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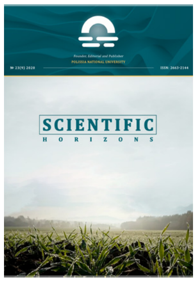

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Analysis of lactation length variability and its relationship to cow milk production

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Abstract. Lactation length is a key trait closely associated with both productivity levels and reproductive characteristics in dairy cattle. This study aimed to analyse the factors influencing lactation length variability and its impact on lactation curve formation, as well as the quantitative and qualitative traits of dairy herd productivity. The study utilised data from 604 complete lactations of cows that calved at PJSC "Plemzavod "Stepnoi" (Zaporizhzhia Region, Ukraine) between 2014 and 2017. Among the studied cows, lactation length ranged from 173 to 1,150 days, with a mean value of 356.1 ± 4.1 days. Cow age (in lactations) had a significant effect on lactation length ($P < 0.001$). No significant effect of the bull sire was observed on the lactation length of primiparous cows. However, when all lactations were considered together, a significant bull sire effect ($P = 0.005$) on lactation length was identified. Additionally, lactation length variability in the studied group was influenced by the year and season of calving. Overall, the lowest LSMestimated lactation length was observed in multiparous cows

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that calved in the autumn months (332.9 days), while the highest values were recorded in cows that calved in winter or autumn (ranging from 386.3 to 397.0 days). Lactation length was significantly associated with total milk yield ($P < 0.001$), whereas a significant correlation with 305-day milk yield was established only in multiparous cows ($P = 0.036$). The fat and protein milk percentages of the studied cows were also significant ($P \leqslant 0.001$-0.020) but negatively associated with lactation length. When approximating the lactation curves of the studied cows using Wood's model, it was found that as lactation length increased, the estimated value of coefficient "*a*" in Wood's model also increased, whereas the estimated values of coefficients "*b*" and "*c*" decreased. Overall, longer lactation length was associated with an increase in daily milk yield estimates for months 8-10, contributing to improved lactation curve persistency

Keywords: extended lactation; genotypic and environmental factors; lactation curve persistency

INTRODUCTION

Traditionally, the lactation cycle of a dairy cow is based on a 12-month interval between calvings, which includes 10 months of lactation and a two-month dry period. This means that a cow must be inseminated within two to three months after calving when she is at peak lactation and metabolically in a negative energy balance. However, due to these complex physiological conditions, it is difficult for a cow to conceive at this time, and therefore, delaying insemination after peak production and, as a result, extending lactation beyond 10 months, may be the most optimal solution to this problem. In addition, extended lactation may have other benefits, such as reducing the number of newborn calves that need to be culled at a young age, reducing health and welfare problems, and finally, improving environmental impacts (reducing greenhouse gas emissions or reducing the use of antibiotics) throughout the animal's life (Stelwagen *et al.*, 2024).

A range of both genotypic and environmental factors influence the lactation length in dairy cows. Among the genotypic factors, the breed of the cow and the breeding bull are primary influences (Alfonso *et al.*, 2024). As noted in the study of A. Toure *et al.* (2019), this factor is particularly significant for the offspring of crosses between dairy breeds of European and/or American origin and various zebu breeds. Among the environmental factors, the year and season of calving are influential. In addition, as indicated by N.S. Dangar and P.H. Vataliya (2021), the age of the cow (in lactation) also affects the variation in lactation length. However, in addition to these factors, it has also been noted that other factors can influence lactation length, such as the sex of the newborn calf. For example, in the research of S.K. Genena and M.H. ElSawy (2024), a significant ($P < 0.05$) predominance of the average lactation length of Friesian cows (Egypt) that calved heifers over the estimates obtained for cows that calved bull calves (318.9 and 268.9 days, respectively) was demonstrated.

The study of R. Kumar *et al.* (2023) demonstrates the complex and multifaceted relationship between the occurrence of subclinical mastitis (SCM) and lactation length in Jersey crossbred dairy cows in India. Increased SCM indicators were often associated with intramammary infection, including subclinical mastitis. Consequently, cows with persistent or severe mastitis experienced shortened lactation lengths due to reduced milk production increased culling rates, or veterinary care issues. In contrast, Friesian cows with a cup-shaped udder in Egypt exhibited higher milk production and lactation lengths (averaging 480.7 days) compared to cows with other udder shapes (Saleh *et al.*, 2023).

Finally, in Karan Fries cows (*Bos taurus* × *Bos indicus*) in India (Magotra *et al.*, 2020), a significant ($P < 0.05$) association between lactation length and the SNP G43737229T of the breast cancer 1 gene (*BRCA1*) was demonstrated, while in the research of D. Worku *et al.* (2022a) on the Sahiwal dairy breed, a significant ($P < 0.05$) association was noted between lactation length and the SNP g.306T > C of the *SIRT1* gene. In addition, in animals of this breed, a significant ($P < 0.05$) association was established between lactation length and the SNP rs41255599: C > T of the LAP3 gene (Worku *et al.*, 2022b). Several positive and negative effects of extending lactation length for dairy cattle have been identified. For example, the study of J. Sehested *et al.* (2019) showed that delaying insemination by extending the voluntary waiting period improves the cow's sexual behaviour and ensures her conception after the cow's energy balance becomes positive. Overall, the strategy of prolonging the lactation length of dairy cows leads to fewer calvings during their productive lifespan, and therefore, to a reduction in morbidity, a reduction in the number of replacement heifers, and a reduction in the number of dry days per cow per year.

