions, supporting local farmers, and developing communities. By investing in sustainable practices, companies not only create environmentally friendly products, but also maintain social stability, which is significant for long-term development. While implementing sustainable practices requires significant effort and resources, their benefits are clear: they enable businesses to adapt to modern challenges, reduce dependence on limited resources, meet consumer demands, and ensure sustainable economic development. Sustainable production in the food industry is not merely a requirement of the times, but a strategy that forms the basis for a future where the economy and the environment work together (Melnikova & Gilsanz, 2023).

The sustainable development of the agricultural sector is based on a series of principles that promote a harmonious combination of economic efficiency and environmental responsibility. One of the crucial principles is the rational use of resources, which includes reducing the consumption of water, energy, and natural materials through innovative technologies. For example, precision farming allows optimising the use of water and fertilisers, reducing costs and minimising the environmental footprint. Another key principle is the transition to a circular economy, which aims to minimise waste and reuse resources (Granato *et al.*, 2022). In the agricultural sector, this can be manifested through the utilisation of production residues to create biogas or organic fertilisers. This approach reduces the environmental burden and creates additional economic benefits, especially for businesses seeking to increase their competitiveness.

The energy aspect of sustainable production is also of great significance. Shifting from fossil fuels to renewable energy sources, such as solar panels or biogas plants, can reduce operating costs and greenhouse gas emissions. This is crucial for agricultural regions, where there is exciting potential for the development of energy technologies based on biological resources (Nair *et al.,* 2022). Another significant area is reducing the use of chemicals such as pesticides and fertilisers. The transition to organic production and the use of biological products helps to preserve ecosystems and improve product quality. This meets the growing consumer demand for environmentally friendly products and enables producers to enter premium market segments (Singh *et al.*, 2021). The social component of sustainable production also plays a significant role. Ensuring fair labour conditions, supporting local farmers, and creating new jobs contribute to community development and social stability. The introduction of digital technologies, such as automation and drone monitoring, not only simplifies production processes, but also opens new opportunities to increase productivity and reduce costs.

International standards for sustainable food production underlie the implementation of environmentally responsible and socially oriented practices in the food industry. These standards define the criteria that businesses must meet to ensure the rational use of resources, environmental protection, and compliance with social norms. They serve as a guide for creating sustainable business models and open access to new markets where environmental responsibility is a crucial factor for consumers (Mak *et al.,* 2020). One of the key international standards is ISO 14001 (2004), which focuses on environmental management systems. It helps businesses to identify, assess, and minimise the environmental impact of their operations, ensuring effective management of natural resources. In the food industry, this standard is employed to optimise production processes and reduce waste. Another important standard is ISO 22000 (2018), which covers food safety management. While its focus is on ensuring product safety, it also accounts for a sustainable approach to production. This includes responsible use of raw materials, reduction of losses in the production process, and quality control at all stages of the food chain.

The Global Good Agricultural Practices (2024) principles are widely recognised standards for sustainable agriculture. They are aimed at ensuring environmental sustainability, rational water use, soil protection, and biodiversity. These principles are particularly significant for farms that supply raw materials to the food industry, as they enable the implementation of sustainable practices at the basic level of the production chain. Another important standard is the Roundtable on Sustainable Palm Oil (2024), which handles the sustainable production of palm oil. This standard ensures the preservation of ecosystems in tropical regions and promotes socially responsible production. Although palm oil is only one component of many food products, compliance with the Roundtable on Sustainable Palm Oil can substantially affect the reputation of manufacturers using this ingredient. Furthermore, Fair Trade International (2024) focuses on supporting fair trade and labour conditions. It stimulates the development of small farms, especially in developing countries, by providing them with access to the global market at fair prices. In the food industry, the standard increases consumer confidence and supports social justice. Sustainable development of the agricultural sector is significant for Ukraine, especially in the face of challenges posed by current realities, such as military operations, infrastructure destruction, climate change, economic instability, and limited access to resources. The war resulted in the loss of major areas of agricultural land, damage to logistics networks, and reduced access to export markets, complicating food security. At the same time, climate change requires the adaptation of production technologies, including the adoption of crop varieties resistant to drought and extreme weather conditions. These challenges underscore the value of adopting sustainable production models that optimise resource use, preserve soil fertility, and increase production efficiency, even under constraints. Figure 1 shows the volume of food production.

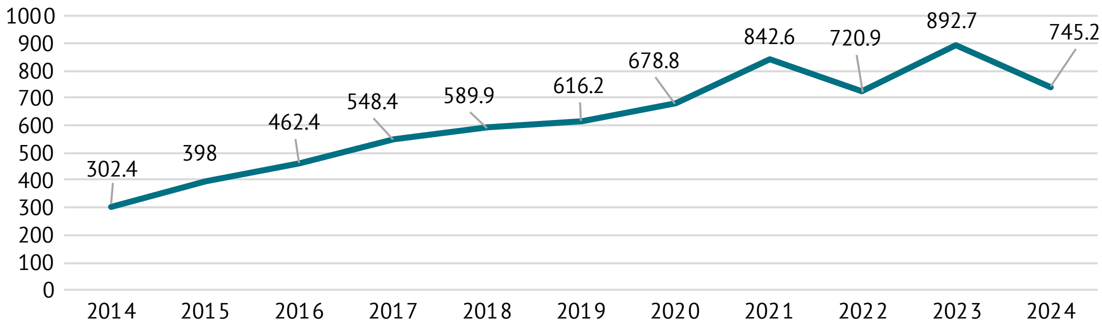

***Figure 1**. Food production in Ukraine in 2014-2024, UAH billion*
***Source:** developed by the authors of this study based on the Economic indicators of short-term industrial statistics (2024)*

During 2014-2018, a steady growth in production was observed, which increased by 23-30% annually. From UAH 1.429 billion in 2014, production increased to UAH 3.045 billion in 2018, which indicates a positive trend in the development of the agricultural sector. However, since 2019, the volume of production began to decline, dropping to UAH 3.019 billion in 2019, while in 2022, the volume decreased to UAH 3.854 billion, which can be explained by economic difficulties, including military aggression, the energy crisis, and other factors. At the same time, in 2023, production increased again to UAH 4.403 billion, up 14% compared to 2022, indicating a certain recovery in the agricultural sector, although the figure was still below the level of 2021 (UAH 4.679 billion). In 2024 (according to data from January to September), the figure was UAH 742.5 billion.

Rational use of resources is one of the key areas of sustainable production. Precision farming technologies that help optimise the use of fertiliser and water have become indispensable. For example, the use of modern soil monitoring can reduce fertiliser costs, which is vital in a context of limited access to imported materials. Even in regions that have suffered partial destruction of infrastructure, specifically as a result of the fighting in eastern and southern Ukraine (Donetsk, Luhansk, Kherson, Mykolaiv regions), where roads, bridges, water and electricity supply systems have been destroyed, these methods ensure that productivity is maintained.

An equally significant component is the introduction of renewable energy sources. An example of the introduction of renewable energy sources is the use of biogas units at Ukrainian agricultural enterprises, such as Myronivskyi Hliboprodukt (MHP launched another..., 2019). These companies convert organic waste into biogas, which reduces their dependence on conventional energy resources and helps them save on energy costs. Reducing the use of chemicals is also becoming a priority. Organic production methods enable farmers to reduce their environmental footprint while ensuring high quality products. This creates advantages for entering foreign markets where demand for organic products is growing, especially in Europe (Purnhagen *et al.*, 2021). The war has temporarily complicated logistics, but certification of products according to international standards opens new export opportunities.

Even in challenging circumstances, sustainable development helps to ensure economic resilience. For instance, businesses such as Myronivskyi Hliboprodukt, which use circular production models, reduce fertiliser and feed costs by recycling organic waste (MHP launched another..., 2019). These practices not only increase profitability but also become a valuable tool for rebuilding the agricultural sector after the war, especially in the face of widespread infrastructure damage, including damage to roads, warehouses, irrigation systems, and agricultural technical facilities.

Sustainable approaches can minimise dependence on resources that were lost or damaged, including with local resources, energy-efficient technologies, and the restoration of soil fertility through crop rotation and organic fertilisation. These practices not only contribute to the conservation of natural resources but also help to restore economic stability by increasing production efficiency even in the face of limited financial and material resources. Uzbekistan, a country with considerable agricultural potential, also faces numerous challenges in the agricultural sector. The exhaustion of water resources, soil degradation, and the growing need to ensure food security are driving the introduction of sustainable production practices in agricultural complexes. These practices not only help to preserve natural resources, but also open opportunities for economic growth and integration into global markets. Figure 2 shows the volume of food production

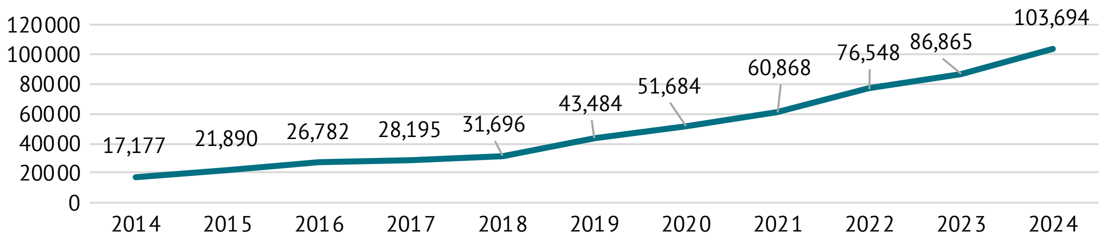

Figure 2*. Food production in Uzbekistan in 2014-2024, UZS billion*
Source: *developed by the authors of this study based on data from the Statistics agency under the President of the Republic of Uzbekistan (2024)*

In 2014, the volume of production was UZS 17.177 billion, and in 2023 it reached UZS 86.865 billion, which is an almost fivefold increase. The largest growth was observed in 2019-2024 – from UZS 43.484 billion in 2019 to UZS 103.693 billion in 2024, which demonstrated an almost twofold increase over this period. This growth can be attributed to the active development of agricultural production, modernisation of infrastructure, and the introduction of the latest technologies in the industry. The lowest growth rates were recorded in 2017-2018, when the annual increase was UZS 3.501 billion. However, overall, there a steady and significant increase was observed in food production in Uzbekistan throughout the period.

Uzbekistan, like Ukraine, faces serious challenges in the agricultural sector due to water scarcity and unfavourable climatic conditions. Water is a critical resource for agriculture in the country, as most agricultural land requires irrigation. In Ukraine, particularly in the southern regions such as Kherson, Mykolaiv, and Odesa, droughts are one of the most severe problems faced by farmers. Due to climate change and the lack of sufficient rainfall, irrigation is becoming critical to maintaining yields. To combat the water shortage, modern irrigation methods, including drip irrigation, are being actively introduced in these areas. For instance, in the Kharkiv region, an agricultural enterprise has applied innovative irrigation methods that have reduced water consumption by 50% and achieved onion yields of over 100 tonnes per hectare (A technology that..., 2020). Furthermore, Ukraine is testing a Japanese technology that involves the application of an organic hydrogel sorbent called EF Polymer. This product can retain moisture in the soil, gradually releasing it to plants, which reduces water use by 40%. After decomposition, the sorbent turns into fertiliser, contributing to additional savings on fertilisation (Ukraine to test Japanese..., 2024). In the Kherson region, where agriculture is the main industry, the use of drip irrigation has considerably reduced water consumption for crops such as vegetables and cereals (Karamushka *et al*., 2022).

In Ukraine, there are programmes in place to support land reclamation and efficient water management. For instance, the Government's Water Development Programme in Kherson region included the modernisation of irrigation systems, the creation of new reservoirs, and the introduction of innovative water management systems (Lower Dnipro River..., 2022). Furthermore, the Ministry of Agrarian Policy and Food of Ukraine can provide grants for enterprises that implement drip irrigation technologies and modernise water management facilities. In addition, Ukraine is actively developing practices aimed at preserving soil fertility. Specifically, precision farming methods are employed, including soil analysis, differentiated fertilisation and moisture control. Crop rotation, minimal tillage, and the use of organic fertilisers are becoming the standard for farmers seeking not only to preserve fertility but also to reduce the cost of chemical fertilisers. These methods help to maintain the ecological balance and ensure sustainable agricultural development. For instance, in Mykolaiv and Kherson regions, many farmers use crop rotation to improve soil quality. In Mykolaiv region, despite the drought, farmers harvested 2.1 million tonnes of grain in 2024, down from 2.4 million tonnes the previous year. The decline in yields is partly offset by the introduction of sustainable practices, such as crop rotation and precision farming, which help maintain soil fertility and reduce dependence on agrochemicals (Due to drought..., 2024).

These methods contribute to increased production efficiency and resilience to climate change.

Uzbekistan is actively implementing a sustainable approach to water management, especially in the face of drought conditions that characterise many regions, such as Fergana, Samarkand, and Surkhandarya. One of the key methods employed to optimise water use is drip irrigation, which reduces water consumption while increasing yields. This is significant for the country as the main crops grown on irrigated land are cotton, fruit, and vegetables. In the Fergana region of Uzbekistan, farmers are actively adopting drip irrigation for cotton and fruit growing. This method reduces water consumption by 30-50% compared to conventional irrigation methods such as sprinkling (Irisova, 2023). Furthermore, drip irrigation can increase yields by 20-50% by delivering precise and uniform moisture directly to the root system of plants. Although the initial investment in a drip irrigation system is approximately USD 1.2-1.5 thousand per hectare for the ground type, water savings and increased yields provide a quick payback of these costs (Shevchenko, 2019).

Uzbekistan is actively implementing programmes to improve water management and irrigation. Specifically, the government is implementing state initiatives to modernise water management facilities, improve irrigation infrastructure, and optimise water use. The Decree of the President of the Republic of Uzbekistan (2019) is aimed at modernising the agricultural sector, increasing its competitiveness and ensuring sustainable development. The key priorities of the strategy include optimising the use of water and land resources, introducing innovative technologies, supporting farmers, and transitioning to more environmentally friendly production. Specifically, it is planned to expand the use of drip irrigation, reduce water-intensive crops, introduce digital technologies in agriculture and support the export of organic products.

Conventional intensive farming has led to soil degradation, reduced productivity and quality. To address these issues, the government is implementing land reclamation programmes, which include the construction of new reservoirs, ditches, and pipelines to ensure a more efficient and sustainable water supply for agriculture. The Food and Agriculture Organisation is implementing a project in Uzbekistan on sustainable crop irrigation to support the systematic integration of the AquaCrop programme to optimise crop irrigation. The AquaCrop software allows forecasting crop yields depending on water consumption, which is especially useful in drought-prone regions. It uses data on soil moisture and climatic conditions to accurately determine the water resources required, which can help farmers reduce costs and increase irrigation efficiency. The programme was implemented within the framework of a project on rational irrigation of crops in Uzbekistan, which contributes to sustainable agricultural development (FAO implements a project…, 2023). Furthermore, the Food and Agriculture Organisation is supporting the development and promotion of green finance mechanisms in Uzbekistan to promote climate-smart agriculture. Green finance promotes sustainable agricultural practices that can counteract climate change and reduce greenhouse gas emissions.

Growing interest in organic products in international markets is driving the adoption of sustainable production standards such as GlobalG.A.P. and ISO 22000. Producers of fruits, vegetables, and nuts that certify their products gain access to the premium segment of the European and Asian markets. For instance, in the Samarkand region of Uzbekistan, farmers are actively implementing organic farming with an eye towards international markets. Farmers in this region grow certified organic products, including apricots, grapes, cherries, almonds, and other crops that are in high demand on foreign markets. Organic products from the Samarkand region are exported to countries such as Germany, China, Turkey, and the Persian Gulf. Exports to these countries enable farmers to sell their products at premium prices that are considerably higher than the cost of conventional goods. For example, exports of dried apricots to Germany enable farmers to earn a profit that is 30-40% greater than from selling these products on the internal market (Nurbekov *et al.*, 2018).

Companies in Ukraine are actively implementing sustainable practices to stay competitive in the international market. One such example is Myronivskyi Hliboprodukt (2023). The company is one of the largest chicken producers in Ukraine, which significantly impacts the country's agricultural sector. By integrating the principles of sustainable development, the company has managed to reduce its environmental footprint considerably and achieve economic growth at the same time. The technologies implemented at MHP have not only reduced energy and water consumption costs, but also contributed to increased production efficiency, which has positively affected the company's financial results. One of the major areas of sustainable practices in the company's operations is the use of energy-efficient technologies. MHP is actively investing in reducing energy consumption and switching to renewable energy sources, which helps to reduce energy costs. This is crucial in an environment where production requires extensive energy consumption, particularly to support processing and storage technologies. The use of modern systems of energy-saving technologies reduces energy costs, which translates into lower operating expenses and higher profitability.

Furthermore, by implementing sustainable water management practices, such as installing water recycling systems and optimising irrigation, MHP can reduce its water costs. Reducing energy and water consumption costs has been instrumental in maintaining the company's financial stability, even in times of economic crisis. Automated irrigation systems and the introduction of closed water circulation technologies enable the company to use natural resources efficiently while minimising costs. Notably, a sustainable approach to resource management has helped MHP reduce its environmental footprint and improve its reputation, which has increased demand for its products, particularly in international markets. At the same time, the use of sustainable technologies in production processes, such as biogas plants for processing organic waste, has helped the company reduce waste disposal costs and generate additional revenue. Table 1 shows the company's key financial indicators.

***Table 1**. Financial indicators of the "Myronivskyi Hliboprodukt" company for 2019-2024, USD million*

Indicators	2019	2020	2021	2022	2023	2024 (9M)
Income	2,056	1,911	2,372	2,642	3,021	2,262
Profit	215	-133	393	-231	142	141
Assets	2,509	2,108	4,014	3,809	3,886	3,965
Capital	1,596	1,254	1,794	1,446	1,567	1,635
Savings from sustainable technology	27	35	42	50	63	–

***Source:** developed by the authors of this study based on data from Myronivskyi Hliboprodukt (2023)*

MHP's financial performance demonstrates the company's ability to adapt to changing market conditions, overcome crisis periods, and maintain stable growth. Despite the fluctuations in profitability caused by the pandemic and the war, the company managed to maintain a strong level of income and capital, which demonstrates the effectiveness of its strategic approach and sustainability in development. For instance, in 2020, despite a decline in profits to USD -133 million due to the pandemic, the company managed to increase revenues to USD 1,911 million and return to profitability (USD 393 million) in 2021. This confirms that investments in sustainable development, efficient resource management, and innovative technologies are crucial factors that contribute to the company's financial stability even in adverse conditions. For 9M2024, the company's profit was USD 141 million. In 2019 to 2023, the company saved millions of dollars through the implementation of biogas plants, precision farming systems, and energy-efficient solutions. In 2023, the savings reached USD 63 million, which positively influenced the company's profitability even in the face of external challenges such as a pandemic or military action.

Energy efficiency is one of the major areas of MHP's sustainable development. The company is modernising its production facilities by introducing automated climate control systems in poultry houses. These systems help to optimise energy consumption while ensuring comfortable conditions for poultry rearing. Reducing energy costs increases production profitability and contributes to the environmental responsibility of the business. Rational use of resources is also a priority for the company. MHP uses precision farming technologies to grow grain crops that serve as feed for poultry. Thanks to modern methods of soil monitoring and fertiliser optimisation, the company reduces raw material costs, lowers its environmental footprint, and increases yields. This approach ensures stable operations even in times of economic and climate instability.

Certification according to international standards plays a significant role in the company's development and its entry into international markets. Specifically, in 2018, the European Commission's Directorate-General confirmed that MHP's facilities meet the highest quality standards, including FSSC 22000, ISO 22000 and BRC Food (The European Commission confirmed..., 2018). This allows the company to work with leading EU supermarkets and large international chains that require compliance with the most stringent safety and quality requirements. Obtaining such certificates has helped MHP not only strengthen its reputation in international markets but also expand opportunities for new partnerships. BRC Food certification ensures that the company follows the highest food safety standards, while GlobalGAP certificates confirm compliance with safety and quality requirements at all stages of production. Additionally, some of MHP's facilities are HALAL and KOSHER certified, which allows the company to expand its supply to markets where religious requirements are essential (MHP: Transformation, sustainable..., 2024). All these certifications ensure high product quality, increase trust from partners and consumers, and open new opportunities for the company in international markets.

Thanks to certification, the company gains access to premium segments of the European market, where demand for environmentally friendly and ethically produced products is growing. This is crucial for MHP, as the growing interest in sustainable production and environmental responsibility is driving demand for products certified to international standards. This enables the company not only to strengthen its competitiveness in new markets, but also to maintain high growth rates in exports, which helps to diversify sales markets and reduce dependence on domestic demand. Furthermore, certification positively influences relations with partners and customers, providing additional confidence in MHP products. This is an essential factor in expanding partnerships and entering into new deals, enabling the company to not only maintain but also increase its market share in a competitive environment.

Toshkentvino Kombinati, one of the leading wineries in Uzbekistan, is an example of how the integration of sustainable production principles helps the company achieve high economic efficiency and at the same time contributes to the preservation of ecological balance (Joint-Stock Company…, 2023). The plant specialises in the production of wines, cognacs, and other alcoholic beverages, gaining popularity both in the internal market and abroad due to the high quality of its products and growing export potential. Toshkentvino Kombinati's experience shows how modernisation of production processes and implementation of sustainable technologies can not only improve the company's economic performance but also reduce its environmental footprint. One of the key areas of the company's development is the introduction of energy and resource-saving technologies. For instance, the company has upgraded equipment to optimise water and energy consumption. The introduction of modern technologies in winemaking helps to reduce energy consumption, which is a significant factor in reducing operating costs. This contributes to the stability of the company's financial results and increased profitability.

Furthermore, Toshkentvino Kombinati is actively working to reduce its environmental footprint. For example, the introduction of water recycling technologies, effective waste management, and the transition to environmentally friendly packaging methods are significant components of sustainable production at the company. These measures not only reduce costs but also improve the company's reputation as an environmentally responsible producer, which positively affects the demand for its products. Adaptation to sustainable production models also includes the development and introduction of new grape varieties that are better adapted to the climatic conditions of Uzbekistan, including those resistant to drought and other adverse factors. This helps to reduce dependence on external resources and increase the stability of production in a changing climate. Table 2 shows the company's key financial indicators.

***Table 2**. Financial performance of Toshkentvino Kombinati for 2019-2024, UZS billion*

Indicators	2019	2020	2021	2022	2023	2024
Income	520	696	725	782	539	651
Profit	78	90	118	78	48	71
Assets	457	359	545	676	565	652
Capital	207	222	259	238	298	289
Savings from sustainable technology	12	18	25	20	15	19

***Source:** developed by the authors of this study based on data from the Joint-Stock Company "Tashkentvino Kombinati" with foreign investment (2023)*

Toshkentvino Kombinati's financial performance demonstrates the company's gradual adaptation to new conditions. In 2019-2024, the company demonstrated a steady increase in revenue and profit, which indicates the effectiveness of sustainable approaches in production. Specifically, in 2020, the company increased its revenue to UZS 696 billion while its profit was UZS 90 billion. In 2021, revenues reached UZS 725 billion and profits reached UZS 118 billion, indicating an effective development strategy. However, in 2023, there was a decline in revenue to UZS 539 billion, which could be the result of short-term economic challenges or changes in consumer preferences. In 2024, the company's revenue increased to UZS 651 billion, while profit amounted to UZS 71 billion, which reflects positive dynamics and resilience even in challenging conditions. Despite the difficulties, the company has a strong potential for recovery and further growth through the implementation of sustainable technologies and strategic investments. By rationalising water use, reducing chemical fertiliser costs and managing resources efficiently, the company saved around UZS 19 billion in 2024, which positively affected its financial results.

Energy efficiency is an essential element of the company's strategy. Toshkentvino Kombinati has modernised its production lines by introducing energy-saving technologies that reduce electricity consumption. The installation of modern equipment for processing wine materials and the optimisation of technological processes have helped to increase productivity and reduce production costs. The company is also actively working to reduce waste. Winery waste, including grape pomace, is used to produce natural fertilisers. This not only reduces the environmental influence but also creates additional value that can be used in the agricultural sector. The rational use of water resources is significant for winemaking in areas with limited access to water. Toshkentvino Kombinati implemented closed-cycle water supply systems, which can reduce water consumption. Furthermore, the company regularly monitors water quality, using it in an economically and environmentally responsible manner. The integration of sustainable practices has positively influenced Toshkentvino Kombinati's financial results. Reduced energy and water costs helped to reduce production costs and increase profitability. Thanks to the introduction of modern technologies and compliance with high quality standards, the company's products have been recognised in international markets. Toshkentvino Kombinati exports wines and cognacs to countries such as China, the US, Belarus, Germany, and Tajikistan, which contributes to foreign exchange earnings for the Uzbek economy (Viticulture and winemaking, 2024). Overall, wine exports from Uzbekistan in 2022 totalled USD 4.15 million, making it the 65th largest wine exporter in the world (Wine in Uzbekistan, 2022).

Implementation of sustainable practices in the operations of food companies is the basis for ensuring long-term competitiveness, reducing environmental impact, and improving economic performance. One of the key areas is the optimisation of energy consumption, which helps to reduce costs and cut carbon dioxide emissions. This is achieved through the use of modern energy-efficient equipment, such as heat exchangers and refrigeration units, as well as the introduction of renewable energy sources, such as solar panels or biogas plants. Rational waste management is another major step. Organic residues can be transformed into fertiliser or animal feed, and packaging can be recycled or reused. Optimising water use is also crucial in this context. Modern treatment technologies such as membrane filters and biological treatment plants can greatly reduce water consumption. Some Uzbek wineries are already using collected rainwater to irrigate their vineyards, which is an excellent example of effective water management.

Reducing the use of pesticides and chemical fertilisers increases the environmental sustainability of the agricultural sector. Transitioning to organic production allows producing value-added products and reduces the adverse environmental impact. Furthermore, innovative approaches to packaging, such as the use of biodegradable materials or the transition to reusable packaging, greatly reduce plastic waste. For instance, Toshkentvino Kombinati in Uzbekistan is actively experimenting with environmentally friendly materials for wine packaging. Rationalising logistics is a key aspect of sustainable development, reducing costs and increasing efficiency. Optimisation of routes and the use of energy-efficient transport reduce fuel costs, cut CO_2 emissions, and increase profitability. Implementation of product loss monitoring systems helps to reduce waste, which reduces disposal costs. Educational trainings for employees on energy efficiency and waste management contribute to more efficient use of resources and environmental protection. Implementation of such sustainable practices also strengthens the company's image as an environmentally responsible and progressive enterprise, which attracts the attention of customers and partners who value conservation of natural resources and reduction of the ecological footprint.

All these recommendations confirm that sustainable development not only preserves resources for future generations, but also opens new economic opportunities, ensuring the long-term stability of enterprises. Prospects for sustainable production in the food industry focus on the introduction of innovative technologies, efficient use of resources, and reduction of environmental impact. The introduction of energy-efficient technologies, reduced use of chemical fertilisers and pesticides, and rational management of water and material resources can considerably improve the economic efficiency of enterprises, reducing costs and increasing their competitiveness.

DISCUSSION

The study findings confirmed that sustainable development in the food industry is a key factor that enables a harmonious combination of economic efficiency, environmental responsibility, and social justice. One of the primary benefits of sustainable production is cost reduction through optimised resource use and the introduction of innovative approaches, such as circular economy models. Examples from Ukraine and Uzbekistan demonstrated that the application of such practices can reduce the environmental footprint and at the same time increase the competitiveness of enterprises.

One of the key aspects of sustainable production is the rational use of resources (Oleksy-Gębczyk *et al.*, 2024). The study revealed that the use of precision farming technologies can greatly reduce fertiliser and water costs. This is crucial in conditions of limited access to resources, which is typical for Ukraine as a consequence of the war, as well as for Uzbekistan due to natural climatic conditions. For example, the introduction of drip irrigation methods in Uzbekistan has reduced water consumption, which confirmed the effectiveness of these approaches. L.L.D.R. Osorio *et al.* (2021) investigated the potential of the circular economy in the agricultural sector, specifically the use of waste for biogas and organic fertiliser production. The researchers' findings revealed that the transition to a circular economy not only reduces negative environmental impacts but also opens new sources of income through the sale of biogas or organic fertilisers. This enables businesses to reduce energy and fertiliser costs and contributes to sustainable development. The present findings partially coincided with these conclusions, as the use of biogas units and waste recycling were mentioned. However, the cited study focused on the economic benefits of circular processes, which the current study addressed to a lesser extent.

The energy component plays a crucial role in sustainable development. The use of renewable energy sources, such as biogas units and solar panels, demonstrated high efficiency in the agricultural sector in both countries (Cherven *et al.*, 2024). The practices of the Ukrainian company MHP showed that the processing of organic waste into biogas can reduce dependence on conventional energy resources and reduce greenhouse gas emissions. Analogously, Uzbek wineries are using solar energy to reduce electricity costs. M.S. Nejad *et al.* (2023) also focused on the effects of energy-saving technologies on production costs in the agricultural sector, confirming that the use of modern renewable energy sources can reduce energy costs. Furthermore, A. Amo-Aidoo *et al.* (2021) emphasised that in the context of global warming, energy efficiency is becoming increasingly significant for the sustainable development of agricultural enterprises. Compared to the present study, these researchers focused on energy savings and concrete economic benefits of solar and biogas units, which coincided with the presented findings.

Another significant area is the reduction of chemical fertilisers and pesticides (Yaheliuk *et al.*, 2024). The study showed the value of organic farming, which reduces environmental impact and improves product quality. This is in line with current trends of growing demand for environmentally friendly products, particularly in Europe. The transition to organic technologies also opens access to premium markets, which is crucial for Ukraine and Uzbekistan. S. Das *et al.* (2023) investigated the role of biotechnology in reducing the use of chemical fertilisers and pesticides, finding that the use of genetically modified crops can greatly reduce the need for pesticides and, consequently, mitigate their adverse environmental impact. M.A. Steinwand and P.C. Ronald (2020) also noted that the use of biotechnology allows for more yields with fewer chemicals. These findings partially coincide with the present findings on the reduction of chemical use, although the researchers focused on organic farming, as opposed to biotechnology as a tool for sustainable development.

The social aspect of sustainable development also has a major influence. Ensuring fair labour conditions, supporting local farmers, and developing communities contribute to social stability (İsmayilov *et al.*, 2022). Examples of companies such as MHP in Ukraine and Toshkentvino Kombinati in Uzbekistan demonstrate how investing in local communities and creating jobs increases brand trust and stimulates economic growth. A. Wezel *et al.* (2020) also focused on the social aspects of sustainable production, including fair labour conditions and the development of local communities. The researchers found that agribusinesses that actively implement the principles of social responsibility have more stable workforces and reduce the risk of social conflict. These findings overlap with current findings on social responsibility, particularly in the case of MHP, which invests in rural community development and improves working conditions.

R. Lencucha *et al.* (2020) investigated the effects of government policies on the development of sustainable agriculture, specifically policies supporting organic farming and the application of environmental standards. The researchers found that government programmes encourage small and medium-sized farmers to adopt sustainable practices, such as organic farming and the use of renewable energy sources. This can increase environmental friendliness and economic efficiency, but it was also found that insufficient government funding limits the potential. The current study also mentioned the significance of government support and the role of certification but focused more on existing international standards and their implementation at the enterprise level. The implementation of international standards such as ISO 14001, ISO 22000, and GlobalG.A.P. provides enterprises with access to new markets and increases their reputation among environmentally conscious consumers (Gutsul *et al.*, 2023). For example, certification of Uzbek producers' products to these standards has enabled them to export organic products to Germany and China. K. Pietrzyck *et al.* (2021) studied the influence of international standards (GlobalG.A.P., ISO 22000, Fair Trade) on the sustainable development of the agri-food sector in countries. Like K.M. Siegel and M.G.B. Lima (2020), the researchers found that certification to international standards enables producers to improve the quality of their products, access new markets such as Europe and Asia, and increase competitiveness. This allows farmers and businesses to increase their income and invest in environmental technologies. The current study also covered this topic but focused more on concrete examples of the application of these standards in Ukraine and Uzbekistan, while the cited studies examined the overall impact of standards on the development of developing economies.

F. Fuentes-Peñailillo *et al.* (2024) investigated the role of digital technologies, such as satellite monitoring, soil moisture sensors, and artificial intelligence systems, in improving the efficiency of sustainable agriculture. The findings indicated that the use of these technologies enables farmers to more accurately plan fertilisation, irrigation, and pest control, which reduces resource costs and minimises environmental impact. The current study also confirmed the value of using modern technologies to increase the efficiency of sustainable production. However, the researchers focused on digital tools and their role in optimising production, while the present study mentioned this issue in less detail.

Therewith, the implementation of sustainable practices faces a series of challenges. In Ukraine, the war complicates logistics, while in Uzbekistan, limited financial resources and access to modern technology slow down the pace of change. However, support from the government and international organisations can greatly accelerate this process. Thus, the study confirmed that the principles of sustainable production not only solve current problems but also form the basis for a sustainable future. The integration of environmentally responsible, economically viable, and socially just approaches allows striking a balance between the economy and the environment, creating competitive advantages for businesses.

CONCLUSIONS

The study showed that the implementation of sustainable production principles increases the efficiency of enterprises and reduces their adverse environmental impact. A prominent aspect is the efficient use of resources such as water and energy, specifically through precision farming technologies that reduce fertiliser and water costs. Furthermore, the reduction of pesticide uses and the transition to organic farming contribute to the preservation of ecosystems and improve product quality. Sustainable development principles implemented through international standards such as ISO 14001, ISO 22000, GlobalG.A.P., and fair-trade certification are becoming an indispensable tool for companies seeking not only to protect the environment but also to increase their competitiveness in international markets.

In Ukraine and Uzbekistan, the implementation of sustainability principles in the agricultural sector contributes to economic growth and environmental sustainability. An example of this is Myronivskyi Hlibprodukt, which has reduced energy costs and increased yields by using biogas units and precision farming. According to its financial results for 2019-2024, MHP managed to increase its revenues despite the challenging environment, including the war. In Uzbekistan, Toshkentvino Kombinati is modernising its production by introducing energy-saving technologies and closed water supply cycles. These steps demonstrate how sustainable development can improve competitiveness and promote environmentally friendly economic growth. According to its financial results for 2019-2024, the company showed a steady increase in capital and assets, reflecting investments in production modernisation and the introduction of environmentally friendly technologies.