When analysing the effects of extending lactation length in high-yielding cows in Mexico, I.J. Rodríguez-Godina *et al.* (2021) found that the average milk yield per lactation increased linearly with the number of prolonged lactations during the productive life, with a maximum yield of 19,099 kg of milk per lactation for cows with five prolonged lactations. At the same time, the average daily milk yield per day of productive use was significantly ($P < 0.01$) lower in cows that did not have any prolonged lactation (30.2 kg) compared to animals that had all five lactations prolonged (32.1 kg).

On the other hand, the implementation of a prolonged lactation length strategy has negative consequences. For example, the study of J.B. Clasen *et al.* (2019) showed that this strategy means an increase in calving intervals, which can have an inhibitory effect on the level of genetic variation in the herd. This occurs primarily due to the genetic lag between the additive genetic level of the cow population relative to the bull sire population. In the research of K. Reindl *et al.* (2024) on Holstein cows, Czech Fleckvieh cows and their crosses, it was shown that extended lactation in high-yielding dairy cows is as demanding on energy metabolism as the initial stages of lactation. In both cases, a significantly ($P < 0.001$) higher content of ketone bodies in milk was found than during the middle (101-200 days) and late (201-305 days) lactation periods.

Negative consequences of extending lactation length, in addition, include the fact that milk yields gradually decrease, which may be associated with an increased risk of cow obesity at the end of lactation. There is limited information on the consequences for cow productivity when lactation is prolonged and for calves born to cows with prolonged lactation. Therefore, a strategy based on individual cow characteristics may become the future approach to selecting high-yielding cows with persistent lactation curves when extending lactation length. This will make it possible to limit the risk of obesity and reduce milk yields at the end of lactation while benefiting from reducing the consequences of calving complications (van Knegsel *et al.*, 2022).

Therefore, the main goal of this study was to analyse the dependence of lactation length variability on genotypic (bull sire) and environmental (lactation number, year and season of calving) factors and to assess its effect on the formation of milk productivity of dairy cows.

MATERIALS AND METHODS

The study utilised data from 604 complete lactations of cows that calved at PJSC "Plemzavod "Stepnoi" (Zaporizhzhia Region, Ukraine) between 2014 and 2017. All animals were descendants of 231 cows and 14 Holstein bull sires, belonging to five lines (Starbuck, Bell, Chief, Vaillant and Elevation) and had an average of 1.9 ± 0.8 (*Mean* ± *SD*) lactations, ranging from 1 to 4 lactations. For each animal, the following data on their milk production were used: total milk yield for the entire lactation (TMY), 305 days milk yield (MY305), fat milk percentage (FP), protein milk percentage (PP), as well as daily milk yield for the test days 1-10 (TD1-TD10), which corresponded to 30, 60, ... 300 days of lactation.

The following factors were selected for the investigation of their influence on the lactation length of the cows in the study group: sire origin (14 subgroups), age in lactations (two subgroups: primiparous cows and multiparous cows with ⩾ 2 calvings), year of calving (three subgroups: 20142016 for primiparous cows and 2015-2017 for multiparous cows), season of calving (four subgroups: winter (December-February), spring (March-May), summer (June-August) and autumn (September-November)). For each subgroup, the least squares mean (*LSM*) estimates for lactation length were calculated based on the General Linear Model (GLM) (Al-Murrani, 2024; Atamanyuk *et al.*, 2019):

$$Y_{ijk} = \mu + \mathrm{Parity}_i + \mathrm{SG}_j + e_{ijk}, \quad (1)$$

where Y_{ijk} is the *LSM* estimate of lactation length; μ is the overall arithmetic mean; Parity_i is the fixed factor of lactation number (two gradations); SG_j is the fixed factor of subgroup, depending on origin, year or season of calving; e_{ijk} is the random error.

Pairwise comparisons of the means of individual subgroups were performed based on Tukey's HSD test (for groups of unequal size). To analyse the relationship between lactation length and milk production characteristics of cows, Spearman's rank correlation coefficient (*Rs*) was calculated. To approximate the lactation curves for the first 305 days of lactation of cows from different subgroups, based on the average daily milk yield estimates for TD 1-10, Wood's model was used:

$$Yt = at^b e^{-ct}, \quad (2)$$

where *Yt* is the daily milk yield at time *t* (30th, 60th, 90th, ... 300th day of lactation); *a*, *b*, and *c* are Wood's model coefficients. The adequacy of Wood's model to the original data was assessed based on the coefficient of determination (R^2).