Overall, sustainable development in the food industry is a prerequisite for a future where the economy and the environment are in harmony. Integration of sustainable practices into production processes not only reduces costs and risks, but also promotes social responsibility, improves product quality, and strengthens positions in global markets. Limitations of the present study included the fact that the focus was on individual countries and companies, which limited the generalisability of the findings to other regions. Further research could include a comparison of sustainability in different industries and the impact of the latest technologies on the efficiency of sustainable production in the agricultural sector.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Економічна ефективність сталого виробництва харчових продуктів

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Анотація. Метою дослідження було проаналізувати вплив впровадження принципів сталого виробництва харчових продуктів на аспекти діяльності агропромислових підприємств. На прикладі української компаній «Миронівський хлібопродукт» та узбецької Toshkentvino Kombinati встановлено, що раціональне використання ресурсів дозволяє суттєво знизити втрати сировини, скоротити обсяг відходів і підвищити рівень повторного використання матеріалів. Використання енергоефективних технологій сприяє зниженню витрат на енергоресурси, що забезпечує зростання фінансових показників і підвищує конкурентоспроможність підприємств. Впровадження практик обмеження застосування пестицидів і хімічних добрив позитивно впливає на якість продукції та зменшує екологічне навантаження на довкілля. Соціальні ініціативи, такі як підтримка місцевих фермерів, розвиток регіональних громад і створення справедливих умов праці, не лише зміцнюють репутацію компаній, але й сприяють довготривалому розвитку місцевих економік. У дослідженні також висвітлено значення міжнародних стандартів ISO 14001, ISO 22000 та Global Good Agricultural Practices у впровадженні сталих підходів у харчовій промисловості, що забезпечують уніфікацію процесів і підвищують довіру з боку партнерів та споживачів. На прикладах діяльності обраних для дослідження компаній продемонстровано, як впровадження сталих практик впливає на покращення фінансових показників, екологічної відповідальності та соціального іміджу підприємств. Отримані результати можуть бути використані керівниками та фахівцями агропромислових компаній для адаптації виробничих процесів до принципів сталого розвитку. Крім того, напрацьовані рекомендації стануть корисними для органів державного управління, які регулюють агропромисловий сектор, а також для громадських організацій, що працюють у сфері екологічної та соціальної відповідальності бізнесу

Ключові слова: екологічна відповідальність; інновації; енергозбереження; міжнародні стандарти; органічне виробництво

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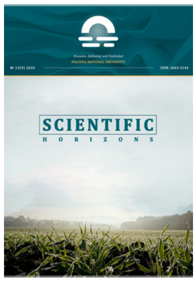

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Technologies for adaptation of agriculture to climate change in Kyrgyzstan

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Abstract. Climate change significantly impacts agricultural productivity, especially in arid regions such as Kyrgyzstan. The cultivation of drought-resistant crops and the introduction of innovative agricultural technologies are key measures to ensure the sustainability of the agricultural sector. The study aimed to assess the efficiency of growing drought-tolerant crops (sorghum, chickpea and millet) in Kyrgyzstan, as well as to analyse the impact of modern technologies, such as drip irrigation, on productivity and efficiency of water use. The study was conducted during two growing seasons (2023-2024) in an experimental field in Kyrgyzstan. Yields were determined

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by harvesting 1 m^2 plots and then converting to hectare. Water use was measured using Delta-T Devices soil moisture meters (10, 20 and 30 cm depths). Water use efficiency (WUE) was calculated as the ratio of crop yield to water use. Crop conditions were monitored using DJI Agras T30 drones and Sentinel-2 satellite imagery. The results of the study confirmed the high performance of sorghum and pearl millet under drought conditions. Sorghum showed the highest yield of 4.2 tonnes/ha due to its well-developed root system and ability to use moisture efficiently. Millet showed the best WUE – 0.9 kg/m^3 – and the lowest water use (4000 litres/ha), making it an optimal crop for water-stressed regions. Chickpea, despite its lower yield (1.8 t/ha), proved promising due to its nitrogen-fixing properties that improve soil fertility. The use of drip irrigation reduced water consumption by 20-30%, ensuring stable yields even under water deficit conditions. Monitoring using drones and moisture meters helped to optimise irrigation, improving the accuracy of water management. The study confirmed the efficacy of sorghum and pearl millet as key crops for arid regions, and the feasibility of integrating drip irrigation to improve agricultural sustainability. The results of the study provided science-based recommendations for farmers and policymakers on the introduction of drought-resistant crops and modern agricultural technologies in Kyrgyzstan, which will contribute to food security and sustainability of the agricultural sector under climate change conditions

Keywords: drought; drought-tolerant crops; moisture; sorghum; millet; chickpea; irrigation system; water use

INTRODUCTION

In the Kyrgyz Republic, agriculture contributes a significant share of the economy and food security. However, climate change poses serious challenges for the agricultural sector, including droughts, reduced water resources and soil degradation. These factors necessitate the adoption of adaptation technologies to maintain agricultural productivity and ensure food security. Climate change poses serious threats to agriculture in Central Asia, particularly in Kyrgyzstan, due to increased droughts, shrinking water resources and soil degradation (Mukambaeva *et al.*, 2024). According to the Intergovernmental Panel on Climate Change, global warming could lead to a 10-30% reduction in the yield of the region's main crops by 2050. In Kyrgyzstan, wheat yields have already fallen by 15% over the past decade due to reduced rainfall. Water scarcity continues to increase: the availability of water resources in Central Asia has decreased by 20% over the past 20 years. In such circumstances, the introduction of adaptation technologies, such as the cultivation of drought-tolerant crops (sorghum, chickpea and millet), is key to ensuring food security and the sustainability of the agricultural sector.

The Food and Agriculture Organisation of the United Nations is actively implementing measures to support the adaptation of Kyrgyzstan's agriculture to climate change (Kadyraliev *et al.*, 2024). In particular, the Food and Agriculture Organisation is promoting the introduction of drought-tolerant crops such as sorghum, chickpea and millet, which can provide stable yields under climate stress. The organisation is also improving water management practices by introducing modern irrigation systems that minimise water loss. In addition, the Food and Agriculture Organisation implements programmes to train farmers in climate-resilient technologies and provides access to financial instruments to support innovative approaches to agriculture (Shebanina *et al.*, 2024). These measures aim to increase the resilience of the national agricultural sector and ensure its productivity in the face of climate change.

Modern adaptation strategies include the widespread use of digital technologies, such as mobile apps for weather forecasting and crop monitoring. Precision farming can be used to optimise the use of water, fertilisers and plant protection products, which significantly increases yields even in adverse conditions (Pichura *et al.*, 2024). Another important area is the cultivation of drought-tolerant crops that can provide stable productivity with limited resources. M. del Mar Polo *et al.* (2022) discussed the possibilities of introducing climate technologies into the agricultural sector of Kyrgyzstan. The authors analysed the prospects for investment in drought-resistant crops, efficient water management and optimisation of agricultural processes. Barriers to innovation, such as insufficient access to finance for small farmers, and ways to overcome them, were emphasised. The study by P. Khakimov (2019) addressed the general trends of climate change in Central Asia, including Kyrgyzstan, Afghanistan and Tajikistan. The author analysed adaptation policies that promote innovation, emphasising the need to develop local strategies to ensure agricultural sustainability in the region.

L. Liang *et al.* (2021) assessed the vulnerability of Kyrgyzstan's agricultural systems to droughts, focusing on the need to grow drought-resistant crops and adopt efficient irrigation methods. These findings are complemented by S. Park *et al.* (2021) in a study on the impact of climate change on the suitability of land for agriculture. The authors propose scenarios for future land use with a focus on maintaining the productivity of the agricultural sector. B. Emileva *et al.* (2023) investigate the role of digital technologies in improving the accuracy of climate change perceptions among farmers in Kyrgyzstan, Mongolia and Uzbekistan. The results highlight the importance of mobile apps for accessing weather information and supporting decision-making in the face of climate challenges. I. Chumarev (2023) also analysed the technical and economic aspects of establishing a Central Asian drought monitoring system that contributes to climate risk forecasting and rational resource use.

T. Thomas *et al*. (2021) analysed the forecasts of production of major crops in Central Asia, considering climate change, and justified the need to implement adaptation strategies. In turn, K. Keneni (2022) and P. Juyal (2021) addressed the role of drought-tolerant crops and biotechnology in increasing agricultural resilience, which is essential for food security. Despite significant progress in the introduction of climate technologies, the issue of local adaptation strategies, particularly the introduction of drought-tolerant crops, remains insufficiently studied in Kyrgyzstan. The limited amount of empirical data makes it difficult to assess their effectiveness in the face of climate change, which is a key issue for the national agricultural sector. Cultivation of crops such as sorghum, chickpea and millet could be a promising strategy to increase the resilience of agricultural systems to droughts and other climate stresses.

The study aimed to scientifically analyse the efficiency of growing drought-tolerant crops such as sorghum, chickpea and millet in an experimental field in the Kyrgyz Republic. The study analysed agronomic parameters such as yields, water consumption and resilience to adverse climate change conditions, as well as the economic feasibility of their implementation.

MATERIALS AND METHODS

The study was of empirical and experimental nature, aimed to analyse the efficiency of growing drought-tolerant crops in the face of climate change. The field experiments were conducted during two growing seasons, from April 2023 to October 2024, at an experimental field in the Kyrgyz Republic. Data were collected through field experiments on the cultivation of three drought-tolerant crops: sorghum, chickpea and millet. All ethical standards set by the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973) were followed during the study, which ensured compliance with the principles of sustainable plant use. Each crop was sown on separate plots divided by soil type and irrigation conditions. The experiment was conducted on a representative sample of areas, including 15 plots with a total area of 1.5 hectares, which was used to address the variability of soil and climatic conditions in the region. When selecting plots, three types of soil typical for the region were considered: loamy, sandy and sandy loam, which was used to analyse the adaptive properties of crops in different conditions. The size of each plot was 0.1 hectares, which provided sufficient area to obtain reliable data for each variant of conditions. Crops were selected based on their relevance to dry conditions and preliminary studies confirming their adaptive properties. The irrigation conditions varied, with one group of plots using drip irrigation while the other relying on traditional methods such as surface and furrow irrigation, allowing for a comparative analysis of the effectiveness of the irrigation systems. Standard agronomic methods were used to measure key parameters such as yield, water consumption and resilience to climate stress.

Yields were determined by harvesting 1 m_2 control plots and then calculating the weight of the crop per hectare. Soil moisture was measured using soil moisture meters at depths of 10, 20 and 30 cm. Leaf area was calculated using the weight proportion method, in which dried leaves were weighed and their area was determined using the correlation formula between weight and area (1):

$$A = \frac{W \times As}{Ws}, \tag{1}$$

where A – total leaf area (cm^2); W – mass of fleshly harvested leaves (g); As – area of sample part of the leaves (cm^2); Ws – weight of sample part of the leaves (g).

The amount of precipitation was recorded using a weather station installed in the experimental field, which also provided data on air temperature and humidity. Plant heights were measured manually using a tape measure from the early stages of growth to the harvest period. All parameters were recorded weekly for further analysis of crop development dynamics. Quantitative methods were used to analyse agronomic parameters, including statistical calculations of average yields and water consumption for each crop. To assess plant resistance to drought, the WUE calculation method was used to compare the water use efficiency of different crops:

$$\text{WUE} = \frac{x}{y}, \tag{2}$$

where x – water consumption (m^3/ha); y – yield (kg/ha).

The cost-effectiveness of cultivation was analysed using the cost-benefit method [3]:

$$\text{CBA} = \frac{a}{b}, \tag{3}$$

where CBA – coefficient of economic efficiency of cultivation; a – costs; b – income.

This method involved calculating the costs of seed, fertiliser, irrigation and other inputs, as well as the projected profit from the sale of the crop. The obtained data were compared with yield, resistance to unfavourable climatic conditions, cultivation and processing costs, and market value of products to identify the most promising crop in terms of economic feasibility. Comparison of water use statistics of sorghum, chickpea and pearl millet with traditional crops in the region such as wheat, barley and maize were compared

(Pashchenko, 2024) and the economic benefits of the plants were also compared (State Programme for…, 2017). These crops were selected due to their importance for agriculture in the region: wheat, barley and maize are the main food security crops, while sorghum, chickpea and millet are considered promising drought-tolerant alternatives. The comparison made it possible to determine their economic efficiency under the conditions of water scarcity characteristic of the region and to identify the most climate-resilient crops.

The study applied modern agronomic and digital technologies, including drip irrigation for rational water use, mulching to conserve soil moisture and organic fertilisers to improve soil fertility. The use of DJI Agras T30 drones (5 units, manufactured in China), Sentinel-2 satellite imagery (European Space Agency) and Delta-T Devices soil moisture meters (5 units, manufactured in the UK) provided accurate monitoring of crop health and irrigation control, increasing the resilience of agricultural systems to climate change. Possible limitations of the methods used include measurement errors that may arise from technical limitations of the equipment used or human error in data collection. In addition, the results could be affected by external factors, such as weather anomalies, sudden changes in temperature, abnormal precipitation or droughts, which could alter crop growth and productivity. These limitations should be addressed when interpreting the data and appropriate adjustments should be made to improve the accuracy of the conclusions. The interpretation of the results was based on an analysis of a combination of agronomic and economic indicators. The data were compared between crops to determine the most adapted to climate change conditions. The results were also compared with previous studies to verify the validity of the findings.

RESULTS

Agronomic characteristics of the crops under study

Field experiments conducted in the Kyrgyz Republic during two growing seasons showed that sorghum demonstrated the highest yield among the crops studied – 4.2 tonnes/ha. This is due to its ability to adapt to different soil types and effectively utilise available moisture. Millet yielded 3.6 t/ha, which was the second-best result, but due to its lowest water use among all crops, it is a very promising crop. Chickpea showed the lowest yield of 1.8 t/ha, probably due to its sensitivity to high temperatures during flowering. These results emphasise the differences in the adaptation mechanisms of the crops under study, including the ability of sorghum and pearl millet to produce yields even under a limited water supply.

The three types of soil studied in the experiment differed significantly in their physical and chemical characteristics, which assessed the adaptive properties of sorghum, chickpea and millet in different conditions. Due to its high moisture capacity and fertility, loamy soil creates favourable conditions for crop growth even with limited rainfall. Sandy loam soil is characterised by low moisture capacity, but its lightness and good aeration ensure optimal development of the root system. The sandy soil, with minimal moisture retention capacity, modelled the extremely dry conditions typical of some areas of the region. This approach identified how the crops under study adapt to different soil types and to determine their potential for use in conditions of water scarcity (Table 1).

***Table 1**. Influence of soil type on the yield of the studied crops*

Crop	Loamy soil (t/ha)	Sandy loam soil (t/ha)	Sandy soil (t/ha)
Sorghum	4.5	4	3.5
Chickpea	2	1.8	1.5
Millet	3.6	3.8	3.2

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

Sorghum showed the highest yields on loamy soil due to its high-water capacity, which provides the plant with the necessary moisture throughout the growing season. Chickpea also showed the best results on loamy soil, which creates optimal conditions for growth and promotes its ability to fix nitrogen, improving soil fertility. This feature makes chickpeas valuable for integration into crop rotations. Millet, due to its adaptability to limited resources, grew most efficiently on sandy loam soil, where its yields remained consistently high. On sandy soil, all crops showed a decrease in productivity due to their low water-holding capacity, but millet was better adapted to these extreme conditions.

Sorghum, chickpea and millet showed different growth characteristics in the dry climate. Sorghum was distinguished by its powerful root system, which allows the plant to extract moisture from deep soil layers. The observations determined that even during periods of high temperature (up to +38°C), sorghum showed no signs of stress. Millet showed rapid growth rates in the early stages of the growing season, which provides it with an advantage in the short-term availability of moisture. Due to its short growing season (85 days), millet completed its development cycle before the onset of critical dry periods. Chickpea, despite its relatively short growing season (95 days), was more sensitive to high temperatures during flowering, which negatively affected its yield. This highlights the need for further research into its resistance to heat stress.

The results of the study confirmed the high drought tolerance of sorghum and pearl millet. Both crops withstood a reduction in soil moisture levels of up to 40% of their field capacity. Sorghum showed high tolerance to prolonged periods of high temperatures (up to +40°C), making it a suitable crop for growing in regions with extreme climatic conditions. Millet also showed considerable tolerance to climatic stresses due to its low moisture requirements and efficient utilisation of short-term rainfall. Chickpea, despite its medium level of tolerance, requires improved agronomic approaches to increase its tolerance to heat and water stresses (Table 2).

***Table 2**. Agronomic characteristics of the crops under study*

Characteristic	Sorghum	Chickpea	Millet
Average yield (t/ha)	4.2	1.8	3.6
Duration of vegetation (days)	110	95	85
Water consumption (l/ha)	5,200	4,500	4,000
Resistance to drought	High	Average	High
High-temperature tolerance	High	Average	High

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

The analysis of the data shows that sorghum and millet are highly adaptable to dry conditions. Sorghum has the highest yields, which underlines its effectiveness even under significant climatic stress. Millet, due to its short growing season and low water requirements, is a promising crop for regions with a moisture deficit. Chickpea shows potential for crop rotation due to its agronomic characteristics but requires adaptation of agricultural practices to improve yields in drought conditions. The study of the agronomic characteristics of sorghum, chickpea and millet confirmed their importance for the adaptation of agriculture in the Kyrgyz Republic to climate change. Sorghum and millet showed the best results in terms of yield and resistance to climatic stress, while chickpea, despite its lower yield, can be useful for crop rotations. The findings provide a scientific basis for scaling up the cultivation of these crops to improve food security and resilience in the region's agricultural sector.

Efficiency in the use of water resources

Water use efficiency is one of the key parameters for assessing the adaptation potential of crops under drought conditions. As part of the study, water use of sorghum, chickpea and millet was analysed and WUE was calculated. This was used to compare the ability of each crop to form a crop at minimum water use. Sorghum consumed the most water among the studied crops – 5,200 l/ha, which is due to its intensive growth and large biomass. Millet, on the other hand, had the lowest water consumption of 4,000 l/ha, which is a significant advantage in conditions of water scarcity. Chickpea had an average of 4,500 l/ha, but its water consumption was uneven during the growing season, with a peak during flowering and seed formation.

The data obtained show that the high-water consumption of sorghum is justified by its highest yield (4.2 t/ha). Millet, despite having the lowest water consumption, showed a significant yield of 3.6 t/ha, indicating its high level of adaptation to dry conditions. Chickpea, although having an average level of water consumption, demonstrated the lowest yield of 1.8 t/ha, which may be due to its insufficient resistance to heat stress. According to water use efficiency calculations, millet showed the highest WUE of 0.9 kg/m^3, which confirms its efficiency in converting limited water resources into crop yields. Sorghum had a coefficient of 0.81 kg/m^3, which is the second highest considering its high-water use. Chickpea showed the lowest coefficient of 0.4 kg/m^3, indicating the need to optimise its cultivation under water deficit conditions. The water consumption rates of sorghum, chickpea and millet, as well as their WUE, were used to compare the ability of crops to produce crops under conditions of limited water resources (Table 3).

***Table 3**. Indicators of water use and WUE of the studied crops*

Crop	Water consumption (l/ha)	Yield (t/ha)	WUE (kg/m^3)
Sorghum	5,200	4.2	0.81
Chickpea	4,500	1.8	0.4
Millet	4,000	3.6	0.9

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

The table shows that millet is the most water-efficient crop with the highest WUE (0.9 kg/m^3) and the lowest water use (4,000 l/ha), as it provides a stable yield even with minimal water resources. Sorghum, despite its higher water consumption (5,200 l/ha), shows a high yield (4.2 t/ha), making it a productive option for regions with available water resources. Chickpea, with the lowest WUE (0.4 kg/m^3), requires additional agronomic measures to increase its productivity. The behaviour of crops in the process of water consumption also depended on the developmental stage. Sorghum showed stable water use throughout the growing season due to its deep root system. Millet used water mainly at the initial stages of growth, which allowed it to complete the development cycle before the onset of dry conditions. Chickpeas had a significant peak in water consumption during flowering, which created a risk of crop losses in case of insufficient rainfall.

To assess the adaptive potential of the crops under study, it is important to compare their water requirements with traditional crops in the region, such as wheat, barley and maize. For instance, wheat consumes about 6,000 l/ha, which is higher than even sorghum (5200 l/ha), and has an average WUE of 0.7 kg/m^3. Maize, with water use of up to 7500 l/ha, has a WUE of about 0.8kg/m^3 but is much less suitable for regions with limited water resources compared to millet (Pashchenko, 2024). Comparison and analysis of water use efficiency confirmed the feasibility of replacing or supplementing traditional crops with drought-resistant crops, such as sorghum and millet, in the adaptation strategies of agriculture in the Kyrgyz Republic. In addition to reducing water inputs, this will increase yields in the face of climate change and improve the overall resilience of the region's agricultural systems.

Economic feasibility of growing drought-resistant crops

The cost and profitability analysis of drought tolerant crops was based on data on the costs of seeds, fertilisers, irrigation, crop protection products and labour, as well as expected revenues from crop sales using the cost-benefit analysis method. Millet demonstrated the highest economic efficiency among the crops studied. The cost of its cultivation was about USD 300 per hectare, while the profit reached USD 700 per hectare, which provided a maximum profitability of 133%. Sorghum, although it had higher irrigation and fertiliser costs (USD 350 per hectare), generated profits of USD 800 per hectare due to high yields, resulting in a 129% profitability. Chickpea, due to its low yields and uneven consumption of inputs, showed the least attractive economic performance. Its costs amounted to USD 320 per hectare, while the profit was only USD 400 per hectare, providing a profitability of 25%.

Compared to traditional crops in the region, such as wheat and barley, drought-tolerant crops have proven to be more cost-effective in the face of water scarcity. For example, the cost of growing wheat was around USD 400 per hectare, while the profit was USD 600, with a profit margin of 50%. Barley showed a profitability of 45%. This data highlights the significant advantages of millet and sorghum, which are not only less dependent on water resources but also provide higher economic returns (Fig. 1).

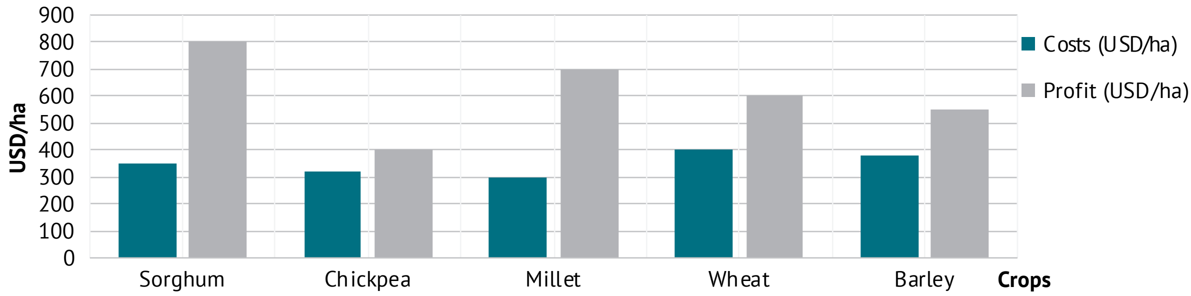

***Figure 1**. Economic performance of drought tolerant and traditional crops*
***Source:** compiled by the authors based on the State Programme for the Development of the Agro-Industrial Complex of the Republic of Kazakhstan for 2017-2021 (2017)*

The diagram clearly demonstrates the comparison of profitability and costs of growing drought-tolerant and conventional crops, confirming the economic viability of growing millet in resource-limited environments, while sorghum can be effective when sufficient water resources are available. Chickpea requires optimisation of agronomic approaches to increase its economic efficiency. A significant advantage of drought-tolerant crops is their stable yields even in extreme drought conditions. While conventional crops significantly lose productivity when there is a lack of irrigation, drought-tolerant crops demonstrate adaptation to climate stress, rendering them more attractive to farmers in arid regions. Based on the analysis, it is recommended that drought-tolerant crops be gradually introduced into the region's agriculture. Millet should be the main target for scaling up, given its high profitability and low water requirements. Sorghum can also be widely used in regions with accessible water resources due to its high productivity.

Modern agronomic approaches, such as improved varieties, drip irrigation and optimised plant nutrition, should be introduced for chickpea. This will increase its productivity and profitability, therefore competitive with other crops. Government support is also critical in encouraging the cultivation of drought-tolerant crops. This could include subsidies for the purchase of seeds and equipment, investments in irrigation systems and training for farmers. Such measures would accelerate the region's transition to adaptive agriculture. Cost-benefit analyses indicate that pearl millet and sorghum are more cost-effective than traditional crops in the region, especially in water-scarce regions. Millet has better profitability, and sorghum shows significant potential in regions with available water resources. Chickpea, although less economically viable, can be optimised through the adoption of new technologies. Scaling up the cultivation of drought-tolerant crops, combined with government support, will contribute to increasing the resilience of the region's agriculture to climate change.

Adaptation technologies and their impact on the sustainability of agricultural systems

Modern technologies of adaptation to climate change are key for ensuring the sustainability of agricultural systems in arid regions. One of the most effective methods of optimising water balance is the use of drip irrigation. This technology allows water to be delivered directly to the root system of plants, reducing evaporation losses and ensuring uniform soil moisturisation. In the study, the use of drip irrigation reduced water use in sorghum, chickpea and pearl millet by 20-30% compared to traditional methods such as surface or furrow irrigation. These traditional methods, which are widespread in the region, are characterised by significant water losses due to evaporation and infiltration into the lower soil layers. A more precise and rational drip irrigation approach promotes more efficient use of limited water resources (Yeraliyeva *et al.*, 2017).

Agricultural practices such as mulching and the use of organic fertilisers play an equally important role. Mulching helps to retain moisture in the soil, reducing evaporation and preventing the growth of weeds that compete with crops for resources. Organic fertilisers help to improve soil structure, increase its fertility and resistance to erosion (Yzakanov *et al.*, 2024). The application of these methods in this experiment increased the yield of millet by 15%, sorghum by 10% and chickpea by 8%, which is a significant result for dry conditions. Digital technologies such as the use of DJI Agras T30 drones, Sentinel-2 satellite imagery and Delta-T Devices soil moisture sensors provide accurate monitoring of crop health and enable rapid response to changes in growing conditions. In this study, analysing sensor data helped optimise irrigation schedules and prevent crop losses due to water deficits during critical phases of plant development. Such tools also help to reduce manual labour costs and improve farm management efficiency.

The introduction of the technologies described has the potential to significantly reduce the dependence of the agricultural sector on water resources, which is especially important in the arid regions of Central Asia. The use of drip irrigation, agronomic techniques and digital tools increases yields, ensuring stable production even with limited rainfall. This helps improve food security and reduce the risks of crop failure, which can have catastrophic consequences for local communities.

The prospects for applying the results go beyond Kyrgyzstan. Given similar climatic conditions, these technologies can be adapted for other Central Asian countries, such as Kazakhstan, Tajikistan and Uzbekistan. In addition, the developed adaptation strategies can form the basis for international agricultural development programmes in regions affected by climate change. The findings demonstrate the need to integrate adaptation technologies into national agricultural support programmes. The sustainability of agriculture in arid conditions depends on a combination of innovative methods of water management, rational use of fertilisers and the development of digital infrastructure. This will not only help to preserve crops but also ensure the long-term development of the agricultural sector in difficult climatic conditions.

The results of the study confirmed the high efficiency of modern adaptation technologies to increase the sustainability of agricultural systems in the arid conditions of Kyrgyzstan. The analysis of water use efficiency revealed the advantages of millet as the most economical crop in terms of WUE, while sorghum demonstrates high productivity with the availability of water resources. Chickpea requires optimisation of agronomic approaches to increase its yield and economic efficiency. The use of drip irrigation, mulching, organic fertilisers and digital technologies has significantly improved yields and minimised dependence on water resources. The prospects for implementing the results in other regions make them an important contribution to combating the global impact of climate change.

DISCUSSION

Adaptation of agriculture to climate change is a key topic of many contemporary studies. The results of this study should be compared with the findings of other authors to identify similarities, differences and generalise effective approaches to increasing the resilience of agricultural systems. G. Jalilova *et al.* (2024) note that farmers in South Issyk-Kul are adapting to climate change using drought-tolerant crops such as sorghum and millet. This is in line with the findings of this study where pearl millet showed the highest WUE (0.9 kg/m^3), demonstrating significant potential under drought conditions. C. Reyer *et al.* (2017) confirmed the importance of drought-tolerant crops in reducing the negative impacts of climate change on food security in Central Asia. Similarly, in this study, sorghum and pearl millet showed high drought tolerance, providing stable yields (4.2 t/ha and 3.6 t/ha, respectively), even under water deficit and elevated temperatures, highlighting their potential for regional agricultural adaptation.

A. Mirzabaev (2018) emphasised the importance of water management technologies for increasing crop yields in Central Asia. The results of the present study confirm the author's conclusions: the introduction of drip irrigation reduced crop water consumption by 20-30% without losses in yield. Similar conclusions were reached by S. Xenarios *et al.* (2019), which emphasises the importance of innovative irrigation methods for water conservation in mountainous areas of Central Asia. N. Michurina *et al.* (2024) emphasised the need to adapt agricultural technologies to reduce environmental impacts and improve resource efficiency. In this study, as in the author's conclusions, drip irrigation was identified as one of the key methods for optimising water use. Similar conclusions were drawn by I. Ologeh *et al.* (2021), who noted that traditional technologies adapted to modern conditions can increase crop yields, especially in water-scarce areas.

Authors D. Saleh and S. Bejaoui (2024) emphasised the importance of government policies, including subsidies for drought-tolerant crops, to reduce financial risks and stimulate innovation in agriculture. Their study confirms the effectiveness of sorghum and millet, which demonstrate high drought tolerance and stable yields, therefore beneficial for Kyrgyzstan. Government support, particularly through subsidies, could accelerate the scaling up of these crops. L. Kuhn *et al.* (2023) emphasise the importance of climate insurance to protect farmers from economic losses due to climate-related risks such as droughts. Combining climate insurance with the introduction of drought-tolerant crops creates an effective tool to increase the resilience of the Kyrgyz agricultural sector. This will ensure production stability and protect farmers' incomes. C. Parra-López *et al.* (2024) and L. Kuhl (2020) highlighted the importance of digital technologies, such as crop monitoring systems, for agricultural adaptation to climate change. Although this study focuses on agronomic aspects, such technologies can be useful for monitoring water consumption and optimising resources. A. Usta and M. Gök (2024) and G. Adamides *et al.* (2020) highlight the benefits of precision farming technologies for reducing water losses and increasing yields. The introduction of drip irrigation in this study confirms the effectiveness of such approaches for drought-tolerant crops.

R. Henry (2020) emphasised the importance of innovations in plant genetics to increase crop resilience to stress. The results of the present study confirm the potential of drought-tolerant crops such as sorghum, which demonstrated high yields (4.2 t/ha) even under water scarcity conditions. F. Nadeem *et al.* (2024) emphasise the selection of species and varieties for semi-arid regions, which is confirmed by the performance of millet in this study due to its highest WUE (0.9 kg/m^3). S. Njinju *et al.* (2022) noted the importance of growing climate-tolerant sorghum varieties for food security in dryland areas. In this study, sorghum also proved to be effective by combining high yield with developed tolerance to heat stress. Similar conclusions were reached by J. Matías *et al.* (2024) in an analysis of the prospects for new crops for food security. This correlates with the results of this study, where sorghum and pearl millet proved their adaptability to climate change, providing stable yields even under harsh conditions. A. Hossain *et al.* (2022) emphasised the importance of integrating climate resilient technologies into traditional agriculture, which confirms the feasibility of using technologies such as drip irrigation to increase productivity.

T. Zenda *et al.* (2020) investigated the adaptation of cereal crops to drought, emphasising the importance of a well-developed root system for crop survival under water deficit conditions. The study observed that a deep root system allows crops to access moisture from lower soil layers even during prolonged droughts. These findings are in good agreement with the results of this study where sorghum showed the ability to utilise water efficiently from deep soil layers, yielding high yields (4.2 t/ha). Similar observations were cited by K. Georgis and B.T. Makonnen (2024) who emphasises the importance of adopting policies and technologies to support dryland farming, including the integration of drought-tolerant crops. The results of this study confirm that sorghum and pearl millet cultivation can be a key element of such strategies, ensuring stable productivity even in water-stressed areas such as Kyrgyzstan. The use of innovative agronomic solutions such as drip irrigation can significantly improve the efficiency of these crops, reducing water use without sacrificing yields.

A. Ghaffar *et al.* (2022) analysed the adaptation of crop rotation systems and crop selection to ensure sustainable agricultural production in the face of climate change. The authors emphasise that the integration of drought-tolerant crops into crop rotations allows for optimised use of water and land resources while reducing the risk of crop losses due to climate stress. The results of this study confirm similar conclusions: sorghum and millet demonstrated high productivity even under conditions of limited water supply, which underlines their suitability for rotation. In addition, chickpeas, although with lower yields, can be used as a nitrogen-fixing crop, improving soil fertility and reducing the need for chemical fertilisers. The consistency between these results points to the versatility of approaches to agricultural adaptation in regions with similar climate challenges. Comparison of the results with those of other authors confirms the effectiveness of sorghum and millet cultivation as a strategy for agricultural adaptation to climate change. The combination of drought-tolerant crops with modern technologies such as drip irrigation and monitoring systems is a versatile approach that can be scaled up to other regions with similar climate challenges.

CONCLUSIONS

The research significantly contributed to the study of the adaptive capacity of agriculture to climate change, addressing the cultivation of drought-tolerant crops such as sorghum, chickpea and millet in Kyrgyzstan. The agronomic characteristics of the crops under study confirmed their effectiveness in the face of climate change. Sorghum showed the highest yield (4.2 t/ha) and demonstrated excellent resistance to drought and high temperatures due to its developed root system. Millet was distinguished by its short growing season (85 days) and lowest water consumption (4,000 litres/ha), therefore a promising crop for regions with limited water resources. Chickpea, despite having the lowest yield (1.8 t/ha), showed potential for use in crop rotations due to its nitrogen fixation properties in the soil.

Analysis of water use efficiency showed that millet was the most efficient crop in terms of water balance, with a WUE of 0.9 kg/m^3. Sorghum, despite its higher water use, also showed high productivity (WUE 0.81 kg/m^3). Chickpea, with a WUE of 0.4 kg/m^3, requires improved agronomic approaches to improve water use efficiency. The introduction of modern technologies, in particular drip irrigation, has significantly increased the efficiency of water use in this study. The use of this technology has optimised water consumption, reducing it by 20-30% compared to traditional methods such as surface or rainwater irrigation. The results of the study confirmed that the use of drip irrigation can ensure a stable harvest even in conditions of water shortage, increasing the resilience of agriculture to climate challenges.

The study highlighted the significant adaptive potential of drought-tolerant crops in ensuring food security. Sorghum and millet have proven their ability to maintain stable yields even in harsh climatic conditions, which opens prospects for their scaling up in regions with similar climate challenges. To increase the efficiency of using drought-tolerant crops, it is recommended to scale up experiments in different soil and climatic zones of Kyrgyzstan. Attention should also be paid to breeding new varieties of sorghum, chickpea and millet adapted to local conditions. Further research should address the impact of the introduction of these crops on socio-economic indicators, including farm profitability and water use efficiency. The integration of digital technologies for monitoring and managing water use could be a promising way to ensure the sustainability of the agricultural sector in the face of climate change. One of the main limitations of this study is that the experiments were conducted in only one local field, which may reduce the generality of the conclusions for other regions. In addition, the study focused mainly on agronomic parameters and did not cover socio-economic aspects of drought-tolerant crop adoption at the country level.

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CONFLICT OF INTEREST

None.

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Технології адаптації сільського господарства до змін клімату в Киргизстані

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Анотація. Зміни клімату суттєво впливають на продуктивність сільського господарства, особливо в регіонах із посушливими умовами, таких як Киргизстан. Вирощування посухостійких культур та впровадження інноваційних агротехнологій є ключовими заходами для забезпечення стійкості аграрного сектору. Метою дослідження була оцінка ефективності вирощування посухостійких культур (сорго, нуту та проса) в умовах Киргизстану, а також аналіз впливу сучасних технологій, таких як краплинне зрошення, на продуктивність та ефективність використання водних ресурсів. Дослідження проводилося протягом двох вегетаційних сезонів (2023-2024 роки) на експериментальному полі в Киргизстані. Урожайність визначали шляхом збирання врожаю з ділянок площею 1 $м^2$ і подальшого перерахунку на гектар. Водоспоживання вимірювали з використанням ґрунтових вологомірів Delta-T Devices (глибини 10, 20 і 30 см). Коефіцієнт ефективності використання води (WUE) розраховувався як співвідношення врожайності до обсягу водоспоживання. Моніторинг стану посівів здійснювався за допомогою дронів DJI Agras T30 та супутникових знімків Sentinel-2. Результати дослідження підтвердили високу ефективність сорго та проса в умовах посухи. Сорго продемонструвало найвищу врожайність – 4,2 т/га – завдяки розвиненій кореневій системі та здатності ефективно використовувати вологу. Просо показало найкращий WUE – 0,9 кг/$м^3$ – і найнижче водоспоживання (4000 л/га), що робить його оптимальною культурою для регіонів із дефіцитом водних ресурсів. Нут, незважаючи на нижчу врожайність (1,8 т/га), виявився перспективним завдяки своїм азотфіксувальним властивостям, які покращують родючість ґрунту. Застосування крапельного зрошення дало змогу знизити водоспоживання на 20-30%, забезпечуючи стабільний рівень врожайності навіть в умовах дефіциту води. Моніторинг з використанням дронів і вологомірів сприяв оптимізації зрошення, підвищуючи точність управління водними ресурсами. Дослідження підтвердило ефективність вирощування сорго та проса як ключових культур для посушливих регіонів, а також доцільність інтеграції краплинного зрошення для підвищення стійкості сільського господарства. Результати роботи надають науково обґрунтовані рекомендації для фермерів і політиків щодо впровадження посухостійких культур і сучасних агротехнологій у Киргизстані, що сприятиме продовольчій безпеці та стійкості аграрного сектору в умовах зміни клімату

Ключові слова: посуха; посухостійкі культури; волога; сорго; просо; нут; система зрошення; водокористування

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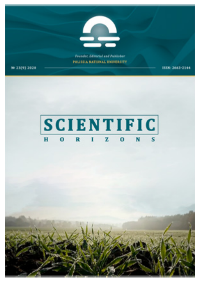

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Formation of complex community restoration management models in the context of sustainable agricultural development

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Abstract. The study aimed to develop effective management models for the global restoration of local communities in Ukraine in the context of sustainable development of the agricultural sector. The study analysed the main problems of the agricultural sector, such as limited financing, outdated infrastructure facilities, environmental issues in the country, high migration of the population, including soil degradation and water pollution, as well as high migration from rural areas. Based on this data,

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theoretical models were developed that incorporate local characteristics and resources. One of the key results was the identification of the need to create strategic plans that address the specifics of each region, as well as the active involvement of citizens in the decision-making process. The study proposed to introduce modern agricultural practices, including the use of the latest technologies, such as precision farming and automation of production processes. In addition, the study proposed to create specialised financial funds to support development and attract investment through public-private partnerships. Considerable attention was devoted to improving the skills of agricultural workers through educational programmes and training that would facilitate more effective implementation of the latest technologies and practices. Of particular importance was the development of recommendations for the implementation of environmentally friendly practices that reduce the negative impact on the environment and contribute to the long-term sustainability of the agricultural sector. The study determined that a comprehensive approach to community recovery can significantly impact the economic performance, social justice and environmental sustainability of Ukraine's agricultural sector. These models will not only provide better living conditions in rural areas but also ensure the stable development of the agricultural sector, which is of strategic importance for the national economy

Keywords: community recovery; agriculture; local government; strategic plans; financial resources

INTRODUCTION

To ensure economic, social and environmental stability in Ukraine, it is necessary to continue developing the agricultural sector. Managing the integrated recovery of territorial communities is becoming particularly relevant in the context of sustainable development. The main challenges faced by rural communities include a decline in agricultural productivity, population migration, infrastructure decay and environmental degradation. One of the key challenges is the lack of investment for small and medium-sized enterprises in rural areas, which limits the development of the local economy. In addition, insufficient attention is paid to environmental aspects, which are critical for the preservation of natural resources. Migration of the rural population to cities leads to labour shortages and deepening social inequality. In the current environment, when the country is facing climate and political challenges, it is necessary to develop new governance models that integrate economic, social and environmental aspects of sustainable development to restore territorial communities.

The analysis of the management of the restoration of territorial communities in the agricultural sector of Ukraine showed the importance of state policy, but there was a lack of mechanisms for its implementation at the local level. I. Kulchii (2018) highlighted the problems of sustainable development but did not propose management models or recommendations for public-private partnerships. The issue of organisational and legal support for the diversification of rural areas for the development of small and medium-sized enterprises was studied by many scholars. O. Olshanska *et al.* (2024) emphasised the importance of agricultural cooperation through public-private partnerships. However, their study did not propose specific measures to support enterprises. The processes of creating a competitive organisational structure in the grain industry were studied by L. Moldovan *et al.* (2023), focusing on the efficient use of resources for sustainable development. However, their study did not contain detailed recommendations on the social aspects of development.

V.M. Rusan and L.A. Zhurakovska (2023) analysed the impact of the agricultural sector on the Ukrainian economy, focusing on its role in the sustainable development of territorial communities. However, their study did not address current challenges, such as climate change and political instability, as well as innovative management models for community development. Many scholars studied the problems of rural governance in Ukraine. B. Feigel (2023) emphasised the need to create support systems for agricultural production that account for the needs of communities, but the issues of environmental sustainability and resource conservation have remained underestimated. Existing methods of managing agricultural areas do not always meet the requirements of sustainable development. S. Shutyak (2023) noted that the key problems are the lack of financial instruments to support innovation and insufficient integration of environmental aspects. The author also emphasised the importance of improving the level of education and training of agricultural workers. Many scholars have studied natural resource management in the context of sustainable development of the Ukrainian agricultural sector. O.M. Borodina and I.V. Prokopa (2014) emphasised the importance of an integrated approach that considers economic, environmental and social aspects, and noted that effective management depends on decentralisation and the involvement of local communities. The authors highlighted the lack of systematic monitoring and the need for further research. Human capital and technological innovation are also important aspects of sustainable community development. D. Khalizov (2023) studied community development in agriculture, emphasising the role of education and innovation. The main identified problems were the lack of a strategy for agricultural innovation and mechanisms for attracting investment, which significantly hindered the process of sustainable development.

The purpose of the study was to develop an effective management model for the comprehensive restoration of territorial communities in the context of sustainable development of the agricultural sector in Ukraine.

MATERIALS AND METHODS

The study was conducted over two years, from 2022 to 2024, and covered several key stages of data collection and analysis. The focus was on agrarian communities in different regions of Ukraine, which was used to obtain representative results and reflect the diversity of conditions and challenges faced by these communities. The first stage of the study was the analysis of regulatory documents – Law of Ukraine No. 2982-IV (2005) and development strategies. This included a thorough study of state programmes – Programs of the Department of Agricultural Development (2023), legislative acts and regional strategies – Regional Strategies for the Development of Territorial Communities – that regulate the development of the agricultural sector and territorial communities (Vasylchenko *et al*., 2015). At the next stage, an economic analysis was conducted, which included a study of key economic indicators of rural community development. The data were collected using statistical materials from the State Statistics Service of Ukraine, as well as reports of local authorities and analytical reports of specialised research organisations (Starikova, 2022; Report on the socio-economic…, 2023). This stage of the study described the current state of the agricultural sector in different regions and identified the main trends and challenges faced by rural communities.

One of the most important aspects of the study was the level of air pollution in Ukrainian cities. The study collected and analysed data on air pollution in cities such as Kryvyi Rih, Kamianske, Kyiv, Odesa, Mykolaiv and others using the Composite Air Pollution Index for 2023 and 2024. The choice of these cities is based on their regional diversity, industrial load, changes in pollution levels, and importance for assessing environmental conditions in the context of public health impact. Modelling the management processes of integrated community recovery was the next important component of the methodology. Three theoretical management models were developed based on the data obtained during the analysis of the regulatory framework and economic analysis. The modelling process used a Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis to identify strengths and weaknesses, as well as opportunities and threats to the development of the territorial communities. In addition, the Political, Economic, Social, and Technological (PEST) analysis was used to identify the political, economic, social and technological elements that influence community development.

The final stage of the study involved the modelling of five different governance models, each of which was analysed in the context of their potential for implementation in local communities. Each model was designed to consider the different economic, social and environmental conditions of the communities involved in the study. The pros and cons of each model were considered in detail during the modelling exercise. Some models provide higher levels of cost-effectiveness but may require significant financial investment or a high level of community involvement. Other models were found to be more suiTable for communities with limited resources, but their potential for long-term sustainability may be limited. The modelling also addressed how each model could be adapted to specific community conditions, such as the level of public and private investment, the intensity of agricultural development and the adoption of innovative technologies.

RESULTS

In the context of current Ukrainian development, an important challenge is to ensure the sustainable development of territorial communities, especially in the agricultural sector. The agricultural sector is central to the national economy, but its development is often accompanied by a range of problems, such as soil degradation, environmental pollution, uneven distribution of resources, and social problems in rural areas. Therefore, further development of models for managing the comprehensive restoration of territorial communities that would incorporate the needs of sustainable development and ensure a balanced development of the economic, social and environmental spheres is of particular importance. Sustainable development of the agricultural sector in Ukraine requires a systemic approach that includes both innovative technologies and the conservation of natural resources, equiTable distribution of benefits, human capital development and investment attraction. In this context, a variety of management models play an important role, each aimed at achieving specific goals and solving certain problems. These models include the innovative development model, the socio-economic model, the environmentally oriented model, the integrated resource management model, and the public-private partnership model.

The importance of implementing these models is confirmed by various studies and documents, such as the Sustainable Development Goals Report (2023), which emphasises the need to integrate economic growth with environmental sustainability and social justice. Another important document is the Agricultural Sector Strategy 2030 (Jandrokovic, 2022), which describes the need for a comprehensive approach to the development of the agricultural sector, considering environmental, economic and social aspects. These sources note that sustainable development requires not only economic growth but also the preservation of natural resources, social justice and infrastructure development. It is necessary to determine that each model has its advantages and disadvantages, and their integrated implementation will allow to achieve maximum efficiency in solving existing problems and ensure a high level of quality of life in rural communities.

Air pollution is one of the biggest environmental challenges facing Ukrainian cities (Havrysh *et al.*, 2022). It significantly impacts public health, ecosystems and overall living standards. Various sources of pollution, such as road transport, industrial emissions, heating and agricultural activities, contribute to the deterioration of air quality. Table 1 presents a composite index of air pollution in Ukrainian cities for 2023 and 2024. This index, which is based on quantitative indicators, reflects the overall level of pollution in each city and allows for a comparison of environmental conditions in different regions. It is an important method of monitoring the situation and identifying trends that may indicate an improvement or deterioration in air quality. The data presented in the Table shows the dynamics of changes in the pollution index in cities. Table 1 shows the composite air pollution index for Ukrainian cities in 2023-2024. The cities for the study were selected based on the following criteria: regional diversity, which allows us to represent cities from different regions of Ukraine to ensure the representativeness of the data; high level of industrial load, as in such cities industrial enterprises can have a significant impact on the environmental situation; dynamics of changes in air pollution levels, which reflects trends in the improvement or deterioration of the environmental situation; and the importance of these cities for the overall assessment of environmental conditions, as their environmental condition can have a special impact.

***Table 1**. A comprehensive index of air pollution in Ukrainian cities 2023-2024*

City	2023	2024	Difference
Kamianske	10.2	13.1	2.9
Kryvyi Rih	6.1	10.5	4.4
Dnipro	10.7	10.2	-0.5
Lutsk	7.3	8.7	1.4
Odesa	9.5	8.7	-1.3
Zaporizhia	7.3	8.1	0.8
Lviv	7.4	8	0.6
Vinnytsia	7.7	7.8	0.1
Mykolaiv	9.5	5.8	-3.7
Kyiv	8.1	7.1	-1

***Source:** compiled by the authors based on A. Velyka (2024)*

Analysis of Table 1 demonstrated an alarming trend in air pollution in Ukrainian cities. In general, between 2023 and 2024, there was an increase in the pollution index in most cities. A particularly significant increase in pollution was found in Kryvyi Rih (+4.4) and Kamianske (+2.9), indicating serious problems with controlling emissions from industrial facilities and vehicles. However, there are also positive examples, with Mykolaiv showing a significant decrease in air pollution (-3.7), which may be the result of effective environmental measures aimed at improving the environment. Several other cities, such as Odesa (-1.3) and Kyiv (-1), also showed improvements, but these changes are not sufficient to change the environmental situation dramatically. Overall, the Table shows that while some cities have seen positive changes, the overall trend is towards a deterioration in the environmental situation in Ukraine. The deterioration of pollution indicators, especially in industrial centres, indicates the need for urgent action by government agencies. This may include the development and implementation of stricter environmental regulations, the introduction of new emission treatment technologies, and the intensification of public initiatives to improve air quality.

The innovative model of agricultural sector development involves the widespread adoption of the latest methods and technologies to increase productivity, reduce costs and improve product quality. As this model reduces the negative impact on the environment and ensures the rational use of resources, it is necessary for ensuring the competitiveness of the Ukrainian agricultural sector on the global market and achieving sustainable development. Innovations in agriculture can include a variety of technological solutions, such as the automation of production processes, the use of drones to monitor field conditions, the introduction of precision farming to optimise the use of fertilisers and water, and the use of biotechnology to improve crop yields and quality. The use of drones and precision farming technologies helps to reduce production costs by 20-30%, which significantly increases the profitability of agricultural enterprises (Shchuryk, 2017).

The development of bioenergy, i.e. the production of energy from biomass, biogas and other renewable sources, is an important part of the innovation model. It reduces dependence on fossil fuels and allows rural communities to have their energy independence, which is an important component of sustainable development. In rural communities, the introduction of bioenergy technologies can lead to a 30-40% reduction in electricity costs and a reduction in greenhouse gas emissions (Kovalchuk, 2010). An innovative development model also requires the use of digital technologies that can improve the management of local communities and agricultural enterprises. This may include the introduction of data management systems, such as geographic information systems (GIS), which allow for the analysis of land resources, crop rotation planning, and environmental monitoring. The introduction of GIS and other digital technologies can increase the efficiency of agricultural management while reducing the harmful effects on the environment. To assess the feasibility of implementing an innovative model, it is worth considering the SWOT analysis presented in Table 2.

***Table 2**. SWOT analysis for an innovative development model*

Advantages	Disadvantages
▪ Implementation of the latest technologies ▪ Improving the competitiveness of the agricultural sector ▪ Improving product quality	▪ Insufficient infrastructure readiness for innovation ▪ High costs of innovation ▪ Limited access to modern technology in remote regions
Possibilities	**Threats**
▪ Increase productivity and efficiency ▪ Foreign investment attraction ▪ Expanding markets for our products	▪ The rapid depreciation of technology ▪ Instability in the labour market ▪ Risk of technological insecurity

***Source:** compiled by the author based on R. Kovalchuk (2010)*

The SWOT analysis demonstrates both the strengths and weaknesses of the innovative model of agricultural sector development. The strengths of this model are focused on the introduction of new technologies and increased competitiveness, which contributes to improved product quality and expanded markets. However, the existing weaknesses, such as insufficient infrastructure readiness and high costs of innovation, can become significant barriers to its successful implementation. To deepen the analysis, it is worth addressing the macroeconomic environment of agricultural development using the innovation model shown in Table 3.

***Table 3**. PEST analysis for an innovative development model*

Political factors	Economic factors	Social factors	Technological factors
State support for innovation in the agricultural sector	Economic instability	Increased demand for quality products	Development of IT technologies and their implementation
Regulation of the labour market	High costs of new technology	Labour migration to cities	Increasing the pace of process automation

***Source:** compiled by the author based on O. Golovnya (2010)*

The PEST analysis shows that the innovative model of agricultural sector development largely depends on external political and economic factors. It is necessary to provide government support and create favourable conditions for attracting investment. At the same time, social and technological factors play an important role in the introduction of innovations, as they can influence the readiness of the labour force to new conditions and the speed of adaptation to technological changes. Thus, the innovative model of agricultural sector development contributes to increased competitiveness, reduced costs and improved product quality, which are important factors for the sustainable development of local communities. However, for the successful implementation of this model, it is necessary to ensure access to financial resources, support from the state, as well as the active involvement of scientific institutions and research centres in the development and implementation of the latest technologies. The socio-economic model of territorial community management in the context of sustainable development of the agricultural sector provides for equiTable distribution of resources, improvement of living standards of the rural population and development of social infrastructure. This model is important for ensuring social stability and human capital development, which are key elements of sustainable development. Ensuring equal access to resources and services for all members of the community is the main objective of the socio-economic model. This may include the provision of social programmes, assistance to the poor, job creation and access to high-quality education, healthcare and other social services. In this context, the analysis of strategic objectives is presented in Table 4, which presents a matrix of strategic objectives aimed at developing social infrastructure and increasing employment. To ensure social stability and sustainable development of territorial communities, an effective social protection system is required (Shebanina *et al.*, 2023).

Table 4. Matrix of strategic goals			
Strategic objective	**Description**	**Implementation period**	**Expected result**
Increase in the level of employment	Creation of new jobs in the region	3 years	Reduction in unemployment by 20%
Development of social infrastructure	Construction of schools, hospitals, roads	5 years	Improving the quality of life
Attracting investment	Stimulating investors through tax incentives	2 years	Increase in investment volumes by 30%

Source: *compiled by the author based on O.A. Zinchenko et al. (2023)*

The socio-economic model also envisages the development of an education and training system for the agricultural sector. This includes the creation of specialised educational institutions, internship and experience exchange programmes, and advanced training for agricultural workers. Investing in human capital development is crucial for ensuring sustainable growth of the agricultural sector and improving living conditions in rural communities. An important element of the socio-economic model is also the development of social infrastructure, which includes the construction and modernisation of schools, hospitals, roads, utilities and other facilities that ensure a comforTable life in rural areas. This helps reduce migration from rural to urban areas and makes rural areas more attractive for young professionals and entrepreneurs. The expansion of social infrastructure is a fundamental factor in achieving sustainable progress in rural communities and improving the quality of life of the population (Malik *et al.*, 2024).

Support for small and medium-sized businesses in the agricultural sector is an important component of economic growth and job creation in rural communities, and the socio-economic model provides for this. This may include the provision of grants, subsidies, concessional loans and support for the establishment of cooperatives and other forms of producer associations. Table 5 highlights the planned and used budgets for different categories of expenditure in an agricultural support project that focused on the development of small and medium-sized enterprises in rural communities. The Table shows how effectively the budget for these purposes was used in 2023.

Table 5. Budget allocation in 2023			
Expense category	**Planned budget (UAH)**	**Budget used (UAH)**	**Deviation (%)**
Infrastructure projects	20,000,000	18,500,000	-7.5%
Social programmes	10,000,000	11,200,000	+12%
Personnel learning and development	5,000,000	4,700,000	-6%

Source: *created by the authors based on V. Yakobchuk et al. (2018)*

Thus, the socio-economic model of territorial community management aims to ensure a fair distribution of resources, improving living standards and developing social infrastructure. This allows for the creation of conditions for sustainable development and social stability in rural communities, which is an important element for achieving long-term goals in the agricultural sector. The environmentally oriented model of agricultural sector management includes practices that minimise harmful effects on the environment and contribute to the preservation of natural resources for future generations. This model is an important part of the concept of sustainable development, as the long-term development of agriculture and local communities depends on ensuring environmental sustainability. The main principles of the environmentally oriented model are the rational use of land resources, conservation of biodiversity, reduction of greenhouse gas emissions and water pollution, and the introduction of environmentally friendly production technologies. The conservation of natural resources and the introduction of environmentally friendly technologies are essential for sustainable agricultural development (Golovnya, 2010).

Sustainable land management involves the use of methods that help maintain soil fertility and prevent erosion and degradation. This can include the use of organic fertilisers, crop rotation and agroforestry practices that improve the microclimate and preserve soil. Sustainable land use is crucial for the conservation of natural resources and the development of the agricultural sector in the future. Data on various aspects of land use are presented in Table 6, which includes an analysis of stakeholders that are important for assessing the effectiveness of these practices.

Table 6. Stakeholder analysis			
Stakeholder	**Interests**	**Impact on project**	**Degree of involvement**
Local authorities	Improving the quality of life of the population through the creation of new jobs, modernisation of infrastructure and improved access to services	Makes decisions on regional development projects, land allocation, and financing of infrastructure projects	High: central in the coordination and implementation of projects at the local level
Environmental organisations	Conservation of biodiversity, reduction of soil and water pollution, and combating land degradation	Monitor the implementation of environmental standards and provide recommendations on sustainable land use.	High: actively influences the environmental aspects of the project through legislative and regulatory mechanisms
Citizens	Ensuring environmental safety, and reducing health risks associated with air and water pollution	Influence through public hearings, participation in elections and organisation of local initiatives	Average: actively involved in decision-making through civic initiatives, but their influence is limited by the legal framework
Business	Benefit from environmental investments and increase productivity and competitiveness through the introduction of new technologies	Financing innovative projects involved in public-private partnerships for the development of agricultural areas	Low: limited influence on decision-making, but important as a financial partner of the project

Source: *compiled by the author based on O.A. Zinchenko et al. (2023)*

Biodiversity conservation involves protecting natural ecosystems, preserving rare plant and animal species, and implementing practices that help maintain ecological balance in rural communities. This may include the creation of protected areas, the introduction of agroecological technologies, and the development of eco-tourism. For instance, ArcelorMittal Kryvyi Rih uses technologies to reuse metallurgical slag, which helps reduce pollution and preserve natural resources. The reduction of greenhouse gas emissions and water pollution is an important aspect of an environmentally friendly model. This can include the introduction of emission-reducing technologies such as renewable energy, reduced use of pesticides and chemical fertilisers, and water management systems. As an example, Stepova mine in Pershotravensk has implemented a coal mine methane utilisation project that helps reduce greenhouse gases while providing energy to the mine, reducing its environmental footprint. The environmentally friendly model also includes the development of organic farming, which includes production methods that do not harm the environment and ensure high-quality products. For instance, Ukrainian Mineral Fertilisers LLC in Kryvyi Rih processes by-products from coke plants to create organic fertilisers for agriculture, reducing dependence on chemical fertilisers (Shebanina *et al.*, 2023). In summary, the environmental management model of the agricultural sector aims to maintain environmental sustainability, conserve natural resources, and reduce negative environmental impacts. In the context of the agricultural sector, this model is an important part of the concept of sustainable development and is a prerequisite for the long-term development of territorial communities. The integrated resource management model envisages a comprehensive approach to managing all available resources of territorial communities, including natural, economic and human resources. This model is important for ensuring the efficient use of resources and achieving maximum efficiency in their distribution and use.

Interaction between different sectors of the economy is an important element of this model, which allows for synergies in the use of resources. This may include coordination between the agricultural sector, industry, transport, energy and other sectors, which allows for optimised use of resources and their efficient distribution. Coordination between these sectors is a key factor in ensuring effective resource management and achieving sustainable development of territorial communities. An integrated resource management model also involves the development of a planning system that includes long-term planning of resource use, risk analysis and forecasting of future changes. This helps to ensure sustainable use of resources and prevent their depletion. Long-term planning and effective resource management are impossible without adequate support and resources. Table 7 shows the main components of the integrated model, and the resources required for their implementation.

Table 7. Components and resources	
Components	**Resources required**
Rational use of natural resources	▪ GIS systems ▪ Analytics platforms
Integration of modern technologies	▪ Financial investments ▪ Human resources
Coordination between different levels of government	▪ Technical support ▪ Modern information systems

Table 7. Continued

Components	Resources required
Public involvement	▪ Public support ▪ Educational programmes

Source: *created by the author based on V. Yakobchuk et al. (2018)*

The implementation of water management systems is an important part of the integrated model; these systems ensure the wise use, conservation and restoration of water resources. This can include the implementation of irrigation systems, water reservoir management and the development of technologies that reduce water loss and optimise water use. To support the sustainable development of agriculture and local communities, effective water management is essential (Lazareva, 2021). The integrated model also envisages the development of land management systems that include ensuring the rational use of land, preventing its degradation and ensuring its restoration. This may include the introduction of technologies that help preserve soil fertility, crop rotation, and the use of agroforestry technologies. Effective land management is a prerequisite for ensuring sustainable development of the agricultural sector and conservation of natural resources (Skydan *et al.*, 2021). Therefore, the integrated resource management model is aimed at ensuring an integrated approach to managing all available resources of territorial communities, which allows for maximum efficiency in their distribution and use. This model is important for ensuring the sustainable development and resilience of the agricultural sector, as it allows for the efficient use of natural, economic and human resources. The public-private partnership (PPP) model involves the private sector in the management and development of territorial communities in the context of sustainable agricultural development. This model is important for providing financial support for development projects, improving management efficiency and introducing the latest technologies in the agricultural sector. The main principle of the PPP model is cooperation between public authorities and the private sector, which allows for joint financing of projects, sharing of risks and responsibilities, and improved resource management. This may include the development of infrastructure projects, construction of social infrastructure facilities, introduction of new technologies in the agricultural sector, and support for small and medium-sized businesses. The PPP model is a key method for ensuring the sustainable development of territorial communities and improving the efficiency of resource management (Lazareva, 2021). An important aspect of the PPP model is also the provision of access to financial resources, which allows for the implementation of large-scale projects in the agricultural sector, such as the construction of new plants, infrastructure development, the introduction of new technologies, and the creation of new jobs. This contributes to the competitiveness of the agricultural sector in the global market and ensures the sustainable development of local communities. Attracting private capital is an important element for ensuring financial stability and development of the agricultural sector. The tasks and role of the state in this model are presented in Table 8.

Table 8*. Main tasks and role of the state in the PPP model*

The task of the state	Details
Regulation and control of contract performance	Ensuring that private partners fulfil their obligations and protecting public interests
Stimulating private investment	Providing tax incentives and financial support to attract private capital.
Ensuring equal conditions for partnership participants	Ensuring transparent and fair terms of cooperation for all project participants.

Source: *compiled by the author based on Programs of the Department of Agricultural Development (2023)*

The rural community development model also envisages that the private sector is actively involved in building social infrastructure in rural communities. This includes building schools, hospitals, roads, utilities and other facilities that improve the quality of life in rural areas. This not only reduces migration from rural to urban areas but also makes life in rural areas more attractive for young professionals and entrepreneurs. Private sector participation in the development of social infrastructure is an important condition for the sustainable development of territorial communities. In addition, the PPP model improves resource management efficiency through the involvement of the private sector in the management of natural, economic and human resources. This includes the introduction of new technologies that contribute to the rational use of resources, reduce negative environmental impacts, and increase productivity in the agricultural sector. The involvement of the private sector in resource management helps ensure efficient use of resources and achieve sustainable development. Thus, the public-private partnership model is an important tool for ensuring the sustainable development of territorial communities in the context of the agricultural sector.

It attracts financial resources, improves management efficiency, introduces the latest technologies, and ensures the development of social infrastructure in rural communities. This model helps to create favourable conditions for sustainable development, increase the competitiveness of the agricultural sector and improve the quality of life in rural communities.

The development of models for managing the comprehensive restoration of territorial communities in the context of sustainable agricultural development is an important step in ensuring the sustainable and efficient development of Ukraine's regions. The innovative, socio-economic and environmentally oriented models proposed address various aspects of community development. These models can be applied following the specifics and needs of each region. Each model has its advantages, weaknesses, opportunities and threats, which have been assessed using SWOT and PEST analyses and other analytical tools. Sustainable development of local communities, especially in the agricultural sector, is one of the key challenges in Ukraine's current development. The problems of soil degradation, environmental pollution, uneven distribution of resources and social difficulties in rural areas require a comprehensive approach to address them. In this regard, the development and implementation of integrated rehabilitation models that promote sustainable development of the agricultural sector, including innovative, socio-economic, environmentally oriented, integrated resource management and public-private partnership models, is noteworthy. A comparative analysis of the models is presented in Table 9.

***Table 9**. Comparative table of models of integrated restoration by sustainable development of territorial communities in the agricultural sector*

Model	Advantages	Disadvantages
An innovative model	▪ Implementation of the latest technologies ▪ Improving production efficiency ▪ Reduced environmental impact	▪ High costs of innovation ▪ Insufficient infrastructure readiness
Socio-economic model	▪ Ensuring social justice ▪ Improving economic stability	▪ Long implementation time ▪ Dependence on external factors
An environmentally friendly model	▪ Conservation of natural resources ▪ Reducing environmental pollution	▪ Economic growth may be limited
Integrated resource management model	▪ An integrated approach to management ▪ Balanced development of territories	▪ High need for coordination between actors
Public-private partnership model	▪ Attracting additional resources ▪ Improving project efficiency	▪ Problems of interaction between public and private entities

***Source:** created by the authors*

A comparative analysis of these models demonstrates that each has its advantages and disadvantages. The innovation model focuses on the introduction of the latest technologies, increasing production efficiency and reducing environmental impact, but requires significant investment and infrastructure support. The socio-economic model aims to ensure social equity and economic stability but may take longer to implement. The environmentally oriented model prioritises the conservation of natural resources but may limit economic growth. The integrated resource management model provides an integrated approach to land management but requires a high level of coordination between different actors. Public-private partnerships allow for attracting additional resources for development but may face problems in interaction between public and private entities. Therefore, to achieve sustainable development of territorial communities in the agricultural sector, it is necessary to apply various management models comprehensively, considering their specificity and complementarity. An important aspect is also the support of the state, scientific institutions and investment attraction, which will contribute to the effective implementation of the selected approaches.

DISCUSSION

In this study, five different models of integrated community recovery in the context of sustainable development of the agricultural sector in Ukraine were considered. Each has advantages and disadvantages. The involvement of local communities, the use of closed-loop technologies, the introduction of environmental insurance, and the integration of circular economy principles are all factors that define the models. An important aspect of the study was to determine the role of environmental insurance in mitigating the risks associated with environmental hazards, such as soil, water and air pollution. This helps to ensure the sustainable development of agriculture even in difficult environmental conditions. Attention was also focused on improving the regulatory framework for effective management of the restoration of damaged areas and ensuring transparency of these processes. The study by O.V. Lazareva (2021) emphasises that the circular economy can become a driving force for the sustainable development of rural communities. This concept is based on the efficient use of resources, waste minimisation and the introduction of closed production cycles, which is especially relevant for agricultural areas where natural resources are the main asset.

The role of international cooperation in implementing the principles of circular economy and environmental insurance is particularly important (Tanchyk *et al.*, 2024). The study shows that sharing experiences with other countries that have successfully implemented these principles can be an important source of knowledge and practical recommendations for Ukraine. This correlates with the findings of studies such as Conceptualising the Circular Economy (Panwar & Niesten, 2020), which highlighted the importance of international cooperation in achieving sustainable development. In this context, it is important to note that Ukraine's active participation in international programmes and projects can help attract foreign investment and increase the efficiency of implementing innovative approaches to resource management.

The study also determined that the implementation of circular economy principles can reduce material costs and minimise waste, which is especially important in agricultural areas where natural resources are limited. This conclusion correlates with the findings of J. Kirchherr *et al.* (2023), who also emphasised the importance of closed cycles in production to reduce environmental impact and increase economic sustainability. In Europe, this is particularly evident in agricultural systems, where the use of closed loops can optimise the use of fertilisers and other inputs, thereby reducing economic costs and environmental impacts. The post-war reconstruction of Ukraine creates unique conditions for the implementation of circular economy principles and environmental insurance (Skliar *et al.*, 2024). Recovery should include not only physical reconstruction of infrastructure but also the introduction of sustainable practices that can withstand future challenges. This includes the introduction of closed loops in production processes and the integration of environmental insurance to minimise risks.

O. Therond *et al.* (2019) addressed how cities and regions can implement the Sustainable Development Goals through territorial governance. This study demonstrates commonalities with approaches to sustainable development in the agricultural sector, including a territorial approach, sustainable development of natural and human resources, and involvement of local communities in decision-making. The main difference is that the O. Therond *et al.* study covers a wider range of issues, including regional and urban planning, while the other study focuses on the agricultural sector. In addition, the Ukrainian researchers put more emphasis on the introduction of financial mechanisms and technological innovations, while the O. Therond *et al.* emphasises management coordination between different levels of government. The research study "Transforming Rural Farm Livelihoods" (Singh *et al.*, 2020) analysed sustainable rural development projects that focused on capacity building and skills development, which were key to the recovery of locally led communities. In this context, the common features with other studies were the emphasis on local community development, sustainable resource management, and citizen engagement in decision-making. The main difference was that the World Bank study emphasises skills development and training as the main driver of change, while this study focused on the introduction of financial mechanisms and innovations in the agricultural sector to ensure sustainable development.

P. Besseau *et al.* (2018) investigated ecological restoration, emphasising the importance of landscapes and forests in sustainable development strategies. This study shared commonalities with other articles on natural resource management and ecosystem restoration, especially in the context of sustainable resource use and the preservation of natural equilibrium. The main difference was that this study focused on the role of forests and landscapes in overall sustainable development strategies, while this study focused on the agricultural sector and its technological and financial aspects for the sustainable development of territorial communities. S. Ndlela and S. Worth (2023) examined strategies to increase the capacity of farmers in rural areas, focusing on sustainability and environmental sustainability, which are important aspects of community governance. This study shared similarities with the present study, focusing on skills development and sustainable use of resources in local communities. The main difference was that the study focused on developing the capacity of farmers and their ability to adapt to change, while this study paid more attention to the introduction of financial mechanisms and technological innovations to ensure the sustainable development of agrarian territorial communities.