In addition, based on the obtained estimates of Wood's model coefficients, Wood's model parameters were also calculated using the following formulas (Kramarenko *et al.*, 2022):

$$Ymax = a\left(\frac{b}{c}\right)^b e^{-b}, \quad (3)$$

$$Tmax = \frac{b}{c}, \quad (4)$$

$$Persistency = c^{-(b+1)}, \quad (5)$$

where *Ymax* is the estimate of peak (maximum) 305 days milk yield; *Tmax* is the time to reach peak milk yield of lactation; *Persistency* is the estimate of lactation persistency, which characterises the rate of decline in milk production from the moment of reaching peak milk yield to the 305th day of lactation.

All mathematical and statistical analysis of the original data was performed using STATISTICA v.7 software (Stat Soft Inc.). When keeping experimental animals on the farm and during all manipulations with them, the provisions of the Law of Ukraine No. 249 (2012) and the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986) were observed.

RESULTS AND DISCUSSION

General characteristics of lactation length variability. In the study group of cows, lactation length ranged from 173 to 1,150 days, with an average of 356.1 ± 4.1 (*Mean* ± *SE*) days. Analysis of their distribution on normal probability paper revealed that the original data sample consists of four subgroups, characterised by a more or less normal distribution, which can be approximated by straight lines on probability paper. The intersection points of these four approximating straight lines correspond to 285, 365 and 435 days of lactation (Fig. 1).

Thus, all original data were divided into four subgroups according to lactation length: short lactation (less than 285 days), normal lactation (286-365 days), prolonged lactation (366-435 days) and extremely prolonged lactation (more than 436 days). The main indicators of variability of individual subgroups of Holstein cows by lactation length are shown in Table 1.

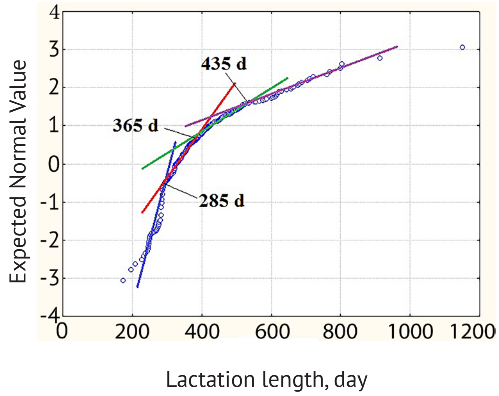

***Figure 1**. Distribution of Holstein cows by lactation length on normal probability paper*
***Note:** different colours indicate straight lines approximating individual lactation length subgroups. 285 d, 365 d, and 435 d – boundary limits for identifying individual subgroups*
***Source:** developed by the authors*

***Table 1**. Variability indicators of individual subgroups of Holstein cows by lactation length*

Lactation length subgroup	Lactation length limits (days)	*n*	*Mean* ± *SE* (days)	*SD* (days)
Short lactation	< 285	118	237.6 ± 1.8	19.1
Normal lactation	286-365	300	319.7 ± 1.4	24.4
Prolonged lactation	366-435	106	398.1 ± 1.9	20.0
Extremely prolonged lactation	> 436	80	558.9 ± 13.7	122.7
Overall	173-1,150	604	356.1 ± 4.1	100.8
F_L (3; 600); *P*	–	–	–	134.13; *P* < 0.001

***Note:** n – number of records; FL – Levene's test estimate for homogeneity of subgroup variances; P – significance level; Mean ± SE – estimate of the subgroup arithmetic mean and its statistical error; SD – subgroup standard deviation*
***Source:** developed by the authors*

Earlier, in the study of H. Mehta *et al.* (2021), Red Dane × Sahiwal × Holstein-Friesian crossbred cows (India) were also divided into subgroups according to their lactation length: short lactation (102-179 days), normal lactation (180-483 days), prolonged lactation (484-560 days) and extremely prolonged lactation (more than 560 days).

Table 2 shows the *LSM* estimates (± *SE*) of lactation length depending on the breed/crossbreed of European/American dairy cattle and the country of breeding. It can be noted that a significant number of the obtained estimates significantly exceeded the traditional 305 days of lactation, which is accepted as the standard. For example, in the research of K. El-Den *et al.* (2020) for Friesian cows, the *LSM* estimate of lactation length in Egypt was 358.3 days, and for Swedish Red cows in Turkey, it reached 361.0 days (Genç & Mendes, 2021). At the same time, for HolsteinFriesian cows and their crosses with Jersey cows in New Zealand, the *LSM* estimates of lactation length were shortest – only about 8 months, which is probably due to a certain technology of the dairy cattle industry in these farms (Curry *et al.*, 2024).