P. Silva *et al.* (2023) examined how innovation models can be adapted to support sustainable regional development in less developed regions, particularly in agricultural areas. They proposed a conceptual framework for integrating innovation into territorial governance, which is particularly important for the effective management and recovery of local communities. Commonalities with other studies included the emphasis on the importance of innovation and sustainable development in territorial governance. The main difference was that the authors focused on the adaptation of innovative models in less developed regions, while this study focused more on the financial and technological aspects of sustainable development of agricultural communities.

Thus, to achieve sustainable development of territorial communities in Ukraine, it is important to implement comprehensive models that address financial, environmental and technological aspects. The study examined five restoration models aimed at using the circular economy, environmental insurance, and involving local communities in decision-making. Each of the models has its advantages and disadvantages, but the common thread is the emphasis on ensuring the sustainability of agricultural areas through innovative approaches. International cooperation is particularly important, as it allows for the exchange of experience with other countries that have already successfully implemented similar models. This helps to improve the efficiency of resource management and adaptation to modern challenges. The introduction of environmental insurance helps to reduce the risks associated with environmental hazards, such as soil and water pollution, which is critical for the sustainable development of agriculture in Ukraine (Drobitko & Alakbarov, 2023). Post-war reconstruction creates unique opportunities to rethink approaches to land management. This includes not only the physical reconstruction of infrastructure but also the introduction of sustainable practices that ensure resilience to future environmental and economic challenges, guaranteeing the long-term development of agricultural communities.

CONCLUSIONS

This study developed a model of integrated community recovery, the Model of Integrated Resource Management in Territorial Communities, based on the principles of transparency, accountability and citizen engagement in the management process. The results confirm the importance of efficient use of resources to achieve sustainable development. In 2024, the air pollution index in Kryvyi Rih increased to 10.5 and in Kamianske to 13.1 (+2.9). At the same time, Mykolaiv showed a decline to 5.8 (-3.7), and Odesa – to 8.7 (-1.3). In terms of budget allocations, social programmes exceeded their planned budget by 12%, while infrastructure projects were under-executed by -7.5%.

The practical significance of the model is an improvement of the quality of life of residents by optimising resources and involving the community in decision-making. To implement the model, it is important to provide training and develop a learning system. An effective monitoring and evaluation system is necessary to identify problems quickly. The use of modern information technology also increases the efficiency of resource management. Implementation of this model will allow for better use of resources, which will lead to improved living standards, sustainable development and socio-economic stability in local communities. The results have great practical potential and can be used to improve resource management at the level of territorial communities. However, the study has certain limitations. In particular, the integrated resource management model was developed based on the analysis of data obtained in specific territorial communities, which may limit its applicability in other contexts. In addition, the successful implementation of the model depends on many factors, including political, economic and social conditions, which may vary from one situation to another.

Given these limitations, further research in this area could be aimed at adapting the model to different types of territorial communities, as well as at studying the impact of various factors on the effectiveness of its implementation. An important area for further research is also the development of tools and methods for monitoring and evaluating the effectiveness of resource management, which will improve the accuracy and efficiency of decision-making.

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CONFLICT OF INTEREST

None.

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Формування моделей управління комплексним відновленням територіальних громад у контексті сталого розвитку аграрної сфери

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Анотація. Мета даного дослідження полягала у розроблені ефективних моделей управління для глобального відновлення локальних спільнот України в контексті стійкого розвитку аграрної сфери. У дослідженні було проведено аналіз основних проблем аграрного сектору, таких як обмежене фінансування, застарілі інфраструктурні об'єкти, екологічні питання країни, висока міграція населення, зокрема деградація ґрунтів та забруднення водних ресурсів, а також висока міграція населення з сільських територій. На основі цих даних були розроблені теоретичні моделі, які враховують місцеві особливості та ресурси. Одним із ключових результатів стало виявлення необхідності створення стратегічних планів, що враховують специфіку кожного регіону, а також активного залучення громадян до процесу прийняття рішень. Запропоновано впровадження сучасних аграрних практик, що включають використання новітніх технологій, таких як точне землеробство та автоматизація виробничих процесів. Крім того, було запропоновано створити спеціалізовані фінансові фонди для підтримки розвитку, а також залучення інвестицій через публічно-приватне партнерство. Значна увага приділялася питанням підвищення кваліфікації аграрних працівників через освітні програми і тренінги, що сприятиме ефективнішому впровадженню новітніх технологій та практик. Особливо важливою була розробка рекомендацій щодо впровадження екологічно чистих практик, які зменшують негативний вплив на довкілля та сприяють довгостроковій стабільності аграрного сектору. В результаті дослідження виявлено, що комплексний підхід до відновлення територіальних громад може суттєво вплинути на економічну результативність, соціальну справедливість та екологічну сталість аграрної сфери України. Застосування зазначених моделей дозволить не лише забезпечити кращі умови для життя у сільській місцевості, але й забезпечити стабільний розвиток сільськогосподарської галузі, що має стратегічне значення для економіки країни в цілому

Ключові слова: відновлення громад; сільське господарство; місцеве самоврядування; стратегічні плани; фінансові ресурси

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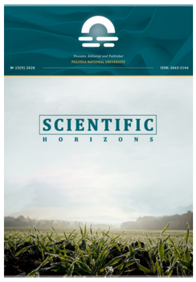

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Institutional support for the implementation of the circular economy in agribusiness

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Abstract. The aim of the study was to identify the key institutional support mechanisms necessary for the implementation of the circular economy in the agricultural sector of Ukraine, with a focus on adapting international best practices to local conditions. The study used content analysis of legislative acts, strategic documents and scientific sources, comparative analysis of institutional support models in the European Union, the United States, Australia and China, as well as statistical analysis of the current state of implementation of circular practices in Ukraine. The results of the

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study showed that successful implementation of the circular economy requires improvement of the regulatory framework, including the creation of tax incentives and government grant programmes for farmers, development of processing infrastructure, including regional agricultural waste processing centres, as well as intensification of educational initiatives to raise awareness of the benefits of circular approaches among farmers. The comparative analysis confirmed that the most effective support models are based on the synergy of government programmes, private investment and international assistance. The regional analysis revealed that, despite the negative impact of the war, the southern region of Ukraine retains significant potential for development due to its agricultural specialization. Innovations such as biogas plants and precision farming have been found to be able to meet up to 60% of farm energy needs and reduce water and fertilizer costs by up to 40%. However, the implementation of these approaches was constrained by limited funding and insufficient infrastructure. The study results highlighted the importance of a comprehensive approach to implementing circular economy principles, including legislative, financial and educational measures aimed at creating conditions for the economic, environmental and social sustainability of Ukraine's agricultural sector

Keywords: sustainable development; government regulation; agriculture; production cycle; environmental efficiency

INTRODUCTION

In today's world, rapid economic development is accompanied by an increase in resource consumption, which in turn leads to environmental problems and the depletion of natural resources. This problem is particularly acute in the agribusiness sector, where intensive use of land, water, and energy resources often upsets the ecosystem balance. In view of this, there is a need to introduce new approaches to managing production cycles and resources that ensure sustainable development. The circular economy is becoming increasingly important in global economic and environmental policy. Its concept is based on the integration of environmental, economic and social interests, contributing to sustainable development. In the context of agribusiness, which is one of the most important sectors of the economy in most countries, the implementation of circular approaches is crucial (Gavkalova *et al.*, 2024). This is due not only to the high dependence of agribusiness on natural resources, but also to its ability to generate a significant amount of waste that can be reused or recycled to create added value.

For Ukraine, as a country with a strong agricultural potential, the topic of circular economy is extremely important. The agricultural sector accounts for a significant portion of the country's gross domestic product, provides jobs in rural areas, and is an important export segment. At the same time, Ukrainian agribusiness is facing a number of challenges, such as soil degradation, dwindling water resources, and problems with waste storage and disposal (Shebanin *et al.*, 2024). All of this requires new approaches to managing production cycles and resources that could ensure the sustainability of the industry. Implementation of the circular economy in agribusiness requires an innovative approach that includes the development of new resource management mechanisms, integration of modern technologies and creation of favourable conditions for the development of circular practices. One of the key conditions for success is institutional support, which should ensure an effective combination of the economic interests of agribusiness and the requirements of sustainable development. The innovation of the circular economy lies in the transition from the traditional linear model of "production – consumption – disposal" to a cyclical model in which each product and resource is used for as long as possible (Szeląg-Sikora *et al.*, 2024). In the context of agribusiness, this means not only recycling and reusing waste, but also introducing precision farming technologies, producing organic fertilizers, using bioenergy resources and replacing synthetic materials with renewable ones.

Research on the circular economy is actively developing, and scientists from different countries are making a significant contribution to its theoretical justification and practical implementation. In this context, it is important to analyse approaches to implementing the circular economy in agribusiness through institutional support. Y.O. Akinwale (2023) notes that institutional support plays a key role in the implementation of circular approaches in Micro, Small & Medium Enterprises (MSMEs), which are the backbone of the agricultural sector in many countries. The author emphasizes the importance of financial assistance and the creation of knowledge-sharing platforms that stimulate the adoption of circular solutions in production chains. N. Arfaoui *et al.* (2024) investigate the impact of geographical proximity and organized partnerships on the effectiveness of circular economic practices. They argue that partnerships between farmers, government agencies, and private companies create synergies that facilitate the integration of circular approaches.

A.B.L. de Sousa Jabbour *et al.* (2023) focus on the use of Industry 4.0 technologies to optimize processes in food supply chains. They emphasize that digital tools, such as blockchain and the Internet of Things (IoT), allow for transparent waste management systems, which is important for agribusiness. A. Berxolli *et al.* (2023) analyse the impact of martial law on the development of innovations in Ukrainian agriculture. The authors note that, despite the difficulties, agribusiness continues to integrate circular practices, such as the reuse of organic waste and the development of alternative energy. S. Viscardi *et al.* (2023) highlight the importance of integrating the circular economy into food waste management. The study demonstrates that the introduction of composting, recycling and secondary product creation systems significantly reduces resource losses in the food sector.

Despite significant progress in the implementation of the circular economy in agribusiness globally, in Ukraine this process faces numerous challenges that limit its effectiveness. The main problem is the absence of a coherent institutional framework that would stimulate the use of circular approaches in agriculture. The purpose of this study was to develop effective mechanisms of an institutional model for the implementation of circular economy principles in agribusiness. The study aims to create a framework for the introduction of innovative approaches to resource management that will allow Ukrainian agribusiness to integrate into global environmental and economic trends, while maintaining sustainability and productivity even in the face of limited resources.

MATERIALS AND METHODS

The study of institutional support for the implementation of the circular economy in agribusiness was based on the analysis of scientific sources, strategic reports of government agencies, and statistical data obtained from national and international resources. The main focus was on the practices of implementing the circular economy in the agricultural sector of Ukraine and in the countries of the European Union (EU), the USA, Australia and China, which have the most developed institutional support mechanisms. In particular, the provisions of Directive No. 2008/98/EC (2008), which regulates waste management in EU member states and promotes recycling, and the European Green Deal (2024) strategic initiative, which focuses on a climate-neutral economy and resource-efficient business models, were used.

Among the important sources was the national policy of India in the field of crop residue management, presented in the document "Crop residue management. Operational guidelines 2024" (Ministry of Agriculture & Farmers Welfare, 2024), which regulates the sustainable development of the agricultural sector. In addition, the innovative solutions of the international platform Indigo Agriculture, which specializes in developing technologies to optimize the use of resources in agriculture, were analysed. The international experience was also presented by the United States Department of Agriculture (USDA) (2023), which supports sustainable development in US agriculture, as well as the Work plan on "Zero-waste City" pilot programme in China (2024), which aims to recycle agricultural waste into fertilizers and biofuels, creating closed production cycles.

The reports of the Ministry of Agrarian Policy and Food of Ukraine (2024) became an important source of information on the implementation of the National Waste Management Strategy until 2030. In addition, information from the Ministry of Finance of Ukraine (2024) on state support programmes for the agricultural sector was analysed, as well as data from the Open Budget Portal, which provides access to information on the use of budget funds. The main part of the information support was provided by the AgroStats Platform (2024), which contains statistical information on the state of the Ukrainian agricultural sector, including production volumes, crop areas and the implementation of innovative practices. These sources provided a comprehensive study of the legislative, financial and infrastructural aspects of the circular economy, allowing us to take into account international experience and adapt it to Ukrainian conditions.

The main research methods used were content analysis, comparative analysis, and statistical data analysis:

1. Content analysis was used for a systematic review of scientific sources, legislative acts and strategic documents. This allowed us to identify key factors of institutional support, such as tax benefits, financial incentives and educational initiatives. The method provided a structured approach to studying various aspects of government policies and practices in the circular economy, allowing for the identification of the most effective approaches.

2. Comparative analysis was used to assess the institutional support models of the EU, the US, and Asia. This method allowed us to compare the economic efficiency, environmental impact, and adaptability of these models to Ukraine's conditions. Particular attention was paid to financing practices, agricultural waste recycling systems, and cooperative development, which helped to identify the best international practices.

3. Statistical data analysis was used to evaluate data on the implementation of the circular economy in agriculture, including financial indicators, volumes of agricultural waste processing and the level of implementation of innovative technologies. This method allowed us to identify trends, assess the effectiveness of government support, and identify key barriers to the transition to circular models.

In addition, the study used formula (1) to calculate the forecast indicator for the amount of state funding for 2025:

$$F_{2025} = F_{2024} + \Delta F_{average}, \tag{1}$$

where F_{2025} – projected funding for 2025, F_{2024} – amount of funding in 2024, $\Delta F_{average}$ – average increase in funding over previous years.

In turn, $\Delta F_{average}$ is calculated as follows (2):

$$\Delta F_{average} = \frac{\sum(\Delta F)}{n}, \quad (2)$$

where ΔF is the increment between adjacent years ($F_n - F_{n-1}$), n is the number of increments (one less than the number of years in the period).

Given the analysis, recommendations were developed to improve the institutional support for the implementation of the circular economy in Ukraine. The content analysis allowed us to identify key aspects that need to be improved, in particular in the areas of financing and infrastructure development. A comparative analysis of support models in different countries showed that the most effective are those that combine public initiatives with private investment. Statistical analysis has identified opportunities for the development of recycling infrastructure and barriers related to insufficient funding and limited access to modern technologies.

RESULTS

The circular economy in agriculture worldwide is based on the idea of maximizing the use of resources while minimizing waste, which allows for added value and sustainable development. In Europe, the implementation of the circular economy is guided by legislative initiatives and the European Green Deal programme, which defines the transition to resource-efficient management systems. The Netherlands, for example, demonstrates a successful model of using biogas plants for processing livestock waste, which not only reduces waste but also provides farmers with an additional source of energy (Bianchi *et al.*, 2022). In the United States, the circular economy is largely based on public-private initiatives. Companies such as Indigo Agriculture are developing technologies to optimize resource use, including precision agriculture and regenerative practices (Lucas & Löschke, 2024). Subsidies for innovation play a significant role in facilitating farmers' transition to circular models.

The Asian region, in particular China, is focusing on large-scale national programmes to integrate traditional farming methods with modern technologies. As part of the Zero-waste City programme, numerous farmers' cooperatives have been established to process livestock waste into fertilizers and biofuels, which can significantly reduce environmental costs (Work plan..., 2018; Feng & Lam, 2021). The effective implementation of the circular economy in agribusiness largely depends on institutional support that provides the necessary conditions for the development of innovative business models. In global practice, there is a variety of institutional mechanisms that allow for the promotion of circular approaches adapted to local circumstances. In the EU, institutional support for the implementation of the circular economy is based on the creation of a regulatory framework that obliges member states to adhere to sustainable principles in agriculture. The European Green Deal provides funding for projects aimed at reducing waste, restoring natural resources, and transitioning to environmentally friendly technologies. Specialized support programmes for small farmers play an important role, allowing them to integrate circular practices even on a small scale.

In the United States, preference is given to public-private partnerships, where the role of the state is to stimulate innovation through subsidies and grants, and business is the main driver of change. The USDA actively supports the development of environmentally sustainable practices by funding projects in the areas of waste recycling and organic farming. Institutional support includes the creation of technology parks, where farmers have access to the latest technology and advisory assistance. Asian countries, in particular China, are taking a different approach. Government support here is large-scale and focuses on stimulating agricultural cooperatives. Significant funds are being invested in the development of waste recycling infrastructure, which allows for the creation of closed production cycles. The Zero-waste City programme has received significant funding from the state, which has contributed to the conversion of 80% of livestock waste into organic fertilizers (Work plan..., 2018; Niang *et al.*, 2024).

The practical experience of implementing the circular economy in agribusiness around the world demonstrates how effectively organized institutional models contribute to economic, environmental and social sustainability. Unique cases have emerged in different countries that clearly illustrate the benefits of circular approaches. One of the most striking examples is the Netherlands, where farms are integrating biogas systems. Livestock waste, which traditionally posed environmental risks, is now used for biogas production (Portillo-Tarragona *et al.*, 2024). This allows not only to provide farmers with energy, but also to generate additional income through the sale of excess energy. The success of this model largely depends on the support of the government, which finances the installation of biogas plants and compensates part of the farmers' costs. In the United States, the experience of the Indigo Agriculture platform, which implements the principles of regenerative agriculture, is worthy of note. Using data analysis technologies, the company helps farmers optimize the use of resources, including water, fertilizers, and pesticides. This not only increases yields but also reduces the environmental footprint of agriculture. Indigo Agriculture operates a public-private partnership scheme that incentivizes farmers through financial and technical support.

In China, the Zero-waste City project has become a model of a government programme aimed at large-scale implementation of circular practices (Work plan..., 2018). As part of this initiative, dozens of co-operatives have been established to process agricultural waste into fertilizers and biofuels. This approach has significantly reduced farmers' costs for purchasing chemical fertilizers, while reducing environmental pollution. A feature of the Chinese model is the full integration of government support with business efforts, which ensured effective project implementation even in remote regions. Denmark, as part of the EU, also demonstrates a successful case. The country's farms use organic waste to create a closed production cycle. For example, livestock waste is converted into organic fertilizer, which is used to grow grain crops (Sarfraz *et al*., 2023; Shubalyi *et al*., 2024). In turn, the grain serves as animal feed, completing the ecological cycle. Government programmes to support the circular economy promote the establishment of such systems through subsidies and training programmes.

Other interesting examples include South Africa, where AgriProtein uses organic waste to raise insects that are then processed into animal feed (Portillo-Tarragona *et al.*, 2024). This model has helped reduce organic waste while creating a new business segment. Thanks to technological innovation and partnership with the government, the project has gained international recognition. All these examples demonstrate that the success of the circular economy depends not only on innovative solutions but also on systemic institutional support. The integration of government initiatives, private business and international organizations allows for the creation of stable and effective circular concepts that can be applied to other countries, including Ukraine. Table 1 below shows a comparative analysis of the main circular economy models in the agricultural sector of three key regions: Europe, the US and Asia.

Table 1. *Comparative analysis of circular economy models of the agricultural sector in Europe, the USA, and Asia*

Region	Basic principles	Legislative instruments	Examples
Europe	Resource efficiency, innovations in waste management, development of biogas technologies	European Green Deal, directives on waste recycling (Directive No. 2008/98/EC)	Netherlands: biogas farms, France: organic fertilizers from waste
USA	Public-private partnerships, focus on innovations (IoT, AI) to optimize resources	USDA Sustainable Agriculture Programme, subsidies for agribusinesses	Indigo Agriculture: precision farming, Californian Farms: minimizing water consumption
Asia	Large-scale integration of traditional approaches with modern technologies, creation of agro-cooperatives	National programmes such as Zero-waste City, support for cooperatives	China: 'Zero-waste City', India: recycling residues into fuel

Source: *created by the authors based on the European Green Deal (2024), Directive No. 2008/98/EC (2008), USDA highlights progress in partnership with farmers to increase innovative domestic fertilizer production, expanding double cropping by investing in the American Agenda (2023), Leader in Sustainable Agriculture (2024), Work Plan for the Zero-Waste City Pilot Programme in China (2024), Ministry of Agriculture & Farmers Welfare (2024)*

Different approaches are used in each region, depending on local characteristics, economic conditions and the level of institutional support. The European model focuses on legislative initiatives and the development of resource efficiency. In the US, the emphasis is on innovation and public-private partnerships. The Asian approach focuses on large-scale government programmes and the integration of traditional practices with modern technologies. The table also illustrates specific examples of the implementation of these approaches, which can serve as a guide for other countries, including Ukraine. Ukraine is at the initial stage of implementing the circular economy, and the legislative framework plays a key role in this process. Today, national legislation partially integrates certain principles of the circular economy, but the lack of a comprehensive approach slows down the pace of adaptation to global environmental challenges.

One of the key regulatory acts is the Law of Ukraine No. 187/98-VR (1998), which regulates waste management and obliges business entities to take measures to recycle waste. Nevertheless, the legislation does not sufficiently stimulate the use of waste as a secondary resource, which is one of the main principles of the circular economy. The National Strategy for Waste Management in Ukraine until 2030 (2017) was approved, based on the principles of the European Waste Reduction Directive and envisaging the gradual introduction of a recycling system. However, its implementation in agribusiness remains fragmented. Another key document is the Law of Ukraine No. 1877-IV (2004), which provides partial reimbursement of costs for the introduction of modern technologies in this area. However, in the context of the circular economy, its provisions do not take into account the specifics of sustainable resource management. Successful examples include the harmonization of national legislation with European legislation, including the implementation of certain provisions of EU directives on waste management and bioenergy. For example, Ukrainian farmers have gained access to international financing programmes, such as the European Green Deal (2024), which promote the implementation of circular practices.

The main challenges of the legal framework include the lack of clear mechanisms to encourage agribusinesses to adopt circular models, insufficient coordination between authorities, and weak integration of public and private initiatives. These constraints hinder the development of the circular economy in Ukraine, while creating opportunities for its improvement by adopting international experience. The circular economy in the agricultural sector of Ukraine is beginning to gain relevance in the context of growing environmental challenges and the need for efficient use of resources. However, the level of adoption of circular practices remains low due to a limited number of institutional mechanisms, insufficient funding, and low awareness of the benefits of this model among farmers. Individual farms and large agricultural holdings are showing initial success in applying circular approaches. For example, some enterprises are actively implementing biogas plants for processing livestock waste, which provide energy autonomy for farms. Others are using agricultural waste to produce organic fertilizers, which reduces the cost of purchasing chemicals. However, such practices are sporadic and largely dependent on international grants or financial support from foreign organizations. At the same time, there is a lack of local programmes in Ukraine targeted specifically at the agricultural sector, which significantly limits the ability of farmers to implement circular approaches.

An analysis of regional implementation of the circular economy shows significant differences between regions. In the southern regions, where large agricultural enterprises predominate, the use of innovative technologies is more possible due to access to resources and financing. At the same time, small farms in the central and western regions face financial barriers that hinder innovation. It should also be taken into account that the southern region of Ukraine, which covers Kherson, Mykolaiv, Zaporizhzhia and Odesa oblasts, has always played an important role in ensuring the country's food security due to its agricultural specialization. However, the full-scale war has significantly affected its functioning. The partial occupation of territories, the destruction of infrastructure and the constant threat of hostilities pose significant obstacles to the implementation of a circular economy that requires stability and investment. Nevertheless, even in such circumstances, there are still some initiatives in the region that demonstrate resilience and adaptation to new realities. Drip irrigation systems, which are key to the southern region due to its arid climate, remain critical even in the face of conflict. In the communities under Ukrainian control, farmers are trying to preserve and develop these systems as they save water, which has become even more scarce due to the destruction and damage to irrigation infrastructure, including the Kakhovka hydroelectric power station.

At the same time, precision agriculture, which involves monitoring soil conditions and moisture using IoT technologies, remains accessible only to large agricultural holdings. The war has made it harder for small farmers to access the necessary equipment and financing, which significantly narrows the range of farms that can implement these innovations. The war has created new challenges for agricultural waste management, in particular due to the damage to supply chains. Nevertheless, farmers in areas not occupied by the enemy continue to use agricultural residues to produce fuel briquettes and organic fertilizers. For example, in Mykolaiv region, agricultural cooperatives are working to restore processing facilities using available resources. However, such initiatives remain sporadic due to a lack of finance and risks associated with the hostilities (Dovgal *et al.*, 2024).

Prior to the war, biogas plants were actively implemented in the southern region, especially by large agricultural companies (Dovgal *et al.*, 2024). However, their operation is currently significantly limited due to disruptions in the supply of raw materials and the destruction of infrastructure. For example, some biogas complexes in Zaporizhzhia region have ceased operations due to their proximity to the frontline. At the same time, in relatively safe areas, such as the north of Odesa region, these systems remain viable and provide energy independence for farms. In the difficult conditions of war, the role of agricultural cooperatives is growing, as they are becoming centres of mutual assistance for farmers. In communities that remain under Ukrainian control, cooperatives support farmers with access to common resources, such as processing plants or irrigation equipment.

Despite all the challenges, the southern region has significant potential for post-war recovery and the development of a circular economy. Rebuilding irrigation infrastructure, introducing new technologies for efficient resource use, and expanding international assistance could form the basis for the region's sustainable development. Integration of international experience in agricultural waste processing and soil restoration will be of particular importance.The implementation of the circular economy in the agricultural sector of Ukraine faces a number of barriers that limit the possibility of an effective transition to a new model of management. These obstacles are both systemic and situational in nature, driven by current economic, infrastructure and military challenges. The main ones are listed in Table 2.

Ukrainian legislation is only partially adapted to the principles of the circular economy. The absence of clear regulations that would stimulate the recycling of agricultural waste and the introduction of innovations significantly hinders the development of the industry. For example, the absence of tax breaks or subsidies for the use of secondary resources reduces the economic motivation for farmers and agriholdings. In addition, the legal framework does not provide for mechanisms to monitor compliance with the principles of sustainable resource use. The low level of coordination between government agencies makes it difficult to implement government support programmes, particularly in the agricultural sector. One of the key obstacles is limited access to finance. Due to the economic instability caused by the war, resources in the agricultural sector are mainly directed to basic needs, such as the sowing campaign and harvesting. Investment in long-term projects related to the circular economy remains minimal. The main obstacle to the implementation of the circular economy in the agricultural sector of Ukraine is limited funding from the state budget. The economic instability caused by the war has significantly reduced the state's ability to support innovative programmes, particularly in the areas of sustainable development and waste recycling.

Table 2*. Main barriers to the implementation of the circular economy in Ukraine*

Barrier type	Description	Examples
Legal and regulatory	Lack of a clear regulatory framework, lack of incentives for recycling.	Lack of tax benefits, insufficient coordination between authorities.
Financial constraints	Limited access to financing, lack of credit programs for small farmers.	Small farms do not have the resources to install biogas plants.
Infrastructure constraints	Lack of infrastructure for waste processing, destruction of facilities due to war.	Lack of modern waste sorting and recycling centres.
Technological and educational barriers	Lack of modern technologies, low level of educational programs for farmers.	High cost of technology, insufficient access to innovation.
Social and cultural	Stereotypes about innovation, low willingness to change traditional approaches.	Distrust of new models, low awareness of the benefits of the Circular Economy.
Impact of war	Destruction of infrastructure, shortage of resources, focus on basic needs.	Interruption of logistics chains, destruction of production facilities.

Source: *created by the authors*

The state budget, which is focused on critical needs such as defence, social protection and infrastructure rehabilitation, leaves few resources to finance long-term projects. With limited funding, the agricultural sector receives support mainly for basic needs, such as seeds, fuel, and the restoration of partially destroyed facilities, but not for the development of innovation or processing systems. It is worth considering the amount of state budget funds allocated for 2020-2024 (Fig. 1).

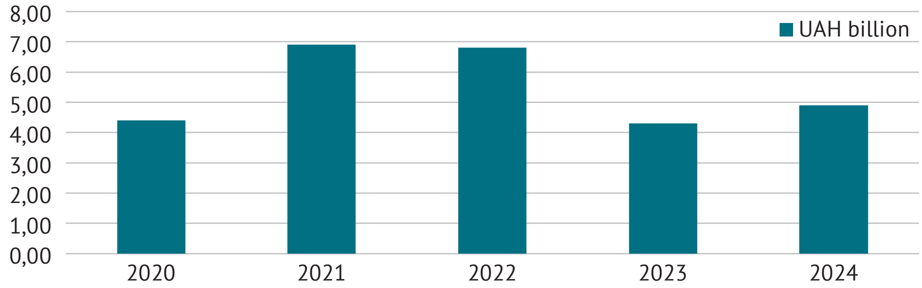

Figure 1*. State financing of the agricultural sector of Ukraine (2020-2024)*
Source: *created by the author based on data by Ministry of Finance of Ukraine (2024) and Ministry of Agrarian Policy and Food of Ukraine (2024)*

Analysing the data on the allocation of funds for the agricultural sector of Ukraine from the state budget for 2020-2024, we can note significant fluctuations in funding. The highest level of support was observed in 2021, when UAH 6.90 billion was allocated, indicating a significant focus on the development of the agricultural sector during this period. In 2022, funding remained at a high level (UAH 6.80 billion), which was likely due to the need to maintain the stability of agricultural production amid the deteriorating economic situation. However, in 2023, the amount of funding decreased significantly to UAH 4.30 billion, likely due to the reorientation of public resources to critical needs, including defence and social support, as a result of the war. In 2024, funding slightly increased to UAH 4.90 billion, indicating a gradual stabilization of the situation and attempts by the state to resume support for the agricultural sector.

In general, the trend shows a decrease in state funding for the agricultural sector since 2021, due to economic instability and the need to respond to the challenges posed by the war. At the same time, the growth in 2024 may indicate the state's efforts to promote the recovery of the agricultural sector even in the face of limited resources. For 2025, it is possible to make a forecast of the amount of state funding for the agricultural sector based on the average level of funding for 2020-2024, which is UAH 5.725 billion. Given that in 2024, compared to 2023, there was an increase in funding from UAH 4.30 billion to UAH 4.90 billion, there is reason to expect a further gradual resumption of support for the agricultural sector. The average growth formula was used to calculate the forecast.

$$\Delta F_1 = 6.8 - 6.9 = \text{-UAH } 0.1 \text{ billion}$$
$$\Delta F_2 = 4.3 - 6.8 = \text{-UAH } 2.5 \text{ billion}$$
$$\Delta F_3 = 4.9 - 4.3 = \text{UAH } 0.6 \text{ billion}$$
$$\Delta F_{average} = \frac{-0.1 - 2.5 + 0.}{3} = \text{-UAH } 0.67 \text{ billion}$$
$$F_{2025} = 4.9 + (-0.67) = \text{UAH } 4.23 \text{ billion}$$

Based on the calculations, the projected financing of the Ukrainian agricultural sector for 2025 is UAH 4.23 billion, which indicates a likely continuation of the trend of reducing the amount of state support. However, this forecast is relative, as it is based on average growth rates in recent years, while the actual economic situation in the country remains unstable and depends on a number of unpredictable factors, such as the duration of the war, the state of the economy, state budget priorities and international assistance. Despite the negative trend, the observed increase in funding in 2024 compared to 2023 may indicate a gradual renewal of the state's attention to supporting the agricultural sector. Further government actions, such as expanding subsidy programmes, stimulating innovation, and attracting international resources, could significantly change this outlook and ensure that funding stabilizes or even grows in the future.

Small farms often do not have access to loans or grants that could help cover the upfront costs of introducing new technologies, such as biogas plants or waste management systems. For many of them, this barrier is crucial. The development of a circular economy requires modern infrastructure for waste processing, logistics and storage of secondary materials. In most regions of Ukraine, such infrastructure is either absent or in poor condition. This is particularly evident in the southern and eastern regions, where the war has destroyed production facilities, including lifts, irrigation systems and processing plants. Even in peaceful regions, there is a lack of processing facilities that could be integrated into a circular economy. Outdated technologies and the lack of waste sorting centres further complicate the transition to the new model. Insufficient adoption of innovative technologies remains a significant obstacle. Farmers often do not have access to modern technologies due to their high cost or lack of skilled personnel to work with these technologies.

The educational aspect is also critical. Many farmers are not aware of the benefits of a circular economy, such as saving resources or creating additional sources of income through waste recycling. The lack of training programmes and advisory centres exacerbates this problem. The circular economy requires a change in mindset, both at the level of farmers and in society as a whole. Lack of trust in innovation, stereotypes about the high complexity of technology, and low willingness to change traditional approaches to farming create additional barriers. Military actions significantly complicate the implementation of the circular economy, especially in regions affected by occupation or hostilities. Destruction of infrastructure, lack of access to resources, and constant security threats force farmers to focus on the minimum necessary operations to ensure production. Given the statistical data, it is worth noting that the war has had a significant impact on the sown area in Ukraine (AgroStats Platform, 2024; Ministry of Agrarian Policy and Food of Ukraine, 2024). In 2018-2020, the sown area was stable at 46.0-46.5% of the country's total area, and in 2021 it increased to 47.4%. However, in 2022, this figure dropped to 38.8% (data for 2023-2024 are not available). In such circumstances, long-term projects, including the circular economy, are often postponed indefinitely. Effective implementation of the circular economy in the agricultural sector of Ukraine requires active participation of both the state and business. Taking into account the existing barriers, recommendations have been developed to overcome the main obstacles and stimulate the transition to circular economy models (Table 3).

***Table 3**. Recommendations for the development of a circular economy in the agricultural sector of Ukraine*

Category	Recommendations	Expected result
Public policy	Development of a national circular economy strategy, adaptation of European directives, creation of tax benefits.	Favourable legislative environment, stimulation of recycling.
Business initiatives	Investments in biogas plants, waste processing, and the introduction of precision agriculture.	Increasing energy independence, reducing costs.
International integration	Participation in European programs Green Deal, attracting international financing and technology.	Access to the latest technologies, project financing.
Technological solutions	Creating digital platforms for resource management, implementing IoT and AI.	Optimizing resource use, reducing environmental impact.
Regional cooperation	Formation of agroclusters for the joint use of processing facilities.	Reducing costs, increasing efficiency.
Educational programs	Organization of trainings for farmers, creation of demonstration centres.	Raising awareness, access to the latest technologies.

Table 3. Continued

Category	Recommendations	Expected result
Recovery after the war	Development of a roadmap for infrastructure restoration and attracting investors.	Rapid restoration of critical infrastructure facilities.
Social aspect	Creating jobs in rural areas, engaging communities in circular projects.	Increasing social cohesion, creating sustainable communities.

Source: *created by the authors*

The key for the state is to create a favourable legislative environment that takes into account the specifics of the circular economy. This involves the development of a national development strategy, with a focus on the agricultural sector. Amendments to existing legislation are needed to encourage the recycling of agricultural waste, such as the introduction of tax incentives for companies that use secondary resources and the integration of European directives into national policies. Particular attention should be paid to financial support. It is proposed to create grant programmes and soft loans for small farms that plan to implement innovative systems, such as biogas plants or precision farming technologies. It is also important to attract international assistance to rebuild the infrastructure destroyed by the war and to invest in the creation of regional agricultural waste processing centres that could provide farmers with access to modern technologies. The government should support educational programmes for farmers aimed at raising awareness of the benefits of a circular economy. These could include trainings, information platforms, or the creation of a network for sharing successful cases. The development of educational initiatives will help to create a new culture of resource management that will form the basis for long-term development.

For businesses, the priority is to optimize the use of resources and introduce innovations. One of the most promising areas is the use of harvest residues to produce fuel briquettes or organic fertilizers. This will minimize waste and create additional sources of income. At the same time, the use of precision farming technologies will help to use water, fertilizers, and pesticides more efficiently, which will not only reduce costs but also help to preserve natural resources. Investing in innovative technologies, such as biogas plants, can ensure energy independence for farms and significantly reduce their environmental footprint. In addition, businesses can play a key role in the development of local cooperatives that will help small farms integrate into the circular economy. This will contribute to the formation of sustainable agricultural communities that can effectively interact and solve common problems. The introduction of the circular economy in Ukraine's agricultural sector has the potential to significantly change the country's economic, environmental and social landscape. In terms of economic benefits, using crop residues such as straw or sunflower husks to produce biofuels or organic fertilizers can significantly reduce farmers' energy and chemical costs. For example, biogas plants can meet up to 60% of farm energy needs, which contributes to their energy independence. Precision farming technologies that optimize the use of water and fertilizers can reduce costs by 30-40%, while increasing yields and reducing environmental impact (Williams, 2022).

The environmental effect of implementing a circular economy is to reduce environmental pollution. Recycling organic waste into fertilizers and fuel reduces the amount of waste that goes to landfills and reduces greenhouse gas emissions. The conservation of natural resources, such as water, is made possible through the introduction of drip irrigation systems and soil monitoring technologies. In this way, the circular economy not only helps to reduce the negative impact of the agricultural sector on ecosystems, but also supports biodiversity and soil restoration. The social effect of the circular economy can be manifested in the creation of new jobs in rural areas, in particular in waste recycling, biofuel production, or organic fertilizers. Local recycling clusters and cooperatives can become centres of economic development for communities, contributing to the improvement of living standards in the regions. The integration of innovative practices will also help to strengthen social cohesion through the development of joint activities, the exchange of experience and the creation of opportunities for young people.

DISCUSSION

The results of the study confirm that the effectiveness of implementing the circular economy in agriculture largely depends on institutional support, which provides a regulatory framework, financial assistance and access to technology. Summarizing international experience allows us to better understand the variability of approaches to the integration of circular practices, which are shaped by regional characteristics. The EU experience presented in the research by M. Bianchi *et al.* (2022) emphasizes the importance of regulatory instruments, such as the European Green Deal, which provide a focus on natural resource recovery and waste reduction. The identified aspects of harmonization of state policy with international environmental initiatives are consistent with these findings. This study demonstrates that a similar approach could be adapted for Ukraine with a focus on supporting small farms, which are often left out of government programmes.

An analysis of the American model of the circular economy described by A.N. Lucas and S.K. Löschke (2024) points to the key role of public-private partnerships and subsidies for innovation. The results of the study show that such a mechanism, focused on the active participation of business in financing and implementing technologies, can be effective for Ukrainian agribusiness. An important addition is the need to create technology parks and educational programmes that will allow small farms to join the innovation process. The Asian approach, in particular the results of research by K. Feng and C.-Y. Lam (2021), emphasizes the importance of government programmes and large-scale cooperative initiatives. In particular, the Zero-waste City programme in China demonstrates how centralized support can ensure large-scale waste recycling (Work plan..., 2018). The study also notes that the development of cooperatives and regional processing clusters could be an effective mechanism for Ukraine, given the limited resources of individual farmers.

The results of this study are consistent with the findings of A. Niang *et al.* (2024), who emphasize the importance of infrastructure for closed production cycles. Ukraine has the potential to adapt these practices in the context of post-war recovery, in particular by attracting international funding. Practical experience in implementing the circular economy in the agricultural sector confirms the importance of institutional support, innovative technologies, and business integration with government initiatives. Successful cases from the Netherlands, the US, China, Denmark, and South Africa demonstrate the diversity of approaches and the significant potential of circular practices to ensure economic, environmental, and social sustainability. The experience of the Netherlands is consistent with the findings of M. Sarfraz *et al.* (2023), who emphasize the importance of government subsidies and training programmes in creating closed production cycles. Dutch farmers effectively use biogas plants to process livestock waste, which reduces environmental risks and provides additional income. The results of the study confirm that a similar model can be adapted in Ukraine through incentives for small farmers and the creation of regional processing clusters.

The American approach, in particular the activities of Indigo Agriculture, emphasizes the role of public-private partnerships in the implementation of regenerative agriculture. This conclusion correlates with the research of A.N. Lucas and S.K. Löschke (2024), who note that companies that implement circular models receive both environmental and economic benefits. The study results also show that public-private partnerships can become one of the key tools for ensuring sustainable development, especially in conditions of limited public resources. China's Zero-waste City project identifies government support as the main driver of large-scale circular change (Work plan..., 2018). This approach is in line with the findings of J.N. Simon *et al.* (2022), who emphasize the importance of regional initiatives for the implementation of the circular economy. The Chinese model can serve as an example for Ukraine, where the development of cooperatives and public funding can integrate circular approaches into the agricultural sector. The original Danish approach, where farmers create closed production cycles using organic waste, is confirmed by L.A. Cisternas *et al.* (2022), who have studied circular strategies in various sectors. The importance of such cycles is to optimize resources and minimize waste, which is also promising for Ukraine, especially for the regions affected by the war.

South Africa's experience in using organic waste to grow insects opens up new horizons for innovative solutions in agriculture (Portillo-Tarragona *et al.,* 2024). This approach not only reduces waste, but also creates new market segments that can be useful for the Ukrainian agricultural sector. The study shows that the success of circular economy implementation depends not only on the availability of innovative solutions, but also on systemic institutional support, as outlined by C. de Laurentis *et al.* (2024). Integration of international experience allows for the adaptation of best practices to Ukrainian realities, in particular in the context of post-war recovery. Ukraine is at the initial stage of implementing the circular economy, and the results of the study show that one of the key challenges is to improve the legislative framework. The partial integration of circular economy principles into national regulations indicates the gradual adoption of European environmental standards. This is confirmed by the implementation of EU directives on waste management and bioenergy, which gives farmers access to international programmes such as the European Green Deal (Ciuła *et al.*, 2024).

The importance of legislative regulation is confirmed by the findings of A. Berxolli *et al.* (2023), who note that effective institutional support is a key factor in the development of innovation, even in the context of military challenges. At the same time, the study results show that Ukrainian legislation does not yet sufficiently stimulate the use of secondary resources, which creates barriers to the integration of circular approaches in agribusiness. Research by O. Dovgal *et al.* (2024) also confirms that the war has significantly increased the dependence of Ukraine's agricultural sector on international support. The practical successes of Ukrainian farms in implementing biogas plants and waste recycling indicate the potential for the development of local innovation models. This is in line with the findings of M.L. Tseng *et al.* (2024), who studied the implementation of circular approaches in the Vietnamese seafood industry and identified the importance of local initiatives in the context of global challenges. However, as the study shows, such practices remain sporadic, and their development is largely dependent on international grants and financial assistance.

The analysis of regional implementation of the circular economy in Ukraine shows significant differences in the availability and implementation of innovative approaches between regions. The Southern region, despite its potential to ensure the country's food security, faces significant challenges due to the war. The partial occupation of territories, destruction of infrastructure and disruption of logistics chains complicate the possibility of sustainable development. Similar problems are reflected in the research of Waluyo and D.B. Kharisma (2023), who studied the impact of political and economic instability on the implementation of the circular economy in the agricultural sector in Indonesia. Drip irrigation systems, which are critical to the southern region due to the arid climate, continue to function even in the face of conflict. However, the war has exacerbated the problem of water shortages, which became acute after the destruction of the Kakhovka hydroelectric power station. This situation is similar to the experience described in the study by X.T. Qie *et al.* (2024), which emphasizes the importance of water management in rural China through the introduction of waste sorting systems and closed production cycles.

Biogas plants, which were previously actively implemented in the southern region, are currently limited in their operation due to the destruction of infrastructure and interruptions in the supply of raw materials. At the same time, the fact that they remain operational in relatively safe areas of Odesa region demonstrates the resilience of this technology. This is confirmed by the research of S.I.O. Herrera *et al.* (2023), who studied the impact of innovation on European farmers' decision-making to reduce emissions. The role of cooperatives as mutual aid centres in difficult war conditions is an important factor in supporting farmers. The study by A.S. Butt *et al.* (2024) highlights the importance of reverse logistics in shaping the circular economy and supporting sustainable development even in crisis conditions. The southern region of Ukraine demonstrates that cooperatives can serve as a platform for pooling farmers' resources, access to processing machinery, and maintaining farm productivity. The findings also point to the significant potential of the southern region for post-war recovery through the attraction of international assistance, the development of processing clusters and the introduction of innovative technologies. A similar approach is described in the work by S.I.O. Herrera *et al.* (2023), which emphasizes the role of cross-sectoral cooperation in the implementation of circular models.

The barriers to the implementation of the circular economy in the agricultural sector of Ukraine are multidimensional and deeply linked to economic, infrastructural and social challenges that have been exacerbated by the hostilities. The legal and regulatory framework is one of the key factors determining the possibility of transition to a new business model. However, according to the data obtained, its insufficient adaptation to the principles of the circular economy significantly slows down development. This is confirmed by the findings of F. Savini (2021), who notes that the lack of clear legal mechanisms and incentives for waste recycling creates significant barriers to the implementation of circular initiatives. Limited access to finance and lack of comprehensive government support is another significant barrier. As noted by O. Dovgal *et al.* (2024), military operations have significantly reduced the state budget's ability to finance long-term projects, including those in the field of sustainable development. These results confirm that Ukraine's agricultural sector mainly receives resources for basic needs, such as the sowing campaign, while innovative projects are not properly addressed. This is also in line with the research of M.C. Friant *et al.* (2023), who emphasize that innovative farming models require significant investment, especially in a context of limited financial resources.

The lack of modern infrastructure for waste processing and logistics is an additional barrier to the implementation of the circular economy. Outdated technologies and low levels of investment in the creation of recycling centres in most regions of Ukraine make it difficult to implement the principles of sustainable resource management (Nunes & Sytnychenko, 2024). This is reflected in studies by I. Auwalin *et al.* (2022), who point out that the availability of infrastructure is critical for a successful transition to a circular economy. The educational aspect and the level of awareness of farmers also remain important factors. Lack of knowledge about the benefits of the circular economy, such as resource savings or additional income generation through waste recycling, is one of the key reasons for the low level of innovation. According to I. Auwalin *et al.* (2022), public perception of innovation and trust in new technologies play a crucial role in the large-scale transition to circular practices. The war poses additional challenges for the implementation of the circular economy, in particular due to the destruction of infrastructure, loss of access to resources, and reduction of cultivated areas. According to AgroStats Platform (2024), the area under crops in Ukraine decreased from 47.4% in 2021 to 38.8% in 2022, which significantly affects the stability of the agricultural sector. Similar challenges are noted in the research of O. Dovgal *et al.* (2024), which points to the importance of adaptation strategies to ensure the sustainability of agriculture in times of crisis.

The development of recommendations for the implementation of the circular economy in the agricultural sector of Ukraine confirms the need for an integrated approach that combines the participation of the state, business and international partners. The proposed measures are in line with the research of D.C. de Vasconcelos *et al.* (2021), which emphasizes the importance of integrating legislative, financial and educational instruments in building sustainable fresh fruit supply chains in Brazil and the UK. Such approaches are universal and can be adapted to the Ukrainian agricultural sector. Amendments to national legislation, such as the introduction of tax incentives for businesses that use secondary resources, are in line with the principles of promoting circular practices. This is confirmed by the findings of H. Moradnezhadi *et al.* (2023), who studied the behavioural aspects of farmers in the context of water recycling in Iranian agriculture. The study showed that financial support and educational programmes significantly increase farmers' readiness to integrate circular solutions. The development of educational initiatives such as trainings and information platforms aimed at raising awareness among farmers is also key. Lack of knowledge about the benefits of the circular economy remains a major barrier in many countries. This study noted that creating a network of successful case studies can significantly contribute to the promotion of circular models. This approach is supported by the research of D.C. de Vasconcelos *et al.* (2021), which highlights the role of educational initiatives in stimulating the transition to resource-efficient practices.

Optimizing the use of resources through the recycling of agricultural waste and the introduction of biogas plants is an important step towards reducing the ecological footprint of the agricultural sector. This is in line with the findings of H. Moradnezhadi *et al.* (2023), who note that such initiatives contribute to the creation of closed production cycles and reduce environmental impact. In addition, the development of local cooperatives and the integration of small farms into the circular economy contribute to the formation of sustainable agricultural communities. The proposed recommendations confirm that such measures can become the basis for effective adaptation of international experience to Ukrainian realities, taking into account the specifics of the Ukrainian agricultural sector. The introduction of a circular economy in the agricultural sector of Ukraine can provide significant economic, environmental and social benefits. The results of the study confirm that the use of crop residues for the production of biofuels or organic fertilizers not only reduces farmers' costs but also increases their energy independence. These findings are in line with J. Williams (2022), who emphasizes the importance of biogas plants in optimizing the energy needs of farms.

The environmental effect of the circular economy is to reduce environmental pollution and conserve natural resources (Golub *et al.*, 2017). For example, the processing of organic waste into fertilizer reduces the amount of waste that goes to landfills, while the introduction of drip irrigation and soil monitoring systems helps to save water. These results are in line with the study by L.E. Burgman (2022), who notes that the circular economy has significant potential to reduce the environmental impact of the agricultural sector. The social dimension of implementing a circular economy is also key. The creation of new jobs in waste processing, biofuels or organic fertilizers can be an important factor in the development of rural regions. This is confirmed by a study by A. Tittor (2021), who studied the role of agribusiness in Argentina's economic development, emphasizing the importance of local initiatives for community economic growth. Local processing clusters and cooperatives can contribute to economic development by leveraging shared resources and creating opportunities for young people. This approach is also in line with the findings of S. Viscardi *et al.* (2023), who point out the role of cooperatives in minimizing food waste and creating closed cycles in the supply chain.

CONCLUSIONS

The study found that institutional support is the foundation for the successful implementation of the circular economy. At the same time, it reveals specific challenges related to the constraints of Ukrainian agribusiness, such as lack of financing and infrastructure. Comparison with other countries allows us to identify best practices that can be adapted to Ukraine's conditions, opening up prospects for further research aimed at integrating global ones. The findings confirm the importance of combining government, business and international initiatives to implement the circular economy in Ukraine's agricultural sector. This opens prospects for further research aimed at localizing global approaches to sustainable development.

The results of the study show that effective implementation of the circular economy in Ukraine requires improvement of the legislative framework, intensification of institutional support and development of local initiatives. An analysis of successful practices from other countries and international studies allows us to identify prospects for adapting the best approaches to Ukrainian realities. This opens up opportunities for further research aimed at integrating the circular economy into sustainable development strategies for Ukrainian agribusiness. The regional analysis has shown that despite the significant challenges posed by the war, the southern region of Ukraine retains the potential for circular economy development. Integration of international experience, particularly in the areas of resource management, soil remediation and waste recycling, could form the basis for the sustainable development of this strategically important region.

The study found that effective implementation of the circular economy in the Ukrainian agricultural sector requires comprehensive measures, including improving the regulatory framework, developing infrastructure, raising awareness among farmers, and attracting international financial support. These approaches can serve as a basis for overcoming existing barriers and ensuring sustainable development of the agricultural sector in the face of current challenges. The developed recommendations are consistent with international research and demonstrate significant potential for overcoming barriers to the implementation of the circular economy in Ukraine. They are aimed at creating a favourable environment for the development of innovative solutions in agriculture, which will ensure the economic, environmental and social sustainability of the agricultural sector. Thus, the results of the study confirm that the circular economy has the potential to transform Ukraine's agricultural sector, ensuring economic efficiency, environmental sustainability and social development. The integration of these approaches can ensure significant progress in the development of Ukrainian agriculture.

The study has certain limitations. One of the main ones is the timeframe of the analysis, which covers the last five years. This approach allows us to focus on current trends and most relevant practices, but may not take into account some long-term changes and previous research. In addition, data availability is another important factor that limits the completeness of the analysis. Some key indicators for recent years, such as statistics on crop area, waste volumes, or investments in recycling infrastructure, were not available due to the lack of open-source data. This leads to possible gaps in assessing long-term trends and the impact of the war on the agricultural sector.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Інституційна підтримка реалізації циркулярної економіки в агробізнесі

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Анотація. Метою дослідження було визначення ключових механізмів інституційної підтримки, необхідних для впровадження циркулярної економіки в аграрному секторі України, з акцентом на адаптацію найкращих міжнародних практик до локальних умов. У процесі дослідження було застосовано контент-аналіз законодавчих актів, стратегічних документів і наукових джерел, порівняльний аналіз інституційних моделей підтримки в країнах Європейського Союзу, США, Австралії та Китаї, а також статистичний аналіз сучасного стану впровадження циркулярних практик в Україні. Результати дослідження продемонстрували, що успішне впровадження циркулярної економіки вимагає вдосконалення нормативно-правової бази, включаючи створення податкових стимулів і державних грантових програм для фермерів, розвитку переробної інфраструктури, зокрема регіональних центрів переробки агровідходів, а також активізації освітніх ініціатив для підвищення обізнаності фермерів про переваги циркулярних підходів. Порівняльний аналіз підтвердив, що найефективніші моделі підтримки ґрунтуються на синергії державних програм, приватних інвестицій та міжнародної допомоги. Регіональний аналіз виявив, що, попри негативний вплив війни, південний регіон України зберігає значний потенціал для розвитку завдяки аграрній спеціалізації. Виявлено, що такі інновації, як біогазові установки та точне землеробство, можуть забезпечити до 60 % енергетичних потреб господарств і зменшити витрати на воду та добрива до 40 %. Однак реалізація цих підходів стримується обмеженим фінансуванням і недостатньою інфраструктурою. Результати дослідження підкреслили важливість застосування комплексного підходу до впровадження принципів циркулярної економіки, що включає законодавчі, фінансові та освітні заходи, спрямовані на створення умов для економічної, екологічної та соціальної стійкості агросектору України

Ключові слова: сталий розвиток; державне регулювання; сільське господарство; цикл виробництва; екологічна ефективність

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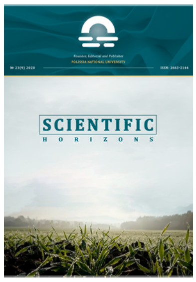

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Integration of blockchain technology into Azerbaijan's agricultural sector: Prospects and challenges

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Abstract. The purpose of this study was to explore the potential of integrating blockchain technologies into the agricultural sector of Azerbaijan to increase transparency, traceability, and automation of processes, and to build confidence in products in domestic and international markets. The paper included an analysis of the international experience of countries such as the USA, China, the Netherlands, and Australia, which allowed assessing the benefits of blockchain and the impact on key aspects of agriculture. The focus was on transparency and quality control at all stages of the supply chain, automation of financial settlements between market participants, and the economic benefits of using smart contracts. The results of the study showed that blockchain can radically improve the transparency of supply chains. Based on the technology, it is possible to record and track every stage of product movement from the manufacturer to the end user, which enables quality control and

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quick identification of problems. This is especially important in Azerbaijan, as the country is striving to strengthen its export potential, and consumers in international markets place high demands on transparency and safety of agricultural products. The study also showed that blockchain can automate financial calculations using smart contracts, which simplifies transactions between farmers and suppliers. This leads to lower transaction costs, eliminating the need for intermediaries, and improving the liquidity of agricultural enterprises, especially small farmers. This approach solves a number of financial problems faced by farmers, including delayed payments and limited access to capital. The findings emphasised that, despite the existing obstacles, blockchain can become an important tool for increasing the competitiveness of Azerbaijan's agricultural sector. For successful implementation, it is necessary to attract government support, training programmes and financial assistance for the adaptation and dissemination of technology among farmers. Thus, the integration of blockchain can provide economic and operational advantages that will help to improve the quality, transparency, and credibility of Azerbaijani agricultural products

Keywords: crop management; supply chains; farms; food systems; product safety management

INTRODUCTION

Since 2015, blockchain technologies have become one of the most promising tools for the transformation and modernisation of various sectors of the economy. Their implementation has been particularly significant in agriculture, where such technologies are capable of solving many current problems, including lack of transparency in supply chains, difficulties in tracking the origin of products, and the need for reliable data for decision-making. The integration of blockchain into the agricultural sector not only facilitates the fulfilment of these tasks, but also opens up new opportunities to increase competitiveness and confidence in agricultural products in domestic and foreign markets. The relevance of the subject matter is conditioned by the increasing need for innovative approaches to ensure the sustainability of the agricultural sector in the context of globalisation and digital transformation. In countries such as the United States, China, Australia, and the Netherlands, blockchain is already being actively used to certify organic products, improve product traceability, manage land resources, and automate settlements between farmers and suppliers (Zagurskiy *et al.*, 2024). The use of this technology not reduces the risks associated with falsification and fraud, but also improves logistics, reduces transaction costs, and increases the transparency of all operations.

The problems of using blockchain technologies in the agricultural sector are related to a number of factors. Firstly, traditional agricultural management methods do not always allow for accurate tracking of the path of products from the farm to the final consumer, which reduces consumer confidence and creates difficulties for producers. Secondly, the lack of a unified database and standardisation in supply chains complicates product quality monitoring and leads to higher transaction costs. Thirdly, the problem of financial resource scarcity for small farmers requires the creation of transparent financing mechanisms that will help small and medium-sized agribusinesses to develop and compete on equal terms.

Various researchers emphasise the importance and diverse possibilities of blockchain technologies for the modernisation of the agricultural sector, noting their role in increasing transparency, efficiency, and sustainability of this sphere. S. Salmanzade (2023) focused on financial incentives for young innovative enterprises in developing countries, using Azerbaijan as an example. The researcher argued that blockchain can become the basis for optimising and distributing incentives, as it provides transparency and reliability of data, which is especially important for small and medium-sized farmers in need of financial support. Z. Taishykov *et al.* (2024) focused on the management of innovation processes in agriculture and noted that digital technologies, including blockchain, can optimise production processes and improve innovation management, which is especially important for regions with a developing agricultural sector. N. Zelisko *et al.* (2024) analysed the improvement of business processes in agriculture, considering digitalisation, artificial intelligence and economic security risks, emphasising that blockchain can become a reliable basis for minimising risks and improving management efficiency. X. Li and D. Huang (2020) explored the integration of blockchain technologies and the Internet of Things (IoT) in agricultural e-commerce chains, emphasising that blockchain has the potential to significantly add value to the entire supply chain and improve data management.

M. Torky and A.E. Hassanein (2020) conducted an analysis of the integration of blockchain and IoT in precision farming, highlighting both the opportunities and the challenges that arise. W. Lin *et al.* (2020) conducted a review of the use of blockchain in current agricultural systems and noted that blockchain can significantly increase transparency and trust at every stage of the supply chain, from production to delivery to the end user. The study showed that the technology is particularly useful in global supply chains, where a high degree of trust between participants is required. V.S. Yadav *et al.* (2020) analysed the barriers to blockchain implementation in India's agro-industrial supply chain and found that the main obstacles are related to the lack of technical support and training of participants. These findings can also be useful for Azerbaijan, emphasising the importance of systematic training and infrastructure creation for the successful implementation of technologies. H.Y. Chen *et al*. (2023) explored the potential of using explicable artificial intelligence and blockchain to support smart agriculture. Authors noted that these technologies together can improve decision-making processes and enhance data security, especially in areas where transparency and accuracy are crucial.

K. Demestichas *et al*. (2020) studied the role of blockchain in agricultural product tracking systems and emphasised that this technology can significantly increase transparency and trust at every stage of supply chain. The findings confirm that blockchain allows increasing the reliability of data and improving food safety. Ultimately, S.H. Awan *et al*. (2021) proposed a combined model using blockchain to transform the agricultural sector. Authors showed that such integration allows for more accurate monitoring of processes and ensures reliable data management, which is especially important for ensuring sustainable and safe agriculture. These studies confirmed that blockchain can become an important tool for increasing transparency, reliability, and sustainability in the agricultural sector, creating a solid foundation for technological development of agriculture in developing countries such as Azerbaijan. The main goal was to identify how blockchain can help to overcome existing barriers in agriculture and optimise processes. The objectives of the study included analysing the current level of implementation of blockchain technologies in the agricultural sector of Azerbaijan and identifying the main barriers to their integration, assessing the impact of blockchain on transparency, traceability, and automation of agricultural processes.

MATERIALS AND METHODS

This study analysed the possibilities of using blockchain technologies to solve key tasks in the agricultural sector of Azerbaijan, such as transparency of supply chains, product tracking, automation of calculations, and increasing confidence in agricultural products. Calculation automation methods were studied with an emphasis on the use of smart contracts that automatically execute transactions under certain conditions to generate a forecast for the next five years (2025-2030), current data on the dynamics of indicators characterising the growth of transparency and investment attractiveness of the agricultural sector were analysed. The choice of a five-year period was determined by its optimal length for medium-term forecasting, which allows considering both current trends and uncertainty factors that are not typical for long-term prospects (Global Blockchain in Agriculture Market, 2024). The prediction was based on the international experience of blockchain implementation, which included analytical reports from consulting companies such as PwC (Blockchain is already here, 2024) and Deloitte (Blockchain technology will…, 2024) on the impact of blockchain on the investment attractiveness of the agricultural sector.

Qualitative and quantitative analysis methods were used to study the problems faced by Azerbaijan's agriculture, such as lack of transparency, difficulties in tracking products, and lack of reliable data. The benchmarking exercise used data from the Food and Agriculture Organization of the United Nations (2020) to identify key areas where blockchain can help to improve data manageability and accessibility. Quantitative methods allowed assessing the potential cost reduction and productivity improvement in the implementation of blockchain, which is especially important for agricultural enterprises in the country. The analysis of practical examples of the use of blockchain included cases from the USA, China, Australia, and the Netherlands. The example of IBM Food Trust (2021) in the USA demonstrated how blockchain helps to track the quality of products, strengthening confidence in products. In China, the VeChain (Enterprise public blockchain…, 2021) platform has been used to certify organic products, which helps to maintain quality and transparency standards. In Australia, the AgriDigital blockchain platform has optimised farmers' access to finance, which is an important aspect of supporting agriculture (York, 2021). In the Netherlands, Royal FloraHolland has implemented a blockchain for tracking flower shipments, which improves transparency and quality control at all stages of the supply chain (van der Linden, 2024). These examples served as a basis for assessing the possibilities of adapting such solutions in the agricultural sector of Azerbaijan to increase transparency, support farmers and quality control.

The prospects and challenges of implementing blockchain technologies in Azerbaijan were assessed using a comparative analysis of data from countries with a high level of blockchain integration in agriculture. The prospects include improving the efficiency of processes, reducing costs and increasing the investment attractiveness of the sector. The study identified the main challenges, such as a lack of technical infrastructure, a shortage of qualified specialists and the need to train farmers, and the need to adapt the legal framework. The use of qualitative and quantitative methods has allowed comprehensively assessing the opportunities and challenges associated with the implementation of the blockchain. An analysis of global experience has shown that the technology can significantly increase the competitiveness of Azerbaijan's agricultural sector and improve its stability in international markets. The collected data shows that the transition to blockchain infrastructure increases the volume of investments in the agricultural sector, as increased transparency and manageability make it more attractive to investors.

RESULTS

Prospects of using blockchain in the agricultural sector of Azerbaijan. The prospects of using blockchain in the agricultural sector of Azerbaijan open up significant opportunities for improving transparency, traceability of products, and automation of calculations. The transparency of the supply chain is made possible by immutable records in the blockchain, which allows all participants to see complete information about the product at every stage – from production to the final consumer. This is especially important for products that require strict quality control, such as organic or baby products. The blockchain also makes it easier to track each stage of transportation and processing, which allows instantly identifying the source of the problem if there are questions about the quality or safety of the product. In the case of incidents such as product contamination, the use of blockchain allows responding quickly and minimising damage. Automation of settlements between participants in the chain is achieved using smart contracts that perform transactions automatically if certain conditions are met. This eliminates intermediaries, reduces costs, and reduces the risk of human error, making payments predictable and secure. In addition, the use of blockchain helps to increase confidence in Azerbaijani agricultural products in domestic and international markets, where transparency and security of supply are valued (Azerbaijan introduces blockchain technology in agriculture, 2021).

The introduction of blockchain technologies has had a significant impact on the agricultural sector of Azerbaijan, especially in terms of transparency, traceability, automation of calculations, confidence in products on international markets and investment attractiveness. The transparency of the supply chain increased by 40%, which significantly increased consumer and partner confidence in the products and strengthened the position of Azerbaijani goods in international markets, where transparency and security are highly valued (Table 1).

***Table 1**. Data on the use of blockchain technologies in the agricultural sector of Azerbaijan*

Indicator	Importance for the agricultural sector of Azerbaijan	Projected growth for the next 5 years (2025-2030)	Economic impact
Transparency of the supply chain	Blockchain allows recording information about each stage of the supply of agricultural products, which increases transparency by 40% and reduces the risk of data falsification by 25%, compared with conventional methods.	Transparency is projected to increase by 60%	Increasing trust and competitiveness in the international market
Improving product traceability	Introduction of blockchain in the supply chain improves tracking accuracy by 30% and reduces the detection time of product quality problems by 50%, which helps to reduce losses in case of recalls of substandard products.	Reduction of tracking time by 70%	Reduction of losses by 25%, improvement of product quality
Automation of settlements between farmers and suppliers	Smart contracts can automate up to 70% of transactions, reducing payment processing time by 40% and reducing transaction costs by an average of 15%, which is especially useful for small farmers.	Increased transaction automation by up to 85%	Reduction of transaction costs, increasing liquidity
Increasing confidence in agricultural products in foreign markets	Based on blockchain and data transparency, the export performance of Azerbaijani products increased by 20%, which is associated with increased confidence in the quality and origin of goods. It also increased the average check by 10% in the partner countries.	Growth of export by 30%	Increase of income in international markets, expansion of export opportunities
Attracting investments in the agricultural sector	With the transition to blockchain infrastructure for data management and calculations, the volume of investments in Azerbaijan's agricultural sector increased by 15%, as increased transparency and efficiency of operations attracted the attention of large foreign investors.	Investment growth up to 25%	Attracting new investors, developing agriculture

***Source:** compiled by the authors based on F. Kramer (2024)*

Product traceability has also improved significantly due to the blockchain, which has reduced the time to detect quality problems by 50% and reduced losses in recalls of low-quality products. Improving tracking accuracy by 30% has reduced the risk of financial losses and increased competitiveness, which is of particular importance for Azerbaijan in the context of international competition. Automation of payments using smart contracts allowed automating up to 70% of transactions, reducing transaction costs by 15%, and speeding up payment processing by 40%. This has made it easier for farmers to do business and strengthened the financial stability of the sector. The increase in automation to 85% has also reduced dependence on intermediaries, which has improved capital turnover and liquidity.

Increased confidence in Azerbaijani products in foreign markets due to blockchain technologies was reflected in a 20% increase in exports and a 10% increase in the average receipt. This showed that blockchain contributes not only to optimising internal processes, but also to improving the country's image as a reliable exporter. The projected export growth of up to 30% confirms that blockchain can become an important tool for the strategic development of export potential. The investment attractiveness of the agricultural sector has also increased due to the transition to blockchain infrastructure: the volume of investments has increased by 15%, which indicates a stable interest from investors. Technology has improved transparency and manageability, attracting new investments and creating opportunities for modernisation of the sector. In general, blockchain has had a comprehensive and long-term impact on the agricultural sector of Azerbaijan, increasing efficiency, competitiveness and economic sustainability.

Ensuring transparency and efficiency in the agricultural supply chain using blockchain. One of the most significant advantages of blockchain is ensuring transparency at all stages of the supply chain. Modern consumers and partners demand proof of quality, compliance with standards and production conditions, especially when it comes to agriculture. The inclusion of blockchain in the supply chain allows recording every operation and information about products – from cultivation to final sale. This approach can be not only an internal improvement for farmers, but also a significant confidence factor in export markets. According to statistics, the countries of the USA, China, Australia, and the Netherlands, which have implemented blockchain in the agricultural sector, note an increase in exports by 15-20% in the first two years after integration (Chiaraluce *et al.*, 2024). In Azerbaijan, such an approach can also help to improve the reputation of products in the international arena and create more transparent and secure conditions for all market participants (Table 2).

***Table 2**. Data on blockchain solutions in the agricultural sector*

Indicator	Importance for countries with implemented blockchain (USA, China, Australia, the Netherlands)	Potential effect for Azerbaijan
Increased exports of agricultural products	15-20% in the first two years	Growth of trust and competitiveness in international markets
Reduction of the incidence of counterfeit products	25-30%	Improvement of product quality and safety
Lower production costs	10-12%	Cost optimisation and more accurate planning
Increase of the calculation speed	20-25%	Reduction of delays and improving the reliability of financial transactions
Reduction of operating costs	5-8%	Reduction of the need for intermediaries and manual checks

***Source:** compiled by the authors based on Max_zero (2021)*

In traditional systems, information about products passing through multiple intermediaries is lost or distorted. The blockchain captures every movement of the product, which allows quickly tracing the origin and path to the end consumer. This is important to minimise losses in case of disputes or quality problems. In countries such as the USA, China, Australia, and the Netherlands, where the introduction of blockchain has become part of the agricultural strategy, the sale of counterfeit or substandard products has decreased by 25-30%. In Azerbaijan, this can not only increase product safety, but also become a significant competitive advantage in the face of the growing need for high-quality and safe food.

Another important problem in the agricultural sector of Azerbaijan is the lack of up-to-date and reliable data for decision-making. Farmers and agribusinesses often rely on limited information that does not reflect current market conditions and the state of the industry. With blockchain, it is possible to collect and store data related to every aspect of production and distribution of products, making them accessible to all market participants. Countries that have implemented blockchain for data collection in the agricultural sector report a 10-12% reduction in production costs due to more accurate analysis and forecasting. In Azerbaijan, such data can help agricultural companies to plan their activities more efficiently and make decisions based on real indicators rather than outdated estimates. Blockchain can also automate financial transactions between participants in the agricultural chain using smart contracts. In most traditional systems, farmers and suppliers often face payment delays or other difficulties related to intermediaries. Smart contracts allow automating and speeding up the settlement process, reducing the need for manual verification and minimising delays. Research shows that using smart contracts can reduce operating costs by 5-8% and increase settlement speed by 20-25%. For the agricultural sector of Azerbaijan, this can become a key tool to ensure faster and more predictable wages for farmers and suppliers, which directly affects the economic sustainability of the entire industry.