***Table 2**. Lactation length depending on the breed/crossbreed of European/American dairy cattle and the country of breeding, days*

Breed/crossbreed	Country	*n*	*LSM* ± *SE*	Source
Friesian	Egypt	1,018	301.0 ± 3.5	A.A. Badr & A.A. Amer (2020)
Friesian	Egypt	1,630	358.3 ± 2.3	K. El-Den *et al.* (2020)
Friesian	Egypt	4,413	319.9 ± 0.3	S.K. Genena & S.Z. Ebrahim (2023)
Friesian	Egypt	1,976	310.1 ± 2.5	S.S. Sanad *et al.* (2020)
Holstein	Costa Rica	17,269	333.0 ± 0.6	B. Vargas-Leitón *et al.* (2024)
Holstein	Morocco	4,737	347.1 ± 0.8	I. Boujenane (2019)
Holstein	Ukraine	604	356.1 ± 4.1	own data
Holstein	Turkey	823	350.0 ± 2.6	S. Genç and M. Mendes (2021)

Table 1. Continued

Breed/crossbreed	Country	*n*	*LSM* ± *SE*	Source
Holstein	Turkey	2,936	357.6 ± 1.3	S. Genç (2022)
Holstein	Turkey	530	316.5 ± 6.9	M. Ozdemir *et al.* (2021)
Holstein-Friesian	New Zealand	231	244.0 ± 1.0	B.A. Curry *et al.* (2024)
Holstein-Friesian	Pakistan	66	285.9 ± 31.8	I. Ali *et al.* (2019)
Holstein-Friesian	Turkey	9,844	350.9 ± 0.8	Y. Öztürk *et al.* (2021)
Holstein-Friesian	Egypt	937	301.0 ± 3.6	A.S. Khattab *et al.* (2021)
Holstein-Friesian	Pakistan	610	278.2 ± 10.9	M. Khalil *et al.* (2021)
Holstein-Friesian × Jersey	New Zealand	84	248.0 ± 2.0	B.A. Curry *et al.* (2024)
Jersey	Ethiopia	2,912	344.9 ± 3.8	N. Beneberu *et al.* (2020)
Jersey	Turkey	824	328.0 ± 2.2	S. Genc & M. Mendes (2021)
Jersey	Pakistan	39	290.5 ± 40.6	I. Ali *et al.* (2019)
Jersey	Ethiopia	3,495	352.9 ± 0.9	K. Abera *et al.* (2023)
Montbeliarde	Turkey	1,448	333.0 ± 3.6	S. Genc & M. Mendes (2021)
Swedish Red	Turkey	36	361.0 ± 15.3	S. Genc & M. Mendes (2021)

Note: *n – number of records; LSM ± SE – least squares mean estimate and its statistical error*
Source: *created by the authors based on literature and their own results*

In general, the lactation length is influenced by both the breed of the animals and the technology chosen in a particular country (or on a particular farm). The lactation length can be affected by the adaptation process. For example, the study of N. Beneberu *et al.* (2020) found that when breeding the Jersey breed, the average lactation length of imported individuals, which were imported from Denmark as pregnant heifers, was significantly ($P < 0.001$) longer than in the offspring of imported animals that were raised in Ethiopia (361.3 and 328.6 days, respectively). In addition, the research of R.E. Alfonso *et al.* (2024) showed that when crossing dairy cows with beef sire bulls, their average lactation length was shorter than when using dairy sire bulls for breeding.

The maximum possible lactation lengths can also vary significantly. For example, the study of J. Mellado *et al.* (2021) noted that in the hot climate of Mexico, Holstein cows are effectively fertilised more than 300 days after calving. Therefore, they are characterised by prolonged lactation with an average length of 696 days. In another research on Holstein cows in Mexico, it was noted that the maximum lactation length could reach 1018 days (Rodríguez-Godina *et al.*, 2021). In Europe, the maximum length of prolonged lactation of Holstein-Friesian cows (Poland) reached 622 days (Salamończyk, 2023), and in Holstein cows in Turkey – 550 days. Finally, in the study of T. Kopec *et al.* (2020), primiparous Simmental cows were studied, the lactation length of which maximally reached 1,348 days.

Analysis of the effect of cow age on their lactation length. The age of the cows (in lactations) significantly affected lactation length (one-way analysis of variance: $F_{3;600} = 8.04$; $P < 0.001$). *LSM* estimates for primiparous cows and multiparous cows for the 2nd, 3rd and 4th lactations were 337.9 ± 6.4, 377.8 ± 6.4, 357.7 ± 9.6 and 310.5 ± 21.1 days, respectively. Using Tukey's HSD test, significant differences were noted only between the lactation length of primiparous cows and animals for the 2nd lactation. Therefore, in further analysis, only two age groups were considered according to lactation length – primiparous cows and multiparous cows, which had two or more lactations. In general, the age of the cows significantly affected the ratio of subgroups by lactation length (Pearson's chi-square test: $\chi^2 = 10.58$; $df = 3$; $P = 0.014$). At the same time, the longer lactation period of multiparous cows was due to an almost twice higher proportion of animals among them that belong to the subgroup with extremely prolonged lactation (> 436 days) and, accordingly, a low proportion of animals with short and normal lactation (Fig. 2).