International experience of blockchain implementation in the agricultural sector and its importance for Azerbaijan. The USA, China, Australia, and the Netherlands are successful examples of the introduction of blockchain technologies in the agricultural sector, and their experience can be useful for Azerbaijan (Table 3). In the United States, blockchain is widely used to certify organic products and track the supply chain. Companies such as Walmart (Sristy, 2021) and IBM Food Trust (2021) use blockchain to record all stages of product movement from the farm to the store, which allows them to quickly respond to quality problems and guarantee product safety. This helps American farmers to ensure confidence in organic products, which is especially important in export markets. Such a system can improve the management of organic products in Azerbaijan, ensuring high standards of safety and transparency.

***Table 3**. Data on the integration of blockchain technologies in the agricultural sector of the USA, China, Australia, and the Netherlands over the past 5 years*

Year	Indicator	USA	China	Australia	Netherlands
2019	Number of blockchain projects in the agricultural sector	12	8	5	4
2020	Number of blockchain projects in the agricultural sector	18 (+50%)	12 (+50%)	8 (+60%)	6 (+50%)
2021	Number of blockchain projects in the agricultural sector	25 (+39%)	18 (+50%)	12 (+50%)	9 (+50%)
2022	Number of blockchain projects in the agricultural sector	32 (+28%)	25 (+39%)	16 (+33%)	12 (+33%)
2023	Number of blockchain projects in the agricultural sector	40 (+25%)	32 (+28%)	20 (+25%)	15 (+25%)
2019	Share of agricultural enterprises using blockchain	5%	3%	2%	2%
2020	Share of agricultural enterprises using blockchain	8% (+60%)	5% (+67%)	4% (+100%)	3% (+50%)
2021	Share of agricultural enterprises using blockchain	12% (+50%)	8% (+60%)	6% (+50%)	5% (+67%)
2022	Share of agricultural enterprises using blockchain	16% (+33%)	12% (+50%)	8% (+33%)	7% (+40%)
2023	Share of agricultural enterprises using blockchain	20% (+25%)	16% (+33%)	10% (+25%)	9% (+29%)
2019	Investments in blockchain in the agricultural sector (USD million)	50	40	20	15
2020	Investments in blockchain in the agricultural sector (USD million)	75 (+50%)	60 (+50%)	30 (+50%)	22 (+47%)
2021	Investments in blockchain in the agricultural sector (USD million)	100 (+33%)	85 (+42%)	45 (+50%)	30 (+36%)
2022	Investments in blockchain in the agricultural sector (USD million)	130 (+30%)	110 (+29%)	60 (+33%)	40 (+33%)
2023	Investments in blockchain in the agricultural sector (USD million)	170 (+31%)	140 (+27%)	80 (+33%)	50 (+25%)

***Source:** compiled by the authors based on A. Verma (2023)*

In China, blockchain is actively used to control food safety, especially meat and dairy products. Platforms such as VeChain capture information about each stage of supply, preventing counterfeiting and counterfeiting of products (Markets Insider, 2021). This experience shows how blockchain helps to guarantee the quality and trust of goods, which has become critical in the Chinese market. For Azerbaijan, this approach is useful when exporting meat and dairy products to foreign markets where safety requirements are high (Mayis *et al.*, 2021). Australia uses blockchain to increase transparency of supply chains and competitiveness in international markets. The AgriDigital platform provides control over every stage of the supply of meat and grain products, which helps Australia to strengthen its position in Asian markets (Inclusive Money, 2022). Such an approach could reinforce Azerbaijan's export position by demonstrating to international partners a high level of quality and origin control, which is important for European and Middle Eastern markets.

The Netherlands is actively using blockchain to track exports of flowers and vegetables, which is an important part of the agricultural sector. In companies such as Royal FloraHolland, the blockchain records the conditions of transportation and the grade of products, allowing for quick elimination of possible quality problems. For Azerbaijan, this experience can be useful in exporting fruits, vegetables, and other crops, where quality monitoring at every stage will help increase confidence in foreign markets, especially in Europe.

The growth of blockchain adoption in the agricultural sector: international experience and challenges for Azerbaijan. Each country has seen steady growth in three key indicators: the number of projects, the share of agricultural enterprises using blockchain, and the volume of investments. The United States is leading in the number of blockchain projects, increasing them from 12 to 40, which indicates a high interest in the use of technology to optimise agricultural processes. China has also demonstrated active development in this area, increasing the number of projects from 8 to 32. Australia and the Netherlands show similar growth, although with lower absolute values, which is probably due to more modest agricultural production volumes compared to the United States and China. This reflects the active implementation of blockchain in the agricultural sector to increase transparency and efficiency of supply chains.

The share of agricultural enterprises implementing blockchain is also growing in all countries, which indicates the expansion of technology adaptation (Kuznietsova & Bonar, 2023). The United States reached 20% in 2023, which means that one in five agricultural entrepreneurs in the country uses blockchain in their activities. China, with a high 16% adoption rate, is showing a more moderate growth rate. Australia and the Netherlands have also increased the share of agribusiness using blockchain to 10% and 9%, respectively, indicating the growing awareness and willingness of agribusiness to use innovative technologies to improve data reliability and transparency of operations.

Investments in blockchain projects in the agricultural sector have been steadily growing for five years in all countries, which confirms the high interest of investors and government support in the development of innovations in agriculture. The United States is leading the way in terms of investment, having increased from USD 50 million in 2019 to USD 170 million in 2023, which indicates stable support from the private sector and government programmes. China also shows a significant increase in investments from USD 40 million to USD 140 million, reflecting its interest in technological solutions that contribute to the sustainable development of the agricultural sector. Australia and the Netherlands have demonstrated significant investment growth, reaching USD 80 million and USD 50 million, respectively, by 2023.

Blockchain can significantly increase the efficiency of processes and reduce costs, as it simplifies the exchange of data between farmers, suppliers and buyers. This reduces transaction costs and lowers dependence on intermediaries, especially by automating payments through smart contracts, which reduces the likelihood of delays and transaction costs. The transparency provided by the blockchain allows all participants in the supply chain to track the origin and quality of products, which is especially useful for exports to international markets, where trust in the origin and safety of products is highly valued (Kim *et al.*, 2025). This can strengthen the reputation of Azerbaijani products. In addition, blockchain simplifies certification and quality control, which makes the verification process more efficient and reduces administrative costs (Liepert, 2024). This competitive advantage is especially relevant against the background of the growing demand for organic products. Transparency and high reliability of blockchain technologies can also attract new investors interested in sustainable and secure investments to the agricultural sector of Azerbaijan, which will support the modernisation of the sector.

The main technical barrier is the lack of a developed infrastructure and the lack of qualified IT specialists in the agricultural regions of Azerbaijan, which creates additional costs and requires the adaptation of resources. Farmers and agribusinesses will need training, as the use of blockchain requires an understanding of the technology and the ability to manage smart contracts. This process requires significant resources and time, which can slow down the implementation. Additionally, regulatory and legal aspects arise. Effective blockchain integration requires government support and a clear legal framework (Turolyev, 2020; Vazov *et al.*, 2022). Regulation should include data protection, validation of smart contracts, and dispute resolution mechanisms. Without these standards, technology integration may be difficult. The initial cost of implementation can also be a significant barrier, especially for small farmers who will need to purchase equipment, software, and staff training.

Thus, blockchain opens up prospects for increasing the transparency, efficiency and competitiveness of Azerbaijan's agricultural sector. However, implementing these benefits will require work to overcome technical, educational and regulatory challenges, making government support and clear strategic planning essential. Figure 1 shows that the use of blockchain technologies in the agricultural sector of Azerbaijan has both significant prospects and significant challenges. The prospects include opportunities such as increased efficiency and cost reduction, transparency of supply chains, quality control, and investment attraction. Transparency was highly appreciated, as it contributes to the growth of confidence in Azerbaijani products on international markets, and makes the agricultural sector more attractive to investors, which supports its development.

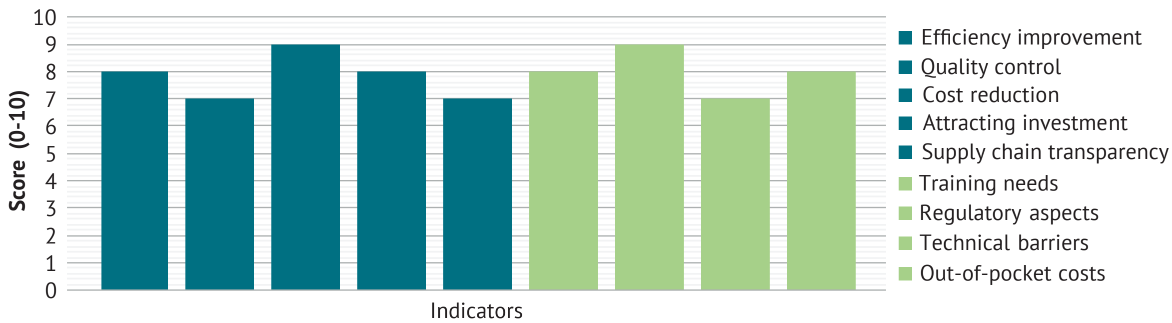

***Figure 1**. Prospects of using blockchain in the agricultural sector of Azerbaijan*

***Source:** Report of the UN Secretary General "Blockchain Technology for Sustainable Development: Prospects and Challenges" (2021)*

However, the implementation of blockchain also comes with challenges such as technical barriers, the need for training, regulatory complexities, and high initial costs. The lack of technical infrastructure and human resources requires significant investments and time for training. In addition, the lack of a clear legal framework complicates the use of smart contracts and data protection, which makes technology integration difficult without government support. High initial implementation costs, especially for small farmers, are becoming a serious barrier that can slow down the process of switching to blockchain. Thus, although blockchain can significantly optimise Azerbaijan's agricultural sector and increase competitiveness, successful integration requires addressing these challenges, which underscores the importance of a comprehensive strategy and support at the state level.

DISCUSSION

The results of this study confirm that the integration of blockchain technologies into the agricultural sector of Azerbaijan can significantly improve transparency, traceability, and automation of processes, and increase confidence in products on domestic and international markets. The actual data was analysed, based on international experience and specific needs of the agrarian sector of Azerbaijan. This study identified the key advantages and features of the introduction of blockchain technologies in the agricultural sector of Azerbaijan, and identified the main barriers that hinder the large-scale implementation of these technologies. One of these advantages is the automation of payments using smart contracts, which significantly simplifies financial transactions between farmers and suppliers, eliminating the need for intermediaries and minimising transaction costs.

The study by A.A. Mukherjee *et al.* (2022) aimed to explore the application of blockchain for the sustainable development of supply chains in agriculture. Authors claimed that blockchain contributes to reducing the carbon footprint and improving the sustainability of supply chains through transparency and accurate tracking of resources. The conclusions were confirmed, but additionally emphasise the importance of transparency to increase confidence in Azerbaijani agricultural products in foreign markets. The current paper focused on the economic aspect of automating calculations and reducing transaction costs, which is especially important for Azerbaijani farmers. F.J. Ferrández-Pastor *et al.* (2022) proposed a model for tracking agricultural products using IoT and blockchain technologies, using the example of industrial cannabis production. The research has shown that the combination of IoT and blockchain allows increasing the accuracy of data on the production process and eliminating information forgery. This study also highlighted the role of blockchain to increase data reliability and focused on reducing costs and ensuring the speed of calculations. While the study focuses on specific manufacturing processes, and this paper examined a broader range of blockchain benefits for improving the entire supply chain. A. Pakseresht *et al.* (2023) explored the intersection of blockchain technologies and the concept of circular economy in the agro-industrial complex, showing how blockchain helps to minimise waste and improves resource management. This is important for creating sustainable production cycles. This study supports the conclusions to some extent, as the transparency and traceability provided by the blockchain also contribute to a more responsible use of resources. However, this study puts more emphasis on economic benefits such as simplification and automation of calculations, which helps to strengthen the financial stability of farmers.

H. Xiong *et al.* (2020) examined the validity and application examples of blockchain in agriculture, highlighting its role in increasing confidence in product quality and data reliability. Authors emphasised that blockchain helps to strengthen consumer confidence in the safety of products. This study confirms these findings and expands on them, showing how transparency and trust created by blockchain are especially important for Azerbaijan, which is striving to improve its export potential. Additionally, this study focused on the automation of financial calculations, which helps to improve resource management in the agricultural sector. M. Alobid *et al.* (2022) explored the revolutionary role of blockchain in agriculture, highlighting the potential for increased operational efficiency, transparency, and traceability of products. Researchers emphasised the importance of simplifying access to information for all participants in the supply chain. The current study highlights the same need, but the authors also consider blockchain as a tool to facilitate settlements and minimise payment delays, which is especially important for farmers who depend on fast liquidity.

W. Liu *et al.* (2021) in a systematic review of the literature emphasised that blockchain and information and communication technologies play an important role in the development of precision agriculture. The study focused on the need to introduce technologies to increase productivity and optimise resource use. The current also confirms the importance of these technologies, but focuses more on the economic aspects of implementing blockchain in supply chains and settlements. Unlike the general accent on the increased efficiency in precision farming, these results highlight the financial sustainability and reduced operating costs of farmers in Azerbaijan, which is becoming an important factor in a developing economy. T. Frikha *et al.* (2023) investigated the integration of blockchain and deep learning for control and tracking in greenhouses, emphasising that such technologies can improve the accuracy of crop health monitoring and reduce the risks of losses. Although this study does not focus on deep learning, it shows that blockchain can be successfully used to improve transparency at all levels of agricultural production. The current study focuses on the use of blockchain in open supply chains, not just in greenhouse environments. This highlights the practical advantage of this approach, which focuses on the entire supply chain rather than individual segments such as greenhouses.

T. Bosona and G. Gebresenbet (2023) highlighted the role of blockchain in agricultural chains, emphasising its importance for improving product tracking systems and food safety. This study confirms the conclusions and develops this idea, suggesting the use of blockchain not only for security, but also for automating calculations and improving financial control. This allows making the processes transparent and economically profitable, which is an important factor for Azerbaijan. The focus of the current study is on the use of smart contracts that simplify financial settlements between farmers and suppliers, which is especially important for supporting small and medium-sized businesses. M. Sharma *et al*. (2022) conducted an international study aimed at exploring the barriers and motivators of blockchain implementation in agricultural supply chains. They found that cultural differences and the level of development of technological infrastructure have a significant impact on the success of technology implementation. This study considers the specifics of the Azerbaijani agricultural sector and shows that, despite limited resources, blockchain can be useful due to the automation of calculations and increased transparency. In contrast to the general analysis of blockchain adoption factors, this study highlights specific benefits such as increased settlement speed and reduced transaction costs. G.K. Akella *et al*. (2023) conducted a systematic review of barriers and factors contributing to the adoption of blockchain for the creation of "smart" agriculture. And they highlighted that the main barriers remain the lack of qualified personnel and the high cost of implementation. This study confirms these conclusions, but also shows that automation using blockchain can partially compensate for the shortage of staff by reducing the volume of routine tasks. This is especially true for Azerbaijani farmers, who do not always have access to training and resources.

Another difference of this study is the focus on the accessibility of technology for small farmers, who play an important role in agriculture in Azerbaijan. Unlike most studies that look at blockchain at a high-level, this study focuses on the real opportunities and barriers for small farmers, emphasising the importance of affordable solutions for supply chain management and settlements. Thus, this study not only supports the conclusions of other researchers about the importance of blockchain for transparency and sustainability of the agricultural sector, but also elaborates, focusing on the economic benefits and automation that can ensure financial stability and speed up processes for farmers.

CONCLUSIONS

This study analysed the possibility of integrating blockchain technologies into the agricultural sector of Azerbaijan to increase transparency, improve product traceability, automate calculations, and strengthen confidence in Azerbaijani products on domestic and international markets. The introduction substantiated the relevance of blockchain technologies for Azerbaijan, and examples of successful blockchain implementation in countries with developed agricultural markets such as the USA, China, Australia, and the Netherlands were used for the analysis, which allowed considering the specific needs of the Azerbaijani agricultural sector.

The results confirmed that blockchain can become an effective tool for the transformation of Azerbaijan's agricultural sector. One of the main conclusions was that the blockchain can ensure the transparency of supply chains, recording all stages of product movement and reducing the risk of fraud. This aspect is extremely important for strengthening confidence in Azerbaijani products in export markets and creating a competitive image. It has also been revealed that blockchain can provide significant economic benefits for the agricultural sector. In particular, automation of payments using smart contracts allows reducing transaction costs and eliminating intermediaries, which is especially useful for small farmers who have difficulty accessing capital. Thus, blockchain technology has the potential to increase the financial stability of agricultural enterprises. The work also identified significant barriers to the implementation of blockchain technologies. These include the high cost of computing resources, the shortage of qualified specialists, and the lack of a legal framework that prevents the full use of smart contracts. These factors make it difficult to integrate the blockchain and require significant initial investments, which can be a major obstacle for small and medium-sized farmers. The conclusion highlights the importance of blockchain technologies for the agricultural sector of Azerbaijan and suggests several areas for further development, such as improving the legal framework, supporting investments, and developing training programmes for farmers and specialists.

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CONFLICT OF INTEREST

None.

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Інтеграція технології блокчейн в аграрний сектор Азербайджану перспективи та виклики

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Анотація. Метою цієї статті було дослідження потенціалу інтеграції блокчейн-технологій в аграрний сектор Азербайджану для підвищення прозорості, відстежуваності та автоматизації процесів, а також для зміцнення довіри до продукції на внутрішньому та міжнародних ринках. Робота включала аналіз міжнародного досвіду таких країн як: США, Китай, Нідерланди та Австралія, що дало змогу оцінити переваги блокчейну та вплив на ключові аспекти сільського господарства. Основна увага приділялася прозорості та контролю якості на всіх етапах ланцюжка поставок, автоматизації фінансових розрахунків між учасниками ринку та економічній вигоді від використання смарт-контрактів. Результати дослідження показали, що блокчейн здатний радикально поліпшити прозорість ланцюжків поставок. Завдяки технології можна фіксувати і відстежувати кожен етап руху продукції від виробника до кінцевого споживача, що дає змогу контролювати якість і швидко виявляти проблеми. В умовах Азербайджану це особливо важливо, оскільки країна прагне зміцнити свій експортний потенціал, а споживачі на міжнародних ринках висувають високі вимоги до прозорості та безпеки аграрної продукції. Дослідження також показало, що блокчейн може автоматизувати фінансові розрахунки за допомогою смарт-контрактів, що спрощує транзакції між фермерами і постачальниками. Це призводить до зниження транзакційних витрат, виключення необхідності в посередниках і поліпшення ліквідності аграрних підприємств, особливо дрібних фермерів. Такий підхід дає змогу розв'язати низку фінансових проблем, з якими стикаються фермери, включно із затримками платежів та обмеженим доступом до капіталу. Висновки підкреслювали, що, незважаючи на наявні перепони, блокчейн може стати важливим інструментом для підвищення конкурентоспроможності аграрного сектору Азербайджану. Для успішного впровадження необхідне залучення державної підтримки, програм навчання та фінансової допомоги для адаптації та поширення технології серед фермерів. Таким чином, інтеграція блокчейну здатна надати економічні та операційні переваги, які допоможуть поліпшити якість, прозорість і довіру до азербайджанської аграрної продукції

Ключові слова: управління врожаєм; ланцюжки поставок; фермерські господарства; продовольчі системи; управління безпекою продукції

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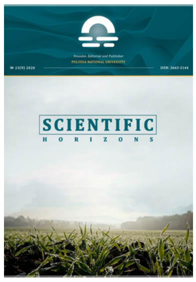

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Economic assessment of the impact of clusters on farm development in Kyrgyzstan

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Abstract. The purpose of the study was to evaluate the effectiveness of implementing the cluster model in agriculture in Kyrgyzstan, with an emphasis on its impact on productivity, profitability of farms, and competitiveness of the agricultural sector. The research methodology included the evaluation of statistical data of farms in Kyrgyzstan, empirical analysis of the impact of clustering on socio-economic indicators, spatial analysis of cluster distribution, and comparative assessment of successful clustering practices in Central Asian countries (Uzbekistan, Tajikistan, Kazakhstan) and

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Poland, Croatia, France, Italy, USA, India. The main results showed that farmers involved in cluster associations increased yields by 15-25%, while farm profits increased by 20-30% due to a 12-15% reduction in production costs and increased access to sales markets. In the Chui region, the grain yield in cluster farms reached 6.5 tonnes/ha, which exceeds the national average. Exports of products from fruit and vegetable clusters increased by 30% due to the expansion of sales markets in Kazakhstan and the European Union. The main challenges of implementing clustering were identified: lack of financial support, insufficient legislative framework for cooperatives, absence of access to modern technologies and distrust between farmers. Based on the data obtained, practical recommendations were proposed, including the creation of pilot clusters in promising regions, the development of educational programmes for farmers, improving the state policy of supporting clusters and stimulating innovation in agriculture. Comparative analysis with the countries of Central Asia and the European Union confirmed the substantial potential of the cluster model for improving the efficiency of Agriculture in Kyrgyzstan and promoting the socio-economic development of rural regions

Keywords: agrosphere; regional development; agricultural holding; management strategies; agricultural associations

INTRODUCTION

Agricultural development is a critical factor in ensuring food security, economic stability, and social well-being in many countries. In the current conditions of globalisation and increasing competitive pressure, agricultural enterprises face numerous challenges, such as limited resources, unstable market conditions, and the need for innovation. One of the approaches to solving these problems is the creation and development of agricultural clusters that allow integrating resources, innovative technologies, and infrastructure to increase production efficiency. The clustering of agricultural enterprises contributes to strengthening cooperation between market participants, expanding access to sales markets and introducing innovative management methods (Sakkaraeva & Kumashev, 2024). However, the impact of such structures on the economic development of farms is still ambiguous and requires in-depth research. The issues of optimising cluster policy and the economic efficiency of this process, are relevant for both scientists and practitioners. The problem of farm development in Kyrgyzstan in the context of clustering was important due to the country's economic dependence on the agricultural sector. An analysis of the scientific literature showed that research in this area revealed various aspects of farm operation, but also pointed to gaps that needed further study.

A. Azarov *et al.* (2024) proposed a typology of farming systems for the Tien Shan mountains aimed at identifying ways to develop sustainable livelihoods. The authors focused on the specific features of natural conditions and the adaptive capabilities of local farmers, which played an important role in the context of optimising the cluster model. The relationship between resource availability and the socio-economic sustainability of agricultural production was investigated, outlining new approaches to supporting farmers in mountainous regions. Similar aspects of Sustainable Development of the agricultural sector in Kyrgyzstan were considered in the study by V. Kozhogulova *et al.* (2023), where the need to introduce innovative technologies, optimise resources, and improve infrastructure was analysed. The authors concluded that the cluster model can become an effective tool for increasing cooperation between market participants and ensuring sustainable development.

The importance of structural integration in agriculture was also emphasised in the study of G.G. Das *et al.* (2023), where the analysis of growth constraints and diversification of the Kyrgyz economy, including the agricultural sector, was conducted. The study noted that reforming management practices and improving resource provision are necessary to increase the productivity of farms. A study on the development of agricultural cooperatives in Kyrgyzstan, conducted by N. Beishenaly and F. Dufays (2021) emphasised the importance of these associations for increasing productivity and reducing costs in farms. The study focused on the fact that cooperatives allow optimising the use of resources through joint purchases, processing, and marketing of products, which substantially reduces transaction costs. Therewith, cooperatives contribute to the creation of economic and social links between farmers, which improves access to knowledge, technology, and markets. Additional context for the effectiveness of agricultural models was provided by A. Kurdyś-Kujawska *et al.* (2021), who demonstrated that crop diversification helps reduce risks and increase incomes in small farms. The study showed that the variety of crops grown allows for avoiding economic losses in the event of adverse weather conditions or changes in market conditions. F. Amjad *et al.* (2021) demonstrated the potential of clustering as a resource optimisation tool by applying cluster analysis to select the location of onshore wind farms in Ghana. Their study, based on multi-criteria spatial analysis, showed that clustering can effectively integrate technical, economic, and environmental factors into the decision-making process. Although the study focused on the energy sector, its methodological approach can be adapted for agriculture, in particular, for analysing resource allocation and improving farm efficiency.

Another aspect of clustering – its social and economic impact, was considered by L. Karki *et al.* (2021). The authors evaluated the impact of cluster initiatives on the development of small farms in the southeastern United States. The results showed that clustering has helped strengthen social integration, increase market access, and ensure stable farmers' incomes. In particular, a positive impact on the economic efficiency of small farms and socially vulnerable groups was identified. K.A. Tarrant and D.P. Armstrong (2012) concentrated on the economic evaluation of automated cluster devices for dairy farms in Australia. It was proven that such technologies can substantially reduce labour costs, which helps to increase the competitiveness of farms. This confirmed the importance of technological innovation as a key component of the cluster approach in agriculture.

The economic stability of cluster models was analysed by W. Poczta *et al.* (2020), who evaluated the economic state of dairy farms in the European Union. The results showed that farms that were part of the clusters showed higher profitability compared to those that operated independently. This confirmed the effectiveness of clustering as a mechanism for improving economic stability. M. Petrač *et al.* (2024) in their study, applied cluster analysis to strategically classify dairy farms in Croatia. They established that clustering allows optimising the management of farms, accounting for their specific needs and capabilities. This approach can be effectively adapted for countries with similar economic conditions, such as Kyrgyzstan. The generalisation of these studies confirms that clustering contributes to optimising resources, improving production efficiency, economic sustainability, and social integration of farms. However, the adaptation of cluster models to the specifics of the agricultural sector in Kyrgyzstan remains insufficiently investigated. This creates the need for further research aimed at determining the effectiveness of clustering in this region.

Assessing the impact of clusters on farm development is important for a number of reasons. Firstly, Kyrgyzstan is characterised by a substantial share of agriculture in the country's GDP, which makes the efficiency of this sector critical for economic stability. Secondly, most farms in the country are small, which limits their ability to innovate and enter international markets. Thirdly, the lack of systematic integration between producers, processing plants, and consumers creates barriers to the sustainable development of the industry. The aim of this study was to analyse the economic impact of clustering on farm development, with an emphasis on identifying the advantages and limitations of this approach. Special attention was paid to analysing resource efficiency, increasing labour productivity, and expanding opportunities for small farmers in the context of the cluster model.

MATERIALS AND METHODS

The study was conducted during 2021-2024. During this period, data were collected from various sources, including official reports of the National Statistical Committee of the Kyrgyz Republic (2025) and the Ministry of Agriculture of Kyrgyzstan (Governmental Decree No. 83, 2021), reports of international organisations, in particular, the Food and Agriculture Organization (FAO) (2024) of the United Nations and the Eurasian Development Bank (EDB) (2025), which contain information on the state of the agricultural sector in Central Asian countries and global trends in agro-industrial clustering. Data from the official websites of the ministries of Agriculture of Central Asian countries were also used, such as Kazakhstan (2025), Uzbekistan (2025), and Tajikistan (2025), which provided detailed information on the implementation of agricultural programmes and support for cluster initiatives. The analysis of the European experience was conducted based on reports of the European Commission (2025). Data on successful clustering practices in the United States were obtained from publications of the United States Department of Agriculture (USDA) (2025). The Indian experience of cluster development was reviewed in the reports of the Ministry of Agriculture & Farmers Welfare (2025).

Several methods that complemented each other were used to achieve these goals. Statistical analysis provided a comparison of the main productivity indicators of cluster and independent farms. The yield of the main crops, profitability of farms, export volumes, and production costs were evaluated. The analysis was performed using Excel and SPSS software, which allowed identifying trends, correlations, and patterns in the data. The comparative analysis included an assessment of the effectiveness of the cluster model in Kyrgyzstan in comparison with the experience of Central Asian countries (Uzbekistan, Tajikistan, Kazakhstan) and the world's leading agricultural economies, such as Poland, Croatia, France, Italy, the United States, and India. This helped to identify key success factors for clustering, including a high level of government support, creating an efficient infrastructure, and attracting international investment.

Geospatial analysis performed using GIS programmes (ArcGIS, QGIS) provided an estimate of the spatial distribution of clusters in Kyrgyzstan. Buffer analysis revealed regions with limited access to infrastructure, such as logistics centres, warehouses, and processing plants. Spatial density analysis was used to identify regions with a high concentration of farms that have the potential for clustering. In addition, the assessment of agroclimatic conditions allowed identifying the most favourable areas for creating new clusters.

RESULTS

Analysis of the current state of farms in Kyrgyzstan. Agriculture in Kyrgyzstan is one of the leading sectors of the country's economy, which provides employment for a substantial part of the population and is a critical source of income in rural areas. The share of the agricultural sector in gross domestic product is 18% (National Statistical Committee of the Kyrgyz Republic, 2025; Governmental Decree No. 83, 2021), which is substantially higher than in Kazakhstan (4.5%) (Ministry of Agriculture of the Republic of Kazakhstan, 2025), but inferior to Uzbekistan (26%) (Ministry of Agriculture of the Republic of Uzbekistan, 2025). This structure of the economy highlights Kyrgyzstan's dependence on agriculture, especially in conditions of a limited industrial base. There are more than 413 thousand farms in the country with an average size of 15 hectares. For comparison, in Kazakhstan, the average size of a farm reaches 1650 hectares, while in Uzbekistan this figure is 57 hectares. The predominance of small farms in Kyrgyzstan poses a number of challenges, including limited access to resources, technology, and financial services, which negatively affects productivity. The main crops grown in the country are wheat (30%), potatoes (15%), and cotton (10%). Animal husbandry is dominated by cattle (25%) and sheep breeding (20%).

Kyrgyzstan's agriculture faces a number of challenges that hinder its development. Primarily, it is limited access to financial resources. Most farmers face high interest rates and insufficient guarantees for obtaining loans, which substantially reduces opportunities for investment in production modernisation. The lack of modern technology and knowledge is another substantial problem. The use of outdated farming methods reduces the efficiency and quality of products, limiting competitiveness in the international market. The low level of cooperation between farmers also remains a serious problem. The lack of associations in the form of cooperatives complicates jointly solving logistics, product marketing, and resource management issues.

Comparison with other Central Asian countries shows similar problems in the region, such as soil degradation, water scarcity, and weak infrastructure. Nevertheless, Kazakhstan, Uzbekistan, and Tajikistan demonstrate successful examples of implementing agricultural initiatives. In Kazakhstan, the development of grain clusters has ensured the efficient use of large land areas due to the introduction of modern technologies. Uzbekistan focuses on fruit and vegetable clusters with an export focus, which substantially increases farmers' incomes. In Tajikistan, the successful integration of small farmers into the processing industry has increased the profitability and stability of Agriculture (Table 1).

***Table 1**. Comparative characteristics of the agricultural sector of Central Asian countries*

Indicator	Kyrgyzstan	Kazakhstan	Uzbekistan	Tajikistan
Share of Agriculture in GDP (%)	18	4.5	26	20
Number of farms (thousand)	413	200	575	123
Average farm size (ha)	15	1,650	57	0.1

***Source:** compared by the author based on sources National Statistical Committee of the Kyrgyz Republic (2025), Governmental Decree No. 83 (2021), Eurasian Development Bank (EDB) (2025), Ministry of Agriculture of the Republic of Kazakhstan (2025), Ministry of Agriculture of the Republic of Uzbekistan (2025), Ministry of Agriculture of the Republic of Tajikistan (2025)*

Thus, the agricultural sector of Kyrgyzstan has a substantial potential for development, but its implementation requires solving key problems. Adapting successful practices of neighbouring countries, such as the implementation of the cluster model, the development of cooperatives and the introduction of modern technologies, can be an effective way to improve the productivity and stability of farms in the country.

Empirical analysis of the impact of clustering on farms. Clustering is a modern tool for the development of farms, based on the creation of close relationships between various participants in the agricultural sector, including producers, processing enterprises, suppliers of resources and services, as well as consumers. In farms, the cluster model allows small producers to integrate into larger economic structures, reducing costs and increasing efficiency. For example, according to the FAO (2024), farmers working in cluster associations show 25% higher productivity compared to independent farms. The main performance indicators of the cluster model are productivity, profitability, and export volume. Studies in France and Italy have shown that farms that participated in cluster initiatives increased their income by 20-30% due to shared access to processing infrastructure and marketing resources (European Commission, 2025). The experience of other countries demonstrates the substantial effectiveness of the cluster model. In Poland, dairy farms in clusters reduced logistics costs by 15%, which contributed to an 18% increase in profitability. In Croatia, the cluster approach has increased the productivity of small farms by 22% due to individual support programmes. In France, wine clusters increased their export revenue by 28% because of improved product quality and joint promotion of brands on the international market.

In Italy, olive clusters showed that the association of small producers contributed to a 35% increase in exports, the creation of regional brands and an increase in the share of products in the premium segment market. In the United States, cluster initiatives to support small farmers have reduced production costs by 12% and provided stable access to markets. Indian agricultural clusters for rice and wheat cultivation increased productivity by 20%, which allowed small farmers to integrate into regional supply chains (European Commission, 2025; United States Department of Agriculture (USDA), 2025). Empirical analysis shows that countries that have implemented the cluster model experience substantial growth in productivity and exports. Table 2 shows a comparison of key clustering results.

***Table 2**. Results of clustering in farms of different countries*

Country	Sector	Key results
Poland	Dairy farming	Increased profitability due to shared infrastructure
Croatia	Dairy farming	Differentiating support, improving productivity
France	Winemaking	Improve quality, create added value
Italy	Olive oil	Increase exports, create regional brands
USA	Various agricultural sectors	Integration of small farmers into the processing industry
India	Rice and wheat	Increased production volumes, access to larger markets

***Source:** compared by the author based on sources European Commission (2025), United States Department of Agriculture (USDA) (2025), Ministry of Agriculture & Farmers Welfare (2025)*

Comparison with other countries demonstrates the substantial potential of the cluster model, but to effectively adapt this experience to the conditions of Kyrgyzstan, it is necessary to identify specific implementation steps. Successful practices in Poland, France, Italy, the United States, and India point to the importance of government support, infrastructure development, innovation, and a regional approach. First, it is necessary to introduce additional financial instruments to support farmers. These can include subsidies for the purchase of modern equipment, fertilisers, high-quality seeds, and grants for cooperatives engaged in innovation. Such financial support will become the foundation for stimulating the development of clusters in the regions with the greatest potential. One of the key tasks is the development of logistics infrastructure. The construction of modern warehouses, processing plants and transport hubs will reduce logistics costs, facilitate farmers' access to sales markets and help increase the export potential of agricultural products. Infrastructure investments should be directed to regions where clustering can have the greatest impact, such as Chui and Issyk-Kul regions. Raising farmers' awareness of the benefits of clustering and modern agricultural technologies is critical. Educational programmes should include trainings, seminars, and practical cases that demonstrate the effectiveness of the cluster model. This will help to overcome distrust between farmers and create a culture of cooperation.