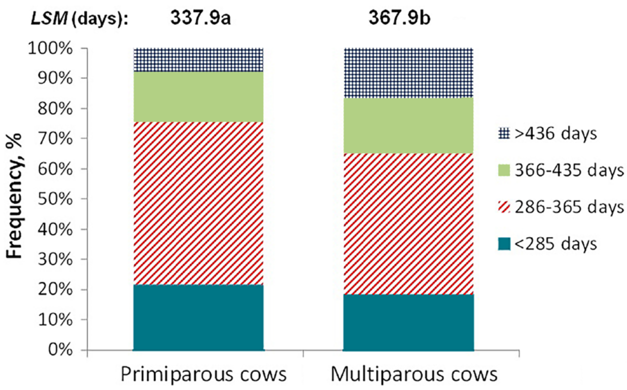

Figure 2*. Distribution by lactation length of primiparous cows and multiparous cows of the Holstein breed*
Note: *LSM estimates for the corresponding subgroups are shown. Significant differences between the means of individual subgroups (P < 0.05) based on Tukey's HSD multiple comparison test are indicated by different letters*
Source: *developed by the authors*

The obtained results are consistent with data previously obtained in studies analysing the influence of cow age on lactation length. Of the 14 studies reviewed, which investigated dairy cattle of European/American origin and crossbred animals, nine reported a significant effect ($P < 0.001$ to 0.05), while the remaining five did not find a significant effect (Table 3). Regarding the pattern of lactation length changes across cows of different ages, it was inconsistent, ranging from a gradual increase in lactation length with each subsequent lactation (as observed in Holstein cows in Turkey (Ozdemir *et al.*, 2021)) to complete similarity in the respective lactation length estimates during the first four lactations, with a significant increase only in the 5th lactation (as seen in Jersey cows in Ethiopia (Abera *et al.*, 2023)).

The most common pattern was characterised by the same lactation length during the 1st and 2nd lactations, but a significant increase during the 3rd lactation. While in the current study, on the contrary, lactation length significantly increased between the 1st and 2nd lactations, but then almost did not change. A similar pattern was also noted for crossbred animals (HolsteinFriesian × Sahiwal) in India (Chopade *et al.*, 2023).

***Table 3**. Results of the effect of cow age (in lactations) on lactation length depending on the breed/crossbreed of European/American dairy cattle and the country of breeding*

Breed/crossbreed	Country	*n*	P_{Parity}	Lactation order	Source
Friesian	Egypt	1,018	< 0.01	-	A.A. Badr & A.A. Amer (2020)
Friesian	Egypt	1,630	< 0.05	1 = 2 > 3 < 4	K. El-Den *et al.* (2020)
Friesian	Egypt	1,300	ns	-	A.A. Saleh *et al.* (2023)
Friesian	Egypt	4,913	< 0.001	1 = 2 > 3 = 4	S.K. Genena and M.H. ElSawy (2024)
Friesian	Egypt	1,976	< 0.001	1 = 2 = 3 < 4	S.S. Sanad *et al.* (2020)
Friesian	Pakistan	608	ns	-	M. Khalil *et al.* (2021)
Holstein	Turkey	530	< 0.05	1 < 2 < 3 > 4	M. Ozdemir *et al.* (2021
Holstein	Ukraine	604	< 0.001	1 < 2 = 3 = 4	own data
Holstein-Friesian	Turkey	796	ns	-	C. Sipahi (2022)
Holstein-Friesian	Egypt	937	ns	-	A.S. Khattab *et al.* (2021)
Holstein-Friesian × Sahiwal	Pakistan	641	ns	-	M.N. Tahir *et al.* (2023)
Holstein-Friesian × Sahiwal	India	9,094	< 0.01	1 < 2 = 3 = 4	M.M. Chopade *et al.* (2023)
Jersey	Ethiopia	2,912	< 0.001	1 = 2 > 3 = 4	N. Beneberu *et al.* (2020)
Jersey	Ethiopia	3,495	< 0.01	1 = 2 = 3 = 4 < 5	K. Abera *et al.* (2023)

***Note:** n – number of records; P_{Parity} – significance level of the effect of lactation number (according to GLM results); ns – P_{sire} > 0.05. Lactation order – the presence of significant differences between LSM estimates for different lactations. The signs "<" or ">" mean that significant differences between adjacent lactations are established, and the sign "=" means that significant differences are absent*

***Source:** created by the authors based on literature and their own results*

Analysis of the influence of the bull sire on the lactation length in cows. No significant influence of the bull sire on the lactation length of primiparous cows was found. However, when considering all lactations together, a significant effect of the bull sire on lactation length was established (one-way ANOVA: $F_{13;590} = 2.33$; $P = 0.005$). These results are consistent with earlier findings on the impact of the bull sire on the lactation length of dairy cows of different breeds (Table 4). Furthermore, the results of an analysis conducted during 18 independent studies on dairy cows or crossbred animals (nine of which considered only the 1st lactation and another nine analysed all lactations) indicate a significant relationship between the lactation number and the influence of the bull sire on lactation length (odds ratio: $OR_{prim/multi} = 0.082$; $P = 0.027$). Thus, the influence of the bull sire on lactation length was more likely to be observed when analysing cows of all age groups, compared to when only primiparous cows were included in the analysis.

***Table 4**. Results of the bull sire's influence on lactation length based on breed/origin and country of dairy cattle breeding*

Breed/crossbreed	Country	*n*	n_{sire}	P_{sire}	Source
			1st lactation		
Holstein	Ukraine	237	14	ns	own data
Holstein-Friesian	India	973	42	ns	V.K. Singh *et al.* (2020)
Holstein-Friesian × Gir	India	421	48	ns	S.S. Jadhav *et al.* (2019)
Kankrej	India	291	66	ns	N.K. Thakkar *et al.* (2021)
Kankrej	India	475	75	ns	K. Ankuya *et al.* (2020)
Sahiwal + Crossbreds	India	965	78	< 0.05	D.G. Girimal *et al.* (2020)
Crossbreds	India	2,204	54	< 0.05	V.A.R. Panwar *et al.* (2022)
Crossbreds	India	529	79	ns	S. Kaur *et al.* (2023)

Table 4. Continued

Breed/crossbreed	Country	n	n_{sire}	P_{sire}	Source
Crossbreds	India	1,029	107	ns	M. Dangi *et al.* (2021)
			All lactations		
Friesian	Egypt	1,018	54	< 0.01	A.A. Badr and A.A. Amer (2020)
Friesian	Egypt	1,300	180	ns	A.A. Saleh *et al.* (2023)
Friesian	Egypt	1,976	117	< 0.001	S.S. Sanad *et al.* (2020)
Holstein	Ukraine	604	14	< 0.01	own data
Holstein-Friesian	Egypt	937	50	< 0.01	A.S. Khattab *et al.* (2021)
Crossbreds	India	529	79	ns	S. Kaur *et al.* (2023)
Holstein-Friesian × Sahiwal	India	9,094	239	< 0.01	M.M. Chopade *et al.* (2023)
Sahiwal	India	567	42	< 0.01	P. Ratwan *et al.* (2019)
Tharparkar	India	284	-	< 0.01	G. Choudhary *et al.* (2019)

Note: *n – number of records; n_{sire} – number of bull sires used in the analysis; P_{sire} – significance level of the bull sire's influence (according to GLM results); ns – $P > 0.05$. Crossbreds – crosses between local breeds and breeds of European origin*
Source: *created by the authors based on literature and their own results*

Analysis of the influence of calving year and season on the lactation length in cows. It was found that the variability in lactation length among cows in the study group depended on the calving year. The calving year significantly influenced the distribution of lactation length subgroups for both primiparous cows (Pearson's chi-square test: $\chi^2 = 16.22$; $df = 6$; $P = 0.013$) and multiparous cows (Pearson's chi-square test: $\chi^2 = 38.64$; $df = 6$; $P < 0.001$). In general, the lowest *LSM* estimate of lactation length was observed for multiparous cows that calved in 2017 (329.2 days) and primiparous cows that calved in 2016 (330.3 days). The highest lactation length was recorded for multiparous cows that calved in 2016 (401.6 days). This prolonged lactation period was mainly due to a significant proportion of animals in the extremely prolonged lactation subgroup (> 436 days) and a correspondingly lower proportion of animals with normal lactation (Fig. 3).

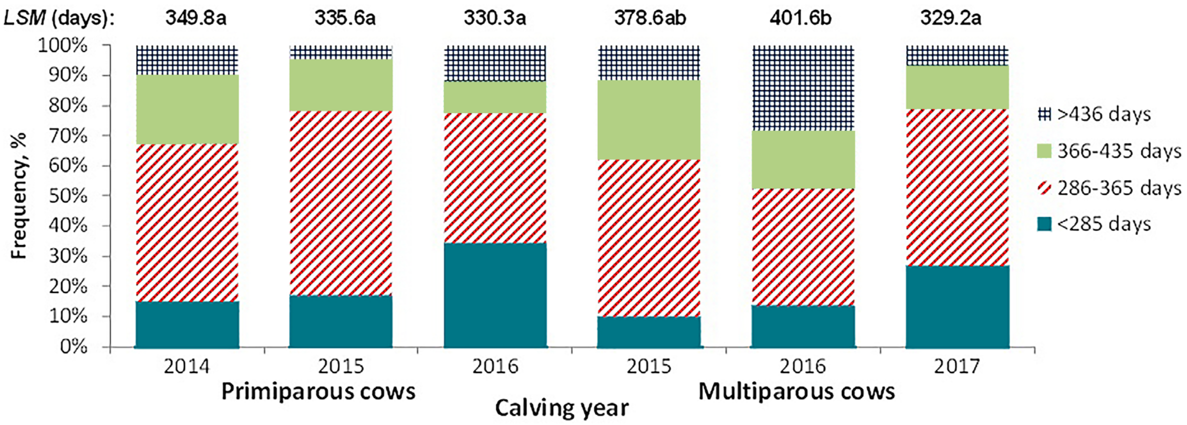

Figure 3*. Distribution of lactation length for primiparous cows and multiparous cows of Holstein breed based on calving year*
Note: *LSM estimates for the corresponding subgroups are shown. Significant differences between the means of individual subgroups ($P < 0.05$) based on Tukey's HSD multiple comparison test are indicated by different letters*
Source: *developed by the authors*

It was also found that the variability in lactation length among cows in the study group depended on the calving season. Similarly, the calving season significantly influenced the distribution of lactation length subgroups only for multiparous cows (Pearson's chi-square test: $\chi^2 = 54.95$; $df = 9$; $P < 0.001$), while no significant influence of calving season was found for primiparous cows (Pearson's chi-square test: $\chi^2 = 8.98$; $df = 9$; $P = 0.429$). Overall, the lowest *LSM* estimate for lactation length was observed for multiparous cows that calved in the autumn months (332.9 days), while the highest estimates were recorded for animals that calved in winter or autumn (386.3 to 397.0 days). Animals that calved in the summer had intermediate lactation length. Notably, among the multiparous cows that calved in summer, the highest proportion of animals had normal lactation length (Fig. 4).