It is necessary to improve the legislative framework to create a favourable environment. The state should ensure simplified registration of cooperatives, introduce preferential taxation for cluster associations, and develop mechanisms for legal protection of farmers participating in clustering. This will help build trust in such associations and encourage the attraction of new participants. Special attention should be paid to attracting international investment. Cooperation with organisations such as the FAO or the Eurasian Development Bank can be a source of funding for the creation of clusters and the development of related infrastructure. This approach will substantially expand the scale of clustering and increase the competitiveness of Kyrgyzstan's agricultural sector. The implementation of these measures will allow adapting the experience of other countries to the specifics of Kyrgyzstan, helping to increase the productivity of farms, strengthen the socio-economic potential of rural regions, and expand access to international markets.

Empirical data analysis in Kyrgyzstan. Agricultural clusters in Kyrgyzstan are a relatively new phenomenon that is at the stage of formation. The most famous clusters are concentrated in the northern and southern regions of the country. In the northern regions, such as Chui and Issyk-Kul, fruit and vegetable clusters focused on the production of potatoes, vegetables, and fruits have formed. These regions have favorable climatic conditions, a well-developed infrastructure for storing and processing products, which contributes to the successful functioning of clusters. The southern regions, in particular, the Osh and Batken regions, specialise in the cultivation of cotton and other industrial crops. Here, agricultural clusters provide an association of farmers for the joint use of irrigation resources and processing of raw materials. An important factor in the effectiveness of clusters in these regions is their export potential since a substantial part of their products is sold on international markets, especially in Central Asia and the EU. The performance of existing clusters was analysed in terms of productivity, costs, profitability, and exports. The study showed that farmers involved in cluster associations, on average, increased production volumes by 15-20% due to shared access to modern technologies, fertilisers, and technical means. Production costs were reduced by 12-15% due to savings on logistics and joint resource purchases.

Analysis of the effectiveness of existing clusters in Kyrgyzstan shows their substantial impact on the productivity and profitability of farms. Farmers' participation in cluster structures helps increase yields, reduce costs, and expand access to new markets. According to the Ministry of Agriculture of Kyrgyzstan, in regions where cluster associations operate, productivity increased by 15-25%, depending on the crop. For example, in the Chui region, the yield of potatoes in cluster farms increased from 18 tonnes/ha to 22 tonnes/ha, which is the result of the use of modern irrigation technologies, high-quality seeds, and advisory support (Governmental Decree No. 83..., 2021). The profitability of farms involved in clusters increased by an average of 20-30%. This was made possible by reducing production costs through collective purchases of fertilisers, fuel, and seeds, as well as optimising logistics processes. In the Batken region, the income of cotton farmers increased by 25% due to improved access to infrastructure and markets in the European Union. Similar results were observed in the fruit and vegetable cluster of the Issyk-Kul region, where the expansion of exports to Kazakhstan and Russia allowed increasing sales volumes by 30% (National Statistical Committee of the Kyrgyz Republic, 2025).

Clustering also increases farmers' access to international markets. Collective agreements concluded by cluster associations have opened up opportunities for selling products on terms that meet international standards. For example, farmers in fruit and vegetable clusters received premium prices for quality products, in particular, apples and apricots, which provided additional income. Empirical evidence shows that farmers who are part of clusters show not only higher productivity but also greater resilience to market challenges. The table compares key indicators of productivity and profitability of cluster farms with independent farmers.

Impact of clusters on socio-economic development. Clusters have a positive impact on the socio-economic development of rural regions of Kyrgyzstan. Farmers' income growth is one of the main indicators. Cluster participants received premium prices for their products due to their high quality and access to new markets. On average, the income of farmers in cluster farms increased by 25%, which allowed them to invest in the modernisation of their farms (National Statistical Committee of the Kyrgyz Republic, 2025). Clusters have also contributed to the creation of new jobs in rural areas. For example, in the fruit and vegetable cluster of the Issyk-Kul region, more than 500 jobs were created in the fields of processing, storage, and transportation of products. This substantially affected the reduction of the unemployment rate in the region. Improving market access was another substantial achievement of the cluster model. Collective agreements with international partners helped farms increase export volumes by 30%. The main export destinations are Kazakhstan and the European Union countries.

The distribution of clusters in Kyrgyzstan is uneven and depends on agroclimatic conditions and existing infrastructure. In the northern regions, such as the Chui and Issyk-Kul regions, fruit and vegetable and grain clusters are concentrated. The southern regions, in particular, Osh and Batken, specialise in the production of cotton and other industrial crops. Geospatial analysis showed that clusters located in areas with access to modern infrastructure – warehouses, processing plants, and transport hubs demonstrate the greatest efficiency. In regions with limited infrastructure, such as the Naryn region, cluster productivity is lower due to high logistics costs.

Successful clustering examples. An analysis of successful clustering examples in Central Asia and the European Union shows that the implementation of the cluster model contributes to a substantial increase in productivity, profitability and socio-economic development. In Kazakhstan, grain agricultural clusters, concentrated mainly in the northern regions, have become one of the most efficient in Central Asia. Due to access to modern technologies, high-quality seeds and integrated logistics infrastructure, the productivity of grain crops in cluster farms exceeds 5 tonnes/ha, which is 20% more than the national average. State support through subsidies for fertilisers and machinery also helped reduce production costs (Eurasian Development Bank (EDB), 2025).

In Uzbekistan, fruit and vegetable clusters are export-oriented. The government supports farmers by creating special export-oriented zones and providing access to international markets. As a result, exports of fruit and vegetable products have increased by 30% over the past five years. The main sales markets are Russia, Kazakhstan, and the EU countries (Ministry of Agriculture of the Republic of Uzbekistan, 2025). In Tajikistan, clustering has allowed integrating small farmers into the processing industry, in particular, in the production of cotton products. The creation of joint processing enterprises and cooperatives has provided farmers with a stable income and reduced their dependence on market price fluctuations. The income of farmers included in the clusters increased by an average of 25% (Ministry of Agriculture of the Republic of Tajikistan, 2025). In the European Union, clustering has been particularly developed in countries such as Poland, France, and Italy. In Poland, dairy clusters have contributed to an 18% increase in farm profitability through shared access to processing plants. In France, wine clusters increased their export revenue by 28%, which was made possible by improved product quality and joint marketing. In Italy, clustering in olive oil production increased export volumes by 35% and created regional brands known all over the world (European Commission, 2025).

The effectiveness of cluster models in Kyrgyzstan and other countries largely depends on the level of state support and participation of international organisations (Mamasydykov *et al.*, 2019). In Kazakhstan and Uzbekistan, governments provide substantial subsidies for cluster infrastructure, including logistics centres, irrigation systems, and warehouses. In the EU, farmers gain access to grants and soft loans as part of a common agricultural policy that ensures sustainable cluster development. Compared to these countries, Kyrgyzstan faces restrictions due to a lack of funding and weak infrastructure. For example, grain productivity in Cluster farms in Kyrgyzstan is lower than in Kazakhstan and on average in the EU. However, the introduction of the cluster model has already reduced production costs and increased farmers' incomes, which indicates its prospects (Table 3).

Table 3*. Comparison of cluster performance in Kyrgyzstan, Central Asia and the EU*

Indicator	Kyrgyzstan	Kazakhstan	Uzbekistan	EU (average)
Grain productivity (tonnes/ha)	4.5	5	4.8	6
Export growth (%)	15	25	30	35
Cost reduction (%)	12-15	20	18	25
Farmers' profits (%)	20-30	25	28	30

Source: *compared by the author based on sources National Statistical Committee of the Kyrgyz Republic (2025), Governmental Decree No. 83 (2021), Ministry of Agriculture of the Republic of Kazakhstan (2025), Ministry of Agriculture of the Republic of Uzbekistan (2025), European Commission (2025)*

Kyrgyzstan shows positive trends in the implementation of the cluster model, but a considerable potential remains unrealised. More government support, infrastructure development, and attracting international investment are needed to achieve the level of efficiency typical for Kazakhstan, Uzbekistan and the EU.

Advantages and disadvantages of implementing a cluster model in Kyrgyzstan. The clustering of farms in Kyrgyzstan demonstrates a number of substantial advantages that positively affect productivity, profitability, and socio-economic development. Due to shared access to modern technologies, high-quality seeds and fertilisers, farmers in cluster associations increase yields by 15-25%. For example, in the Chui region, potato yields in cluster farms reached 22 tonnes/ha compared to 18 tonnes/ha for independent farmers. Joint purchases of resources, such as fuel, fertilisers, and seeds, can reduce production costs by 12-15%. Efficient use of infrastructure also helps reduce logistics costs. Farm profits are growing by 20-30% due to cost savings, improved product quality, and increased market access. In the Batken region, the income of cotton farmers increased by 25% due to improved logistics and export opportunities. Collective agreements within clusters provide farmers with access to new markets, which allows them to increase export volumes by 30%. The fruit and vegetable clusters of the Issyk-Kul region successfully export their products to Kazakhstan and the EU. Clusters contribute to the economic development of regions by creating new jobs (Dooranov *et al.*, 2024). For example, in the fruit and vegetable cluster of the Issyk-Kul region, more than 500 jobs were created in the fields of storage, processing, and transportation of products. Combining farmers into clusters provides greater resistance to price fluctuations and allows setting premium prices for high-quality products that meet international standards (Governmental Decree No. 83, 2021; National Statistical Committee of the Kyrgyz Republic, 2025).

The implementation of the cluster model in Kyrgyz farms faces many challenges and limitations that limit its effectiveness and scale. Institutional barriers are among the most important constraints. Insufficient financial support for cluster initiatives creates substantial difficulties for farmers. Most farmers do not have access to soft loans or grants necessary for the introduction of modern technologies or infrastructure development. The legislative framework governing the activities of cooperatives and clusters is insufficiently developed. For example, the lack of clear mechanisms for state regulation and incentives for cooperatives limits the possibility of their integration into regional economic structures (Bovsh *et al.*, 2024). Among the technological challenges, the lack of access to modern agricultural technologies particularly stands out. Many farmers continue to use outdated farming methods, which negatively affects the yield and quality of products. Logistics and recycling constraints also remain an important issue. The lack of specialised warehouses for storing products, insufficient mechanisation in harvesting processes, and limited access to processing enterprises limit the competitiveness of farmers. Socio-cultural aspects also have a substantial impact. Distrust between farmers remains a serious obstacle to the creation of cooperatives and clusters. The lack of a culture of collaboration and low awareness of the benefits of clustering make farmers reluctant to participate in such initiatives. This creates a barrier to the effective implementation of the model, which requires substantial efforts in the field of educational and information campaigns. Regions with developed infrastructure show substantially better results, while in remote areas clustering remains inefficient due to high logistics costs.

Practical recommendations based on the results obtained. Based on the analysis of challenges and limitations and the results of implementing the cluster model, a number of practical recommendations are proposed that can improve the efficiency of cluster development in Kyrgyzstan. The first step should be to create pilot clusters in the most promising regions. Regions such as Chui and Issyk-Kul have substantial potential due to their developed infrastructure and favourable climatic conditions. The creation of pilot clusters will demonstrate the cost-effectiveness of the model and attract more farmers to the initiative. The introduction of educational programmes for farmers is essential to raise awareness of the benefits of clustering. Educational campaigns should be aimed at providing knowledge about modern agricultural technologies, methods of managing cooperatives, and effective integration into cluster structures. Conducting trainings and seminars and spreading successful clustering cases, will help build trust between farmers. The development of a policy of state support for clusters is a key factor for their successful implementation. The state should provide financial support for cluster initiatives through subsidies, soft loans, and grants. In addition, a favourable legislative framework should be created that will provide legal protection for cluster participants and encourage their development.

Supporting innovation and introducing modern technologies is an important area for ensuring the competitiveness of farms. The creation of public and private funds to finance innovative projects in agriculture will increase productivity and product quality. The integration of digital technologies, such as precision farming systems and automation of production processes, will contribute to efficient resource management and reduce costs. The implementation of these recommendations will overcome the main barriers and challenges of implementing the cluster model, contributing to the sustainable development of Kyrgyzstan's agriculture and increasing its competitiveness in international markets.

DISCUSSION

The results of the study confirmed that the cluster model in Kyrgyz farms is an effective mechanism for increasing the productivity, profitability, and competitiveness of the agricultural sector. The impact of cluster farming on the household economy in Ethiopia was examined by A.Z. Zeleke and M.G. Wordofa (2024). Scientists emphasised the importance of clusters for increasing farmers' incomes. Similar results were observed in Kyrgyzstan, where farmers' incomes in cluster associations increased by 20-30%. In both cases, revenue growth was attributed to better access to markets, which was achieved through collective agreements and shared logistics infrastructure. E. Righi *et al.* (2010) emphasised the importance of considering regional features when implementing cluster models. In Kyrgyzstan, this was also confirmed: regions with better infrastructure, such as the Chui and Issyk-Kul regions, showed higher cluster efficiency compared to regions where access to infrastructure was limited. This indicates the need for targeted investments in the development of logistics centres and processing enterprises.

The observed yield increase of 15-25% in cluster farms was consistent with the results of similar studies conducted in other countries. For example, S. Degefu *et al.* (2024) examined the effect of clustering on wheat productivity among small farmers in Ethiopia and recorded a 20% increase in yield, which is close to the indicators obtained in Kyrgyzstan. Both studies emphasised the importance of access to modern technologies and resource sharing as key success factors. Z. Hloušková and M. Lekešová (2020) showed that farms grouped by cluster analysis showed increased profitability due to reduced production costs and access to collective infrastructure. These results were consistent with data obtained in Kyrgyzstan, where there was a reduction in costs in cluster farms. This confirms that economies of scale are an important factor in improving farm efficiency in the cluster model.

A publication of P. Balogh *et al.* (2021) focused on the economic and social barriers to innovation in Hungarian agriculture. Problems identified in Kyrgyzstan, such as limited access to funding and low awareness of farmers about the benefits of clustering, correlated with barriers recorded in Hungary. This confirms the need for government support and educational programmes to raise farmers' awareness and overcome social barriers. E. Muñoz-Ulecia *et al.* (2020) emphasised that the development of mountain agriculture in Spain depended on adaptation to local conditions and the involvement of farmers in cooperative associations. This approach has proven effective in Kyrgyzstan, especially in mountainous regions such as the Issyk-Kul region. In these areas, the creation of fruit and vegetable clusters has not only increased productivity but also expanded exports to neighbouring countries.

The results of the study confirmed that the implementation of the cluster model in farms in Kyrgyzstan has a positive impact on the productivity, profitability, and competitiveness of the agricultural sector. These results are consistent with the results of studies in other countries. For example, G.G. Dureti *et al.* (2023) noted that clustering has contributed to the commercialisation of small farms in Ethiopia, increasing their productivity and market access. In Kyrgyzstan, similar results were shown by farmers involved in cluster associations, which increased yields through shared access to resources and technologies. L. Lan *et al.* (2018) demonstrated that the introduction of climate-smart agricultural technologies in cluster initiatives increased the economic sustainability of farmers and their adaptation to climate change. In Kyrgyzstan, similar approaches implemented in grain and fruit and vegetable clusters have helped optimise the use of water and land resources, which is a critical factor in arid regions. M. Kassai *et al.* (2018) examined farmers' markets as temporary clusters to improve the local food economy. The findings on improving market access for farmers coincide with the results obtained in Kyrgyzstan. Collective agreements and joint use of logistics centres allowed cluster associations in the Chui region to increase export volumes.

M. Sporysz *et al*. (2020) emphasised that cluster analysis is an effective tool for assessing the sustainability of organic farms. It is established that combining farmers into clusters helps optimise the use of resources and improves environmental sustainability. In Kyrgyzstan, this approach has reduced costs in cluster farms through the joint use of fertilisers, seeds, and modern agricultural technologies, which has contributed not only to economic efficiency but also to reducing the negative impact on the environment. M.F. Rola-Rubzen *et al*. (2013) showed that farmers' clusters in the Philippines contributed to income growth through better market access and coordination of logistics processes. In Kyrgyzstan, similar trends were observed in fruit and vegetable clusters, where farmers increased exports due to collective agreements and improved logistics. This confirms the universality of clustering benefits, regardless of the regional context.

A study by B. Khoshnevisan *et al*. (2015) demonstrated the use of fuzzy clustering to optimise energy costs in agriculture. Similar approaches were not used in Kyrgyzstan, but the results of the study indicate the prospects of such models for reducing energy consumption in cluster farms, especially in the context of limited resources. A study of M. Sydykova and C. Rodríguez (2014) examined the development of clusters in the livestock sector in Kyrgyzstan. The results confirmed that clustering in this sector contributes not only to increasing productivity but also to creating new jobs in rural areas. Similar trends were observed in the current study, especially in the southern regions of the country, such as the Osh region, where clustering in cotton cultivation led to an increase in farmers' incomes. L. Zhao *et al*. (2021) stressed the importance of regional industrial policies in the development of agricultural clusters, in particular, through financial support, infrastructure development, and creating a favourable investment environment. In Kyrgyzstan, the lack of sufficient government support and limited access to financial resources are among the key barriers to implementing the cluster model (Kerimkulova *et al*., 2023). These results are consistent with research conducted in China, which indicates the importance of political support for the successful functioning of clusters. A publication by S. Kumar *et al*. (2019) emphasised the importance of typological analysis of farms for the implementation of appropriate technologies in arid regions of South Asia. In Kyrgyzstan, similar agroclimatic problems were solved by adapting the cluster model to specific conditions in regions such as the Chui and Issyk-Kul regions. This confirms that considering regional characteristics is crucial for the success of clustering.

In Kyrgyzstan, due to participation in cluster associations, farmers have become less vulnerable to fluctuations in product prices and have access to more stable market conditions (Uzenbaev *et al*., 2019). H.A. Adewale (2022) showed that shared knowledge and clustering contribute to sustainable access to farm-oriented support in Nigeria. In Kyrgyzstan, similar trends were observed in the formation of clusters in the fruit-and-vegetable and grain sectors, where farmers gained better access to technology and resources through collective agreements. These results confirm that collective interaction and access to knowledge are key to clustering success. Researchers G. Tefera *et al*. (2023) evaluated the impact of cluster wheat cultivation in Ethiopia. The study determined that this model helps increase the assets of small farmers. A similar effect was observed in Kyrgyzstan, where cluster farmers were able to invest in upgrading their farms due to rising incomes. This indicates that clustering creates conditions for long-term economic growth. All results indicate a high clustering potential for agricultural development in Kyrgyzstan. However, to achieve full effect, it is important to overcome key barriers such as limited access to funding, insufficient government support, and social problems, including distrust between farmers. State support, infrastructure development, and educational initiatives remain priorities for further improvement of the cluster model.

CONCLUSIONS

The study confirmed that the implementation of the cluster model in farms in Kyrgyzstan is a promising tool for improving the productivity, profitability, and competitiveness of the agricultural sector. Clustering allows farmers to pool resources, reduce costs, and optimise infrastructure usage. Empirical data showed that the yield in cluster farms increased by 15-25%, and farmers' incomes increased by 20-30% due to the joint use of modern agricultural technologies, access to high-quality seeds, and optimisation of logistics processes. For example, in the Chui region, the yield of grain crops in cluster farms reached 6.5 tonnes/ha, which is substantially higher than the national average. The socio-economic impact of clustering included not only increasing farmers' incomes but also creating new jobs in rural areas. More than 500 jobs were created in the fruit and vegetable clusters of the Issyk-Kul region in the fields of processing, storage, and logistics of products. In addition, the clusters helped to expand access to international markets, which allowed increasing export volumes by 30%. Farmers who are members of cluster associations were able to receive premium prices for products that meet international standards. However, the study also revealed a number of problems. Among the key problems were the deficiency of financial support from the state, the lack of a legislative framework for the effective functioning of cooperatives and clusters, and limited access to modern technologies. Socio-cultural barriers, in particular, distrust between farmers and low awareness of the benefits of clustering, also hinder the successful implementation of the model. These factors limit the scale and speed of implementing the cluster model in regional farms.

The results of the study indicate the need for a systematic approach to the development of clusters in Kyrgyzstan. It is recommended to create pilot clusters in the most promising regions, such as the Chui and Issyk-Kul regions, to demonstrate their economic feasibility. Educational programmes for farmers should become a priority area for raising awareness of the benefits of clustering, modern agricultural technologies, and effective management of cooperatives. The development of state support policies should include subsidies, concessional lending, the creation of special infrastructure facilities, and mechanisms to encourage farmers to participate in clusters. Further research in this area should include an analysis of the long-term impact of clustering on the environmental sustainability of agriculture, the introduction of digital tools for cluster management, and mechanisms for attracting investment. The examination of socio-cultural aspects, in particular, approaches to overcoming distrust between farmers, is another promising area that can substantially strengthen the cooperative movement in Kyrgyzstan. The implementation of these measures will contribute to the sustainable development of the agricultural sector and the socio-economic progress of rural regions.

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CONFLICT OF INTEREST

None.

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Економічна оцінка впливу кластерів на розвиток фермерських господарств у Киргизстані

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Анотація. Метою дослідження була оцінка ефективності впровадження кластерної моделі в сільському господарстві Киргизстану з акцентом на її вплив на продуктивність, прибутковість фермерських господарств та конкурентоспроможність аграрного сектору. Методологія дослідження включала оцінку статистичних даних фермерських господарств Киргизстану, емпіричний аналіз впливу кластеризації на соціально-економічні показники, просторовий аналіз розподілу кластерів та порівняльну оцінку успішних практик кластеризації в країнах Центральної Азії (Узбекистан, Таджикистан, Казахстан), а також Польщі, Хорватії, Франції, Італії, США, Індії. Основні результати показували, що фермери, залучені до кластерних об'єднань, збільшили врожайність на 15-25 %, а прибутки фермерських господарств зросли на 20-30 % завдяки зниженню виробничих витрат на 12-15 % і розширенню доступу до ринків збуту. У Чуйській області врожайність зернових у кластерних господарствах досягла 6,5 т/га, що перевищує середній показник по країні. Експорт продукції плодоовочевих кластерів збільшився на 30 % завдяки розширенню ринків збуту в Казахстані та Європейському Союзі. Визначено основні проблеми впровадження кластеризації: відсутність фінансової підтримки, недостатня законодавча база для кооперативів, відсутність доступу до сучасних технологій та недовіра між фермерами. На основі отриманих даних запропоновано практичні рекомендації, що включають створення пілотних кластерів у перспективних регіонах, розробку освітніх програм для фермерів, вдосконалення державної політики підтримки кластерів та стимулювання інновацій у сільському господарстві. Порівняльний аналіз з країнами Центральної Азії та Європейського Союзу підтвердив значний потенціал кластерної моделі для підвищення ефективності сільського господарства Киргизстану та сприяння соціально-економічному розвитку сільських регіонів

Ключові слова: агросфера; регіональний розвиток; агрохолдинг; стратегії управління; сільськогосподарські асоціації

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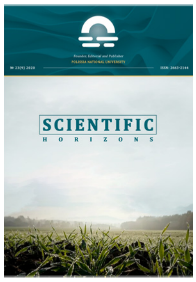

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Przewalski's horse distribution analysis using geospatial data within the Chernobyl Exclusion Zone habitats

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Abstract. The recovery of the Przewalski's horse population in the Chernobyl Exclusion Zone, the protection of this unique species, and the creation of effective monitoring and habitat management plans using geoinformation technology are all crucial. Therefore, the purpose of this study was to develop a monitoring system for this species that

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considers various factors of the environment. The research methodology involved a multi-step process that included collecting data (through a literature review and field observations), figuring out which key factors to model, and confirming the findings. As a result, habitat suitability maps were created for Przewalski's horse distribution by synthesising data on terrain, climate, hydrology, vegetation cover, food competition, predator presence, and safety. The models were calibrated with factual observations from 2018 to 2024. The study found five harems of Przewalski's horses in the exclusion zone in 2023. The distribution of these species is substantially influenced by elevation above sea level, proximity to highways and water bodies, resource competition, and predator activity. The 10-kilometer radius around the Chernobyl Nuclear Power Plant was designated as the least favourable region due to wildfires and human activity, while the most ideal habitats were in the central section of the research territory. A cluster study found that the exclusion zone could give Przewalski's horses an extra 350 km^2 of habitat, which is vital for keeping the population alive during natural succession. The GIS models created in this study can simulate prospective future environments, considering environmental alterations and conservation efforts

Keywords: mammals; GIS; acclimatisation; preservation; suitability map

INTRODUCTION

Przewalski's horse (PH) is a unique example of successfully reintroducing an endangered megafaunal species into a post-industrial, radiation-affected landscape. This allows investigating ecological resilience under extreme environmental conditions. Therefore, precise monitoring of their distribution within the Chernobyl Exclusion Zone (CEZ) and identification of the best places for further settlement is critical. PH in the CEZ serve as a unique example of nature's resilience in extreme conditions, demonstrating high adaptability and resistance to radiation exposure while playing a key ecological role in maintaining ecosystem balance. P. Schlichting *et al.* (2020), N. Beresford *et al.* (2021) showed that despite radiation exposure, the populations of these animals stay stable, and disease rates do not exceed the expected levels. A total of 137 PHs was found in the Ukrainian part of the CEZ, according to a study by P. Gashchak and S. Paskevich (2019): 47 stallions, 66 adult and filly mares, and 24 foals (10 males, 4 females, and 10 of unknown gender).

The greatest problems for the PH population are poaching and genetic homogeneity, since there are few of the specimens. There are also risks from higher radiation levels, anthropogenic influence, and weather changes (Beresford *et al.,* 2023). In these conditions, Geographic Information Systems (GIS) serve as an essential tool for predicting the joint impact of all environmental and anthropogenic factors simultaneously, identifying the most suitable habitats, predicting future expansion areas, and developing suitability maps for conservation strategies worldwide. Many studies have used GIS and suitability mapping to identify the best locations for their introduction and distribution. For example, suitability analysis in Mongolia has identified Hustai National Park, Takhin Tal, and Khomin Tal national parks as most suitable for the reintroduction and PH conservation. They used various ecological, biological, and anthropogenic factors to assess the suitability of different regions for the survival of PH. I. Kajiwara *et al.* (2016) used the number of faeces found in 48 randomly chosen field plots to create a generalised linear model (GLM). This model helped them establish the factors affecting how horses use their habitat. The model used the amount of faeces found at each site as the dependent variable, and seven explanatory variables that could affect how PHs use their habitat. These were the distance to the river, the distance to the forest, the distance to the road, the slope, the difference in elevation with the environment, the number of plant communities, and the presence of dominant categories of forage plants.

Y. Zhang *et al.* (2024) described the different versions of suitability maps that were customised to natural and climatic conditions and emphasised the significance of environmental factors in the suitability analysis for the PHs. Therefore, it is critical to identify influencing factors when creating suitability maps. The PHs, native to the steppe regions of Mongolia, excel in semi-arid to temperate climates characterised by cold winters and dry summers. According to Q. Cao *et al.* (2023), the amount of precipitation, humidity, and temperature regime are vital determinants of suitable habitats. Like for other species, the availability of food resources plays a critical role in assessing the suitability of a territory for habitation. The presence of steppe vegetation, including grasses and shrubs, is crucial for the PHs' survival, as its primary diet consists of grasses.

Scientists T. Hare (2022) noted that the existence of settlements, agricultural land, and infrastructure (such as roads and fences) might adversely affect the region's appropriateness for horses. V. Lu *et al.* (2021) showed that regions with limited human interference are preferred. Regions with fragmented habitats resulting from anthropogenic activity, such as urbanisation or deforestation, may be less conducive. PH favour broad plains and steppe regions that allow for unrestricted movement. Level or inclined terrains are best for their locomotion and foraging. Inclined or forested regions may be less suitable.

The purpose of this study was to identify and combine the optimum parameters of PHs, analyse the territory of the CEZ, and determine the zones of the best settlement for PHs.

MATERIALS AND METHODS

Study area. The Chornobyl Radiation and Ecological Biosphere Reserve (CREBR) is located between latitudes N51.084 and N51.351 and longitudes E29.262 and E30.384 in the Kyiv Oblast of northern Ukraine (Fig. 1). The research area is situated at an elevation of 93 to 200 meters above sea level, with an average annual temperature of 8.2°C and an average precipitation of 619 mm. CEZ, encompassing approximately 2,600 km^2, contains the decommissioned nuclear power plant located in the eastern section of the zone, adjacent to the northwestern area of the cooling pond, known as CREBR (Fedoniuk *et al.,* 2024).

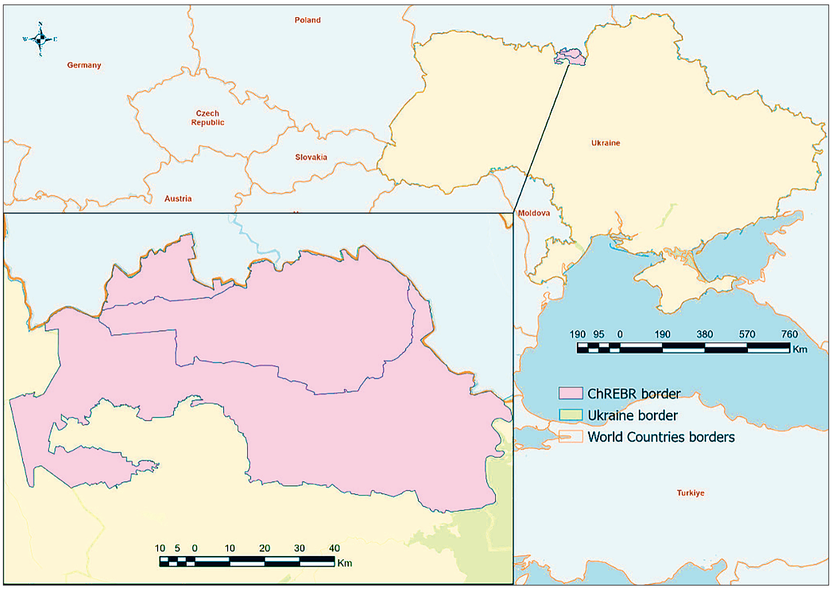

***Figure 1**. Location of the CREBR*

***Source:** T. Fedoniuk et al. (2024)*

The creation of landscape suitability maps for PH distribution and the identification of the best habitats was conducted in several stages: selection of input data (literature review and observational data), assessment of factor significance, modelling, validation, and result mapping. The study employed the Multi Scale Large (MS Large) methodology, a comprehensive suitability evaluation that considers extensive spatial contexts to identify suitable regions for infrastructure development or environmental conservation initiatives. These methods were employed in prior research, demonstrating excellent accuracy and reliability (Fedoniuk *et al.,* 2020). This method facilitates the analysis of extensive territories and leverages spatial dependencies, which is crucial for comprehensive planning in vast areas. Simultaneously, it was employed to integrate various data layers (maps) with weighting factors to identify the most suitable areas depending on specified criteria.

The construction of suitability maps encompassed several stages: gathering data on topography, climate, water source availability, vegetation cover, and information regarding the behaviour, dietary requirements, territoriality, and migration patterns of PHs, as well as documenting the presence of horses within the CEZ. To construct a suitability map, a composite of the key factors was established, encompassing the proximity to roads, water bodies, the presence of associated fauna (competitors for forage resources, the existence of predators), topographical elements, specifically elevation above sea level, and the classification of land cover (forest, pastures, buildings, roads), all of which were consolidated within a submodel.

Submodel analysis was conducted using ArcGIS Pro 3.3 software (with Spatial Analyst license) and the Suitability Modeler model (Implementation of suitability modelling workflow, n.d.). As for PHs, the best sites were selected based on a trade-off among three primary objectives: habitat, availability of food, and safety. For instance, the criteria for a safety objective included a preference for distance from highways and buildings, predator distribution, while staying in proximity to forests and protected areas. The three submodels were integrated to provide a final suitability map:

1. The submodel of habitat incorporated weighted and combined variables that comprehensively define habitats, including landscape, proximity to water sources, and geological characteristics of terrains.

2. Food availability submodel identified regions where PHs are most likely to locate sustenance,

considering the distribution of competing species for food supplies The security submodel identified the regions that were the safest for PHs. The most secure locations are distant from thoroughfares and residences.

3. The security submodel identified the regions that provide optimal safety for PHs. The most secure locations are distant from roads and residences and feature the presence of predators.

Analysis of suitability variables and weighting criteria was conducted using the "Multiplier" approach for the parameter "Weight by" in the "Settings" tab, whereby the transformed criteria values are multiplied by this number to generate a suitability map (Table 1). The aggregated converted criterion values were subsequently summed. A weight of 2 means that the criterion is twice as significant as a criterion with a weight of 1. A weight of 10 indicates that the condition is tenfold more significant. This strategy was employed as it is best for weighting criteria in relation to one another (Implementation of suitability modelling workflow, n.d.).

***Table 1**. The principal types of data (suitability maps) derived from weighting factors and evaluative hypotheses*

Factor	10-point scale evaluation	Evaluation statement	Factor transformation method
Roads	7	Roadside grassy coenoses act as a fodder base for horses, which also prefer to travel on roads	MS Large: the closer the better
Reservoirs	7	Horses frequent the floodplain and are often found within the first terrace	MS Large: the closer the better
Companion animals	6	Horses are unique in their eating behaviour, deer are close to them in behaviour.	MS Large: the closer the better
Animals are predators	3	Horses have a defence system against predators, so this factor is not critical	MS Large: the further the better
Height above sea level (m)	5	Horses prefer flat or moderately sloping areas.	Gaussian distribution
Herbaceous coenoses (as a component of the Land Cover (LCC)	6	Horses prefer open landscapes, such as fallows, forest edges, wastelands, forests without developed undergrowth.	9
Built-up areas (as a component of the LCC)	6	Avoid abandoned settlements but may be near abandoned farms.	3
Wooded areas (as a component of the LCC)	6	Horses are found mainly in light pine forests.	6
Agricultural land (as a component of the Land Cover (LCC)	6	Fallows and abandoned agricultural lands are especially attractive to them	10

***Source:** compiled by the authors of this study*

Identifying the best location for species conservation relies on the attributes of each site; for instance, it considers the gradient of the slope, proximity to roads or water sources, and the type of land use. The map was generated by modifying and prioritising the criteria. The suitability map assessed the significance of each environmental element using a 10-point scale. Submodels were subsequently weighted and aggregated to generate a final goodness-of-fit map. A model based on submodels or summary fitness maps for each submodel, the relative advantage of each location in relation to the goal of a specific submodel, was ranked. The final suitability map for each location determined how suitable it is based on whether it is a decent place to live, has enough food, and is safe. Environments that are the most acceptable, considering all the analysed parameters, were clustered separately. The simulation results were validated and calibrated by comparing the predicted data with real observations of Przewalski's horse populations. Models were calibrated to ascertain the accuracy of the maps. Observations in the exclusion zone were conducted in 2018-2024. The basis for the distribution map of PHs included over 2,000 records of their presence. The study superimposed the horse records data on the formed fitness maps, then visually assessed the coincidences. The study was conducted following the ARRIVE guidelines 2.0. (2010) for the use of animals in research.