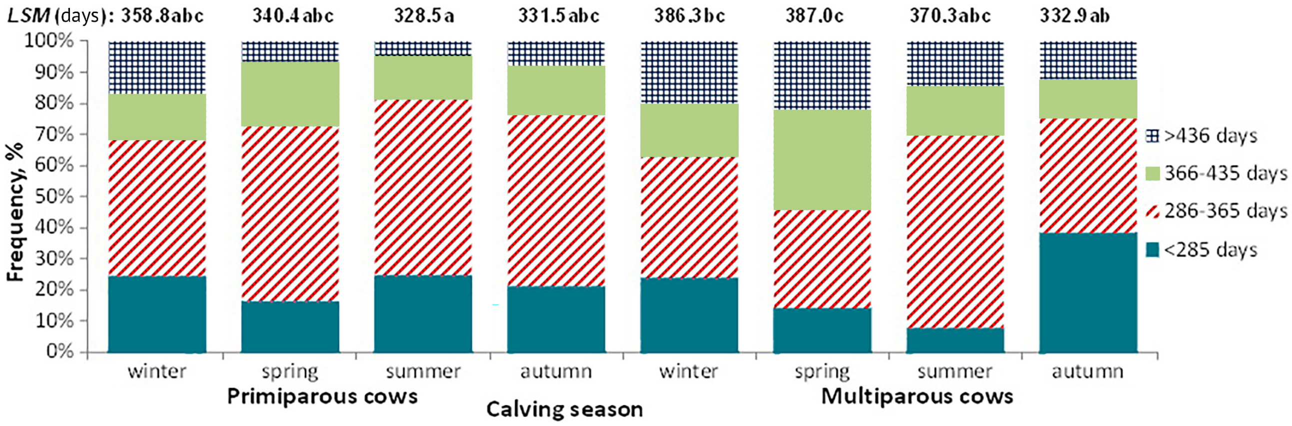

Figure 4. *Distribution of lactation length for primiparous cows and multiparous cows of Holstein breed based on calving season*

Note: *LSM estimates for the corresponding subgroups are shown. Significant differences between the means of individual subgroups ($P < 0.05$) based on Tukey's HSD multiple comparison test are indicated by different letters*

Source: *developed by the authors*

The results, in general, are consistent with previously obtained results of the analysis of the effect of year and season of calving on the lactation length of dairy cows of different breeds (Table 5). Of the 15 analysed studies in which European/American dairy cattle and crossbred animals were studied, 12 cases showed a significant effect ($P < 0.001$ to 0.05) of calving year (Table 5). At the same time, the chance of establishing a significant effect of the year of calving on lactation length was not related to either the length of the study period (in years) or the number of periods into which the study period was divided. However, this change had a significant relationship with the total number of animals included in the analysis (non-parametric Mann-Whitney test: $Z = -2.02$; $P = 0.044$). Thus, with an increase in sample size, the chance of obtaining confirmation of the hypothesis regarding the significant effect of the year of calving on the lactation length of cows increased.

On the other hand, out of the 15 analysed studies in which European/American dairy cattle and crossbred animals were studied, nine cases showed a significant effect ($P < 0.001$ to 0.05) of the season of calving (Table 5). In this case, the chance of establishing a significant effect of the season of calving on lactation length was not related to the total number of animals included in the analysis (non-parametric Mann-Whitney test: $Z = 0.72$; $P = 0.514$).

In general, studies by other authors confirmed the results obtained regarding the longest lactation length of cows that calved in winter or spring, in contrast to animals that calved in autumn and/or summer (Fig. 4). Similar results were obtained for Friesian cows in Egypt (ElDen *et al.*, 2020; Genena & ElSawy, 2024) and for crossbred cows based on the HolsteinFriesian Crossbreds in Pakistan (Ihsanullah *et al.*, 2020; Tahir *et al.*, 2023). In countries with very hot climates, the lactation length of cows that calved during the wet season of the year was also longer than in animals that calved during the dry season of the year (Hakoueu *et al.*, 2022; Chopade *et al.*, 2023)

Table 5. *Results of the effect of year and season of calving on lactation length depending on the breed/crossbreed of European/American dairy cattle and the country of breeding*

Breed/crossbreed	Country	n	$n_{Y/P}$	P_{YoC}	P_{SoC}	Order of the seasons	Source
Friesian	Egypt	1018	6/6	< 0.01	< 0.01	na	A.A. Badr & A.A. Amer (2020)
Friesian	Egypt	1,630	10/10	< 0.01	< 0.01	(win + spr) > aut	K. El-Den *et al.* (2020)
Friesian	Egypt	4,913	36/5	< 0.001	< 0.05	(win + spr) > (sum + aut)	S.K. Genena and M.H. ElSawy (2024)
Friesian	Egypt	1,976	12/12	< 0.001	ns	-	S.S. Sanad *et al.* (2020)
Friesian	Pakistan	608	16/16	< 0.001	na	na	M.Khalil *et al.* (2021)
Holstein	Ukraine	604	4/4	< 0.001	0.003	(win + spr) > aut	own data
Holstein-Friesian	Turkey	796	7/7	ns	< 0.05	sum > win	C. Sipahi (2022)
Holstein-Friesian	Egypt	937	6/6	< 0.01	na	na	A.S. Khattab *et al.* (2021)
Holstein-Friesian Crossbreds	India	529	30/6	< 0.01	ns	-	S. Kaur *et al.* (2023)
Holstein-Friesian × Gir	India	161	10/2	ns	ns	-	M.G. Mote *et al.* (2020)

Table 5. Continued

Breed/crossbreed	Country	*n*	$n_{Y/P}$	P_{YoC}	P_{SoC}	Order of the seasons	Source
Holstein-Friesian × Jersey × Gir	India	114	8/2	ns	ns	-	M.G. Mote *et al.* (2020)
Holstein-Friesian × Sahiwal	India	9,094	36/4	< 0.01	< 0.05	rainy > sum	M.M. Chopade *et al.* (2023)
Holstein-Friesian × Sahiwal	Pakistan	641	20/4	< 0.001	< 0.001	win > sum	M.N. Tahir *et al.* (2023)
Holstein-Friesian Crossbred	Pakistan	1,131	17/-	na	0.01	(win + spr) > (sum + aut)	M. S. Q. Ihsanullah *et al.* (2020)
Holstein-Friesian Crossbred, Jersey Crossbred	Cameroon	403	14/-	na	< 0.05	rainy > dry	F. Hakoueu *et al.* (2022)
Jersey	Ethiopia	2,912	31/11	< 0.001	ns	-	N. Beneberu *et al.* (2020)
Jersey	Ethiopia	3,495	17/6	< 0.01	ns	-	K. Abera *et al.* (2023)

Note: *n – number of records;* $n_{Y/P}$ *– number of years and study periods;* P_{YoC} *– significance level of the effect of the year/period of calving (according to GLM results);* P_{SoC} *– significance level of the effect of the season of calving (according to GLM results); ns –* $P > 0.05$*; na – data not available. The sign ">" means that significant differences between the corresponding calving seasons are established. win, spr, sum, aut – winter, spring, summer and autumn calving season; rainy, dry – wet and dry calving season*
Source: *created by the authors based on literature and their own results*

Analysis of the effect of lactation length on cow milk production. Lactation length was significantly associated with total milk yield in both primiparous cows and multiparous cows (Spearman's rank correlation coefficient: $P < 0.001$ in both cases). As for 305 days of milk yield, a significant correlation was found only for multiparous cows (Spearman's rank correlation coefficient: $Rs = 0.109$; $Rs = 0.036$). In addition, milk yields for the TD6-TD10 were also significantly (in all cases: $P \leqslant 0.001$ to 0.030) correlated with the lactation length of multiparous cows, while in primiparous cows a significant estimate of the Spearman's rank correlation coefficient ($Rs = 0.169$; $P = 0.024$) was found only for milk yield on the TD9 (Table 6). The fat and protein milk percentage of the cows in the study group were also significantly (in all cases: $P \leqslant 0.001$ to 0.020) associated with lactation length, but unlike the quantitative characteristics of milk production, for qualitative characteristics, the Spearman's rank correlation coefficient estimates had a negative sign. At the same time, in multiparous cows, the strength of the relationship between fat and protein milk percentage depending on lactation length was more pronounced than in primiparous cows.

Table 6*. Spearman's rank correlation coefficient (Rs) estimates of lactation length of primiparous cows and multiparous cows with milk production traits*

Traits	Primiparous cows		Multiparous cows	
	n	*Rs* (*P*)	*n*	*Rs* (*P*)
TMY	237	0.692 ($P < 0.001$)	367	0.602 ($P < 0.001$)
MY305	237	0.064 (ns)	367	0.109 ($P = 0.036$)
FP	237	-0.251 ($P < 0.001$)	367	-0.475 ($P < 0.001$)
PP	237	-0.151 ($P = 0.020$)	367	-0.341 ($P < 0.001$)
TD1	176	0.028 (ns)	364	-0.013 (ns)
TD2	179	-0.051 (ns)	364	-0.090 (ns)
TD3	180	-0.074 (ns)	363	-0.080 (ns)
TD4	180	-0.062 (ns)	363	-0.024 (ns)
TD5	180	-0.042 (ns)	363	0.047 (ns)
TD6	180	-0.047 (ns)	362	0.121 ($P = 0.022$)
TD7	180	-0.044 (ns)	359	0.114 ($P = 0.030$)
TD