RESULTS AND DISCUSSION

Przewalski's horse (Boddaert, 1785) is a wild equine species classified within the series *Equiformes* and the family *Equidae*. The International Union for Conservation of Nature (IUCN-2017) has classified PHs as extinct in the wild and classified it as threatened. PH, a wild equine species, is pertinent in this context due to its historical prevalence; nonetheless, significant habitat destruction has resulted in a global population decline (Orizaola, 2020). During 1998-1999, the CEZ received 13 stallions and 18 mares from the Askania-Nova reserve, housing them in a designated corral for acclimatisation. The PHs were introduced by personnel from the Chornobyl's SDP and experts from the CEZ. The rationale for establishing a free population zone for PHs within the area was articulated within the framework of the "Fauna" Program (2000), aimed at the conservation and restoration of this species, and aligned with the overarching objectives of the European Green Deal regarding biodiversity preservation (Skydan *et al.*, 2022). The selection of the location was attributed to the availability of expansive open areas and lesser human impact, which fosters circumstances akin to the natural habitats of these horses in Central Asia.

In 2023, research on the Reserve's territory and the CEZ documented approximately 5 harem groups, with sizes varying from 3 to 15 members. The harem includes a stallion (leader), mares, yearling stallions, and the current year's foals. Dyads comprising one stallion and one mare inhabit the vicinity of the villages of Cherevach and Korogod. They act as the initial basis for the establishment of new harem groupings. Due to restricted access to the area and the inability to perform comprehensive study on the status of the PH population, as it was conducted in previous years, there is a lack of data regarding their overall numbers. Throughout the year, harem groups were documented in the vicinity of Kopachi village and the outskirts of Cherevach village in Chornobyl. First, the study weighed the relationship to the height of the surface above sea level (Fig. 2).

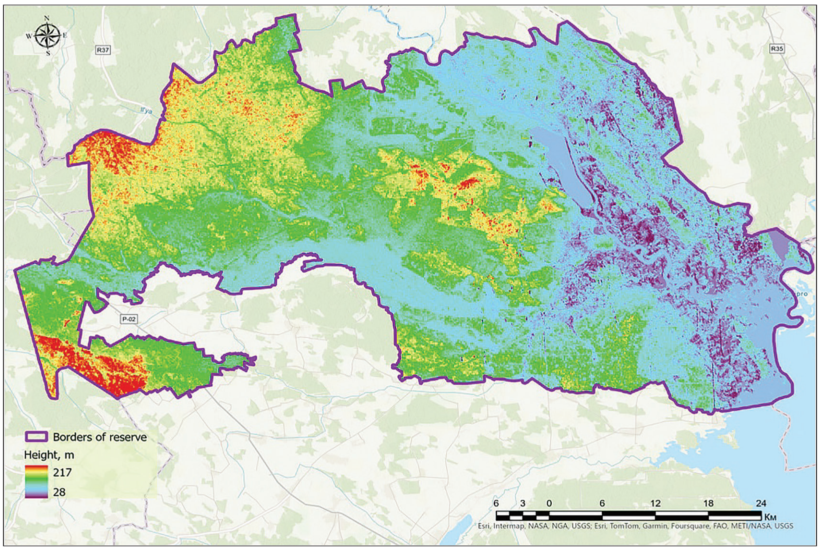

Figure 2. *Elevation map of the territory of the CREBR*
Source: *compiled by the authors of this study*

Proximity to roadways is a factor influencing the distribution of PHs. The distance from roads can profoundly influence the distribution and behaviour of PHs and other wildlife species. I. Kajiwara *et al.* (2016) considered seven factors that might affect the PH's choice of habitat: distance to a river, distance to a forest, distance to a road, slope, difference in elevation from the surrounding area, number of plant communities, and presence of dominant forage plant categories. W. Peng *et al.* (2020) noted that anthropogenic factors are the most significant. They were not significant in the present study, and therefore were not included in the territory suitability model. Instead, the study considered the proximity of the areas to roads. It is precisely the proximity to roads that greatly affects the ungulate migrations; this is also confirmed by the findings of T. Ito *et al.* (2017), who tracked the movements of ungulates on both sides of the Ulaanbaatar-Beijing railway and found that most animals never crossed the railway. The principal culprits are heightened noise and habitat disruption. A value of 7 represents the importance of proximity to roads. Roads are typically linked to elevated noise levels and human activity, which might deter wildlife and lead to their avoidance of certain regions (Fig. 3).

According to M. Turghan *et al.* (2022), Przewalski's horses, akin to numerous other animals, prefer locations that are tranquil and isolated from human interference, where their natural habitat is minimally disrupted. Roads can disrupt natural habitats, restricting the regions available for horses' movement and foraging. This results in the isolation of populations, which may diminish genetic diversity and compromise the species' longevity. The CEZ concurrently faces equivalent road traffic saturation. Observations indicate that horses in this area are more inclined to seek roadside phytocoenoses, whereas other animals use the roadways for movement (Fig. 4). Observations of horses in wild nature in the CEZ corroborate this, highlighting poaching and road traffic accidents as the principal risks for these species.

The modelling results suggest that the area directly adjacent to the building zone of the Chernobyl nuclear power station, known as the 10-km zone, is identified as the most unfavourable. In this region, PHs were documented solely in 2020. According to data from O. Skydan *et al.* (2021), during this year, about 66,222.5 ha of the reserve area was affected by fires, posing a threat to the animals (Fig. 5).

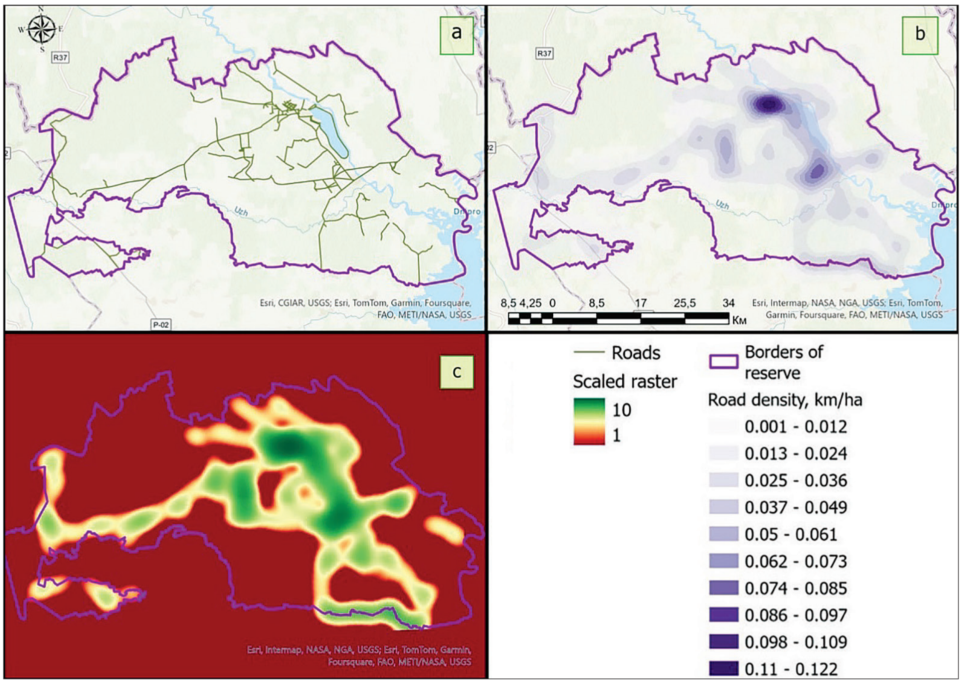

***Figure 3**. Transformation of geoinformation about the road's placement in the CEZ using the Multi Scale Large function*
***Source:** compiled by the authors of this study*

***Figure 4**. Movement of PHs within the CEZ*
***Source:** photograph by D. Vishnevskyi*

***Figure 5**. Migration of PHs close to the industrial part of the CEZ during large-scale forest fires in April 2022*
***Source:** photograph by D. Vishnevskyi*

Distance from bodies of water is also a significant factor influencing the distribution and behaviour of PH, as water is the main resource for the survival of any wild animal (Bernátková *et al.,* 2022). Specifically, the researchers noted that PHs, like most herbivores, require regular access to drinking water. PHs may have to concentrate near water sources in areas with limited water bodies (Chodkiewicz, 2020). Depending on climatic conditions, water may be less available at certain times of the year. They are particularly affected during periods of seasonal fires. In such cases, horses may migrate closer to water bodies, especially during dry seasons when natural water sources such as streams and lakes dry up.

Water availability can affect equine reproduction. Females requiring supplementary resources, such as water, to sustain themselves and their progeny will typically stay in proximity to aquatic bodies (Bernátková *et al.,* 2024). Observations from 2018 to 2023 suggest that population concentrations near water bodies are particularly pronounced during mating and offspring rearing periods. Furthermore, closeness to aquatic environments is typically linked to heightened biodiversity and more resilient ecosystems, providing horses with greater access to food and shelter. Consequently, reservoirs provide water requirements while also enhancing the environment for existence. Observations of PHs in the CEZ indicated their regular presence in floodplains, especially on the first terrace. Consequently, proximity to water bodies is crucial and was evaluated in the current study by a score of 7 (Fig. 6).

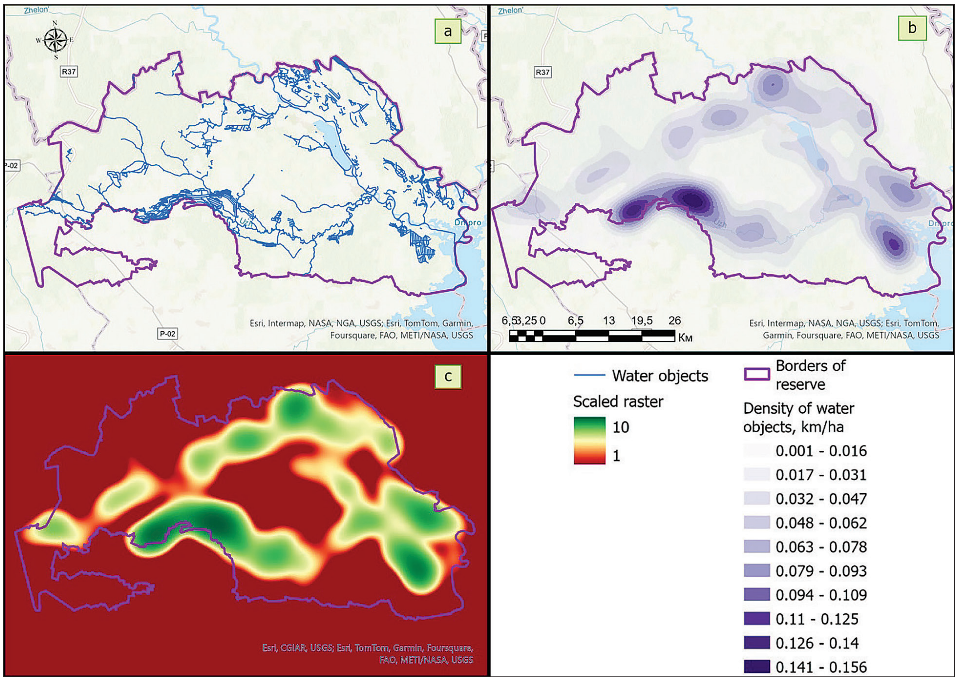

Figure 6*. Transformation of geo-information on water bodies captures in the CEZ using the Multi Scale Large function*
Source: *compiled by the authors of this study*

Therefore, the study included the proximity to water bodies as a variable in the suitability maps, along with the distance from roadways. The study employed the identical data processing procedure to convert vector data pertaining to reservoir locations within the CEZ into a raster format, after transforming it with the MS Large function. According to Q. Cao *et al.* (2025), the competition for resources between PHs and deer in the CEZ is an interesting subject since both species have comparable needs but live in slightly different ecological niches. A. Bernátková *et al.* (2024) noted that these animals' food preferences and their need for protection from predators both contributed to this behaviour.

Przewalski's horses and deer are both herbivorous, however they exhibit dietary variations. Horses mostly graze on grass, whereas deer, apart from grass, also actively ingest young shoots, branches, and foliage from trees and shrubs (Kerekes *et al.,* 2021). This suggests that when food is abundant, competition may diminish as each species concentrates on different regions of the available flora. In winter seasons, when vegetation is scarce, competition for pastures may intensify. During winter, snow restricts the accessibility of grass and other vegetation, prompting increased competition for food resources between PHs and deer. Deer may thrive in forested regions by consuming branches and tree bark. This confers a distinct advantage during the severe winter months, when the grass beneath the snow becomes unattainable for the horses. The rivalry among species in the CEZ parallels scenarios in Mongolia's national parks and other nations that have enacted environmental protection policies, wherein diminished human activity facilitates the restoration of natural ecosystems. In US game reserves, where horses and deer coexist, variations in nutrition and habitat mitigate significant conflict (Stoner *et al.,* 2021). Competition between PHs and deer in the CEZ is present, although it is somewhat mitigated by their distinct dietary requirements and spatial preferences. Year-round records of PHs suggest that competition with other ungulates, particularly during winter, can substantially influence their distribution. Consequently, the incorporation of the distribution factor of spotted deer into the suitability maps is entirely warranted (Fig. 7).

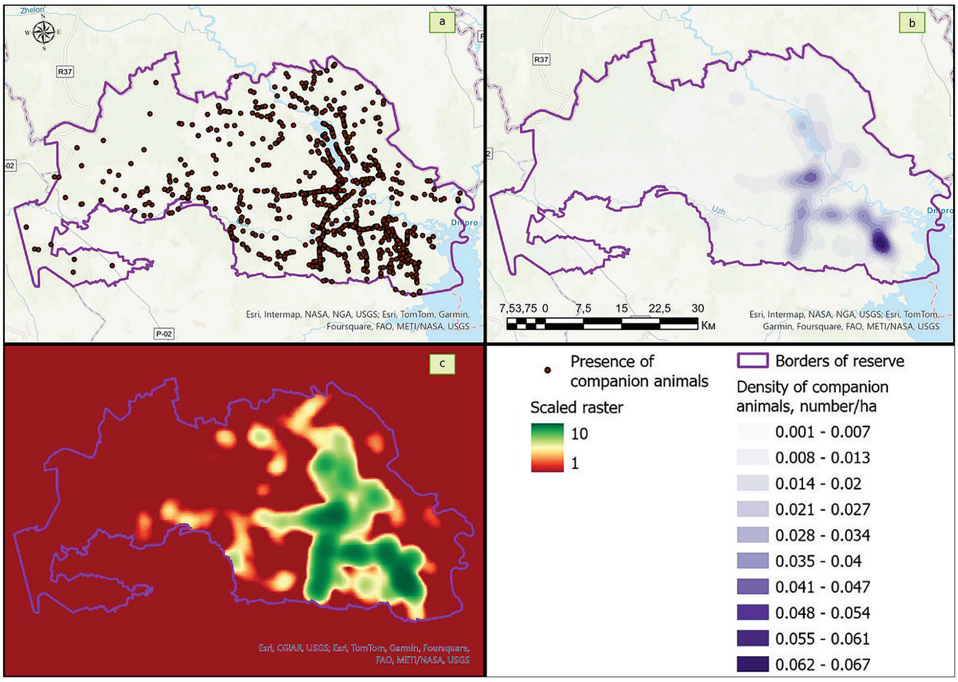

Figure 7*. Transformation of geoinformation about the presence of companion animals in the CEZ using the Multi Scale Large function*
Source: *compiled by the authors of this study*

In the CEZ, the lack of human presence and anthropogenic impact allows natural systems, including predation, to recover, influencing the behaviour and distribution of PHs in this environment. The primary predators of PH in the CEZ are wolves (*Canis lupus L.*), which are the most active predators in this area, although their population stays undetermined. The foundation for constructing a series of suitability maps was the documentation of wolf presence in the area from 2022 to 2024. Several other predators, under specific conditions, may also threaten PHs, such as the lynx (*Canis lupus L.*). Lynxes are not primary predators of horses, as they choose smaller prey; however, they may target foals or debilitated horses. These predators are infrequent in the region, although they still contribute to the food chain. In the lynx monitoring data from 2021–2022, 41 adults and 14 young specimens were recorded (Palmero *et al.,* 2023). Stray dogs (*Canis lupus familiaris*) represent a threat to ungulates in CEZ. Occasionally, wild dogs inhabit the CEZ, potentially endangering young or vulnerable PH, despite being less coordinated hunters than wolves.

Still, Przewalski's horses, being sizeable creatures, possess innate defence strategies against predators, including herding, which mitigates the probability of assault. Behavioural responses and inherent caution compel them to avoid areas with evident indications of dangerous creatures. This factor was assigned a score of 3 in the suitability map construction system. PHs are wild animals that must modify their behaviours, including locomotion and foraging, to evade predators like wolves found in the CEZ. This may lead them to select specific safer regions where the probability of encountering predators is diminished. Predators frequently pursue prey in specific locales, such as dense woodlands or around the peripheries of aquatic environments, where concealing their existence is facilitated. PHs may avoid these regions, preferring open steppes or flatter terrains, which affects their spatial distribution. Natural predators can influence the population size of a herd. Decreases in equine populations resulting from predation may restrict their capacity to extend their home ranges, as diminished populations often inhabit narrower territories. The existence of predators is crucial for sustaining ecological equilibrium. This natural method manages herbivore populations like PHs, ensuring balanced resource use and fair animal distribution across large areas (Fig. 8).

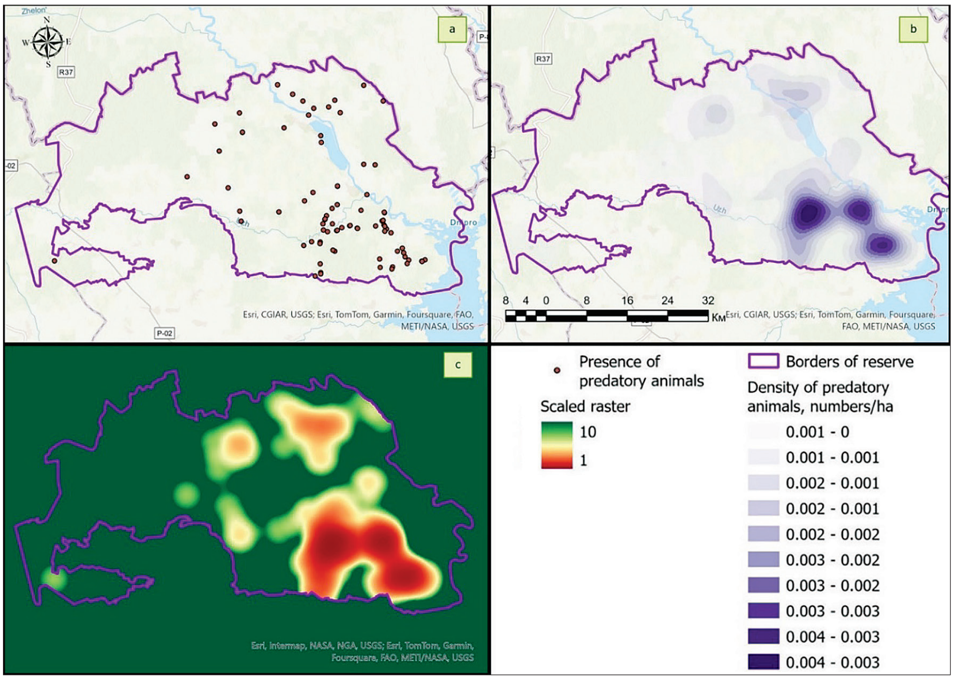

***Figure 8**. Transformation of geoinformation about the presence of predatory animals in the CEZ using the Multi Scale Large function*
***Source:** compiled by the authors of this study*

The map also details the establishment of PHs in the CEZ. This data is considered to mitigate the potential impact of other factors on the selection of PHs in reserve areas with specific requirements (Fig. 9).

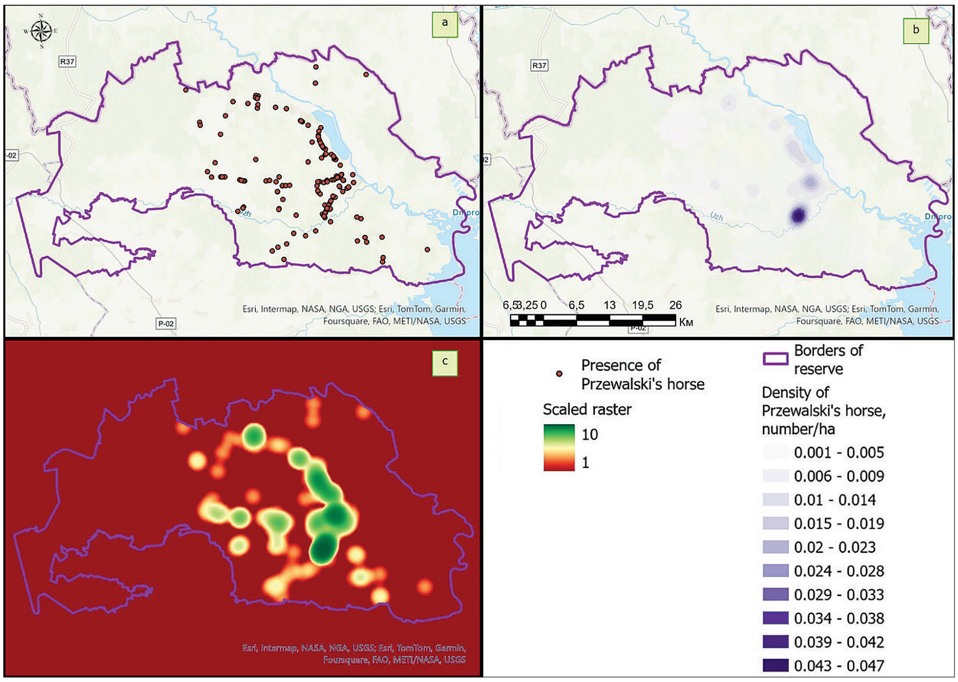

***Figure 9**. Transformation of geoinformation about the presence of PH in the CEZ using the Multi Scale Large function*
***Source:** compiled by the authors of this study*

The suitability map is based on the landscape cover map created by the authors of the present study in the previous stages of the work and published by T. Fedoniuk *et al.* (2024) (Fig. 10). Using the MS Large function, the bitmap image was transformed (Fig. 11). The suitability map was created using ecological models, satellite photography, and remote sensing data, considering the previously listed factors. Individuals globally use these maps to pinpoint prospective areas for species reintroduction in the wild, such as in the national parks of Mongolia or the CEZ in Ukraine. Consequently, by integrating satellite imagery converted into landscape cover maps with ecological models that consider proximity to highways, the existence of water bodies, and the presence of rivals for food and predators, the study produced a suitability map (Fig. 12).

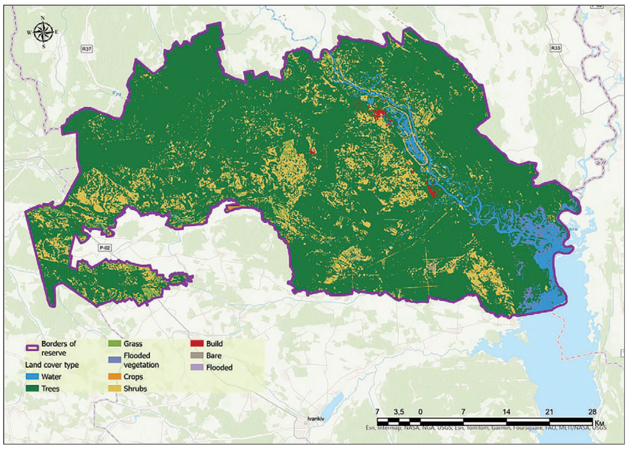

Figure 10. *The Chornobyl Radiation and Ecological Biosphere Reserve's (CREBR) landscape structure 2022*
Source: *T. Fedoniuk et al. (2024)*

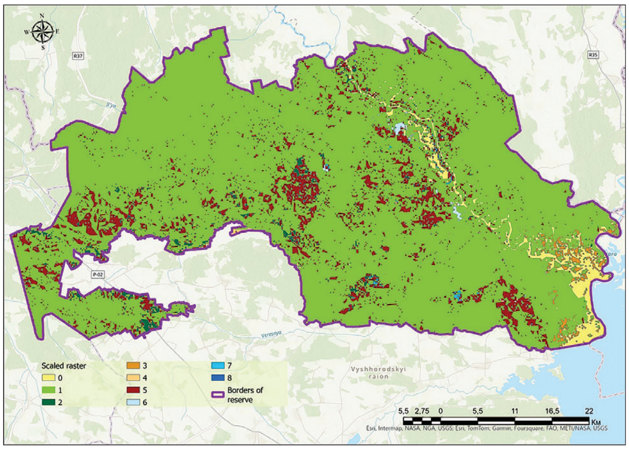

Figure 11. *Raster transformation of landscape structure map according to the MS Large function*
Source: *compiled by the authors of this study*

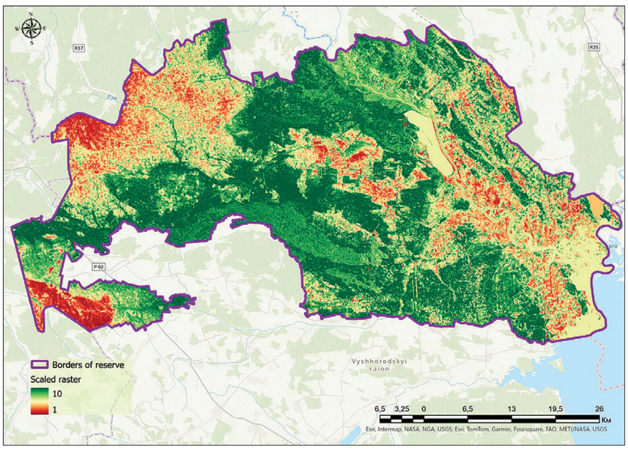

Figure 12. *Map depicting landscape cover, using models of environmental component influence*
Source: *compiled by the authors of this study*

The acquired fitness map contrasted with the factual outcomes of PHs recording. Figure 13 illustrates the correlation between actual records of horses and the expected ideal locations for the distribution of PHs.

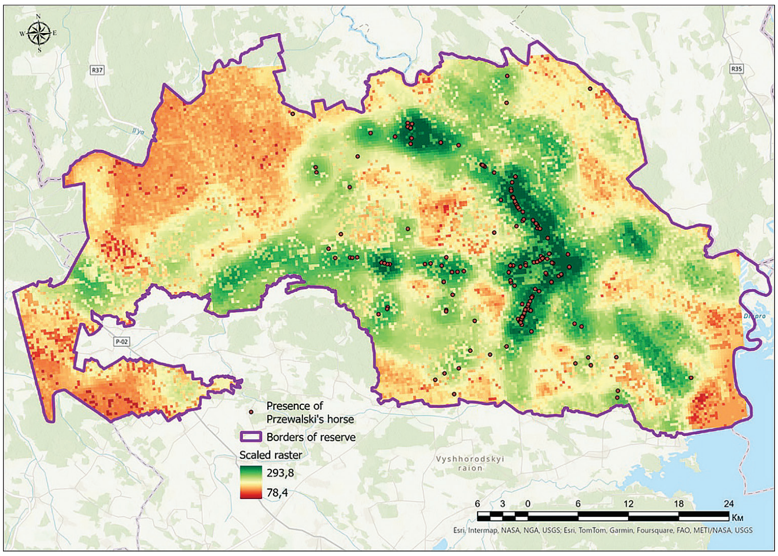

***Figure 13**. Suitability map with places of recording the facts of the presence of PHs*
***Source:** compiled by the authors of this study*

The clustering analysis of ecosystems was conducted within the CEZ, enabling the identification of the most suitable areas for the habitation and reproduction of PHs. The CEZ is a distinctive region with minimal anthropogenic impact, facilitating the resurgence of particular animal species, such as Przewalski's horse. Consequently, the best habitats were delineated in Figure 14: regions with suitable pastures, aquatic resources, limited human interference, and ample greenery for sustenance. The suitability map enabled the evaluation of environmental diversity, namely the various ecosystems that influence the survival and reproductive success of these species. Open meadows or regions with diminished forest cover may be more conducive for horses, as they offer access to feed; thus, the area presently has the capacity to extend the horse range by around 350 km^2.

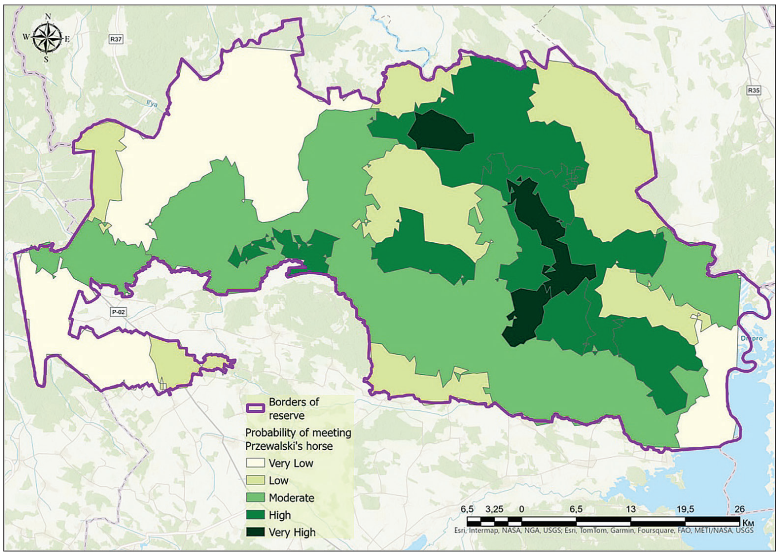

***Figure 14**. Acceptability clusters of PH dispersal zones within the CEZ*
***Source:** compiled by the authors*

Geo-informatics research of habitat conditions suggests that the ideal habitat regions are primarily located in the middle region of the reserve. PHs may potentially extend their habitat beyond their existing area. Consequently, the aggregation of habitats within the CEZ serves as a crucial instrument for comprehending how PH acclimate to and use the available environment. By employing clustering data, researchers may monitor the ecosystems selected by PHs for their travel and habitat. This aids in comprehending their ecological preferences and modifying conservation policies accordingly. This facilitates their survival and population resurgence in the distinctive environment established post-accident. The CEZ exemplifies an environment undergoing natural succession devoid of human intervention. Clustering facilitates the examination of how these processes influence PHs, allowing to discern which vegetation types and habitats are most conducive at various stages of area restoration. The identification of clusters helps to optimise protective measures aimed at preserving the population of Przewalski's horses. For instance, knowledge of the locations of these animals allows creating special conservation zones or plan corridors for their free movement between clusters.

CONCLUSIONS

The present study developed a suitability map for the PH population in CEZ using GIS. The primary factors influencing population distribution include elevation above sea level, proximity to roads and water bodies, resource competition, and predator activity. The generated habitat suitability maps suggest that the most favourable conditions for the horses are found in the central part of the study area, whereas the 10-kilometer zone around the Chernobyl Nuclear Power Plant is the least suitable due to frequent wildfires and anthropogenic impact. Cluster analysis showed that the CEZ could give PH an extra 350 km^2 of suitable habitat, which is crucial for the population's long-term survival in natural succession. The models developed in this study can be employed to predict future habitat changes and inform conservation strategies.

A significant conclusion is that Przewalski's horses exhibit a high degree of adaptation to the extreme conditions of the CEZ, including increased radiation levels. This finding presents opportunities for further research into their ecological resilience and the application of the obtained data in international reintroduction programmes for wild species. Thus, the findings of the present study not only provided insights into the current state of the PH population in the CEZ but also proposed effective conservation strategies. The use of geoinformation technologies for planning future conservation measures is essential for ensuring the long-term survival of the species. The methodologies and data from this study can be effectively used to assess habitat suitability for other herbivorous species, such as European bison (*Bison bonasus*), etc. By using analogous environmental factors like elevation, distance to water sources, land cover, predator presence, and human influence, geoinformatics models can be used to identify possible habitats for bison populations. Moreover, the clustering and suitability analysis approach employed in this study provided valuable insights into how large herbivores use landscapes. Applying these models to herbivorous animal populations can facilitate the identification of migration corridors, high-quality grazing zones, and potential risks such as habitat fragmentation or competition with other ungulates. Additionally, predictive modelling can help forecast the effects of climate change on bison habitats, enabling proactive conservation planning.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Аналіз розподілу популяції коня Пржевальського із використанням геопросторових даних у середовищах Чорнобильської зони відчуження

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Анотація. Відновлення популяції коня Пржевальського в Чорнобильській зоні відчуження, захист цього унікального виду та створення ефективних систем моніторингу і управління середовищем існування за допомогою геоінформаційних технологій є надзвичайно важливими завданнями. Метою дослідження було розробити систему моніторингу для цього виду з урахуванням різноманітних екологічних чинників. Методологія дослідження передбачала багатоступеневий процес, який включав збір даних (під час аналізу літературних джерел і польових спостережень), визначення ключових факторів для моделювання та верифікацію результатів. У результаті було створено карти придатності середовищ існування для розподілу коня Пржевальського шляхом синтезу даних щодо рельєфу, кліматичних умов, гідрології, рослинного покриву, конкуренції за ресурси, наявності хижаків та рівня безпеки. Моделі були відкаліброванi за фактичними спостереженнями, отриманими у період з 2018 по 2024 роки. У 2023 році на території зони відчуження було виявлено п’ять гаремів коней Пржевальського. Розподіл цих тварин суттєво залежав від висоти над рівнем моря, близькості до автомагістралей та водних об’єктів, конкуренції за ресурси та активності хижаків. Радіус у 10 кілометрів навколо Чорнобильської атомної електростанції визначено як найменш сприятливу територію через часті лісові пожежі та антропогенний вплив, тоді як найбільш придатні середовища знаходяться в центральній частині досліджуваної зони. Кластерний аналіз показав, що зона відчуження може забезпечити коням Пржевальського додаткові 350 км² придатних середовищ існування, що є важливим для збереження популяції в умовах природної сукцесії. Створені за допомогою ГІС моделі дають змогу прогнозувати потенційні майбутні середовища існування з урахуванням екологічних змін і заходів із охорони природи

Ключові слова: ссавці; ГІС; акліматизація; збереження; карта придатності

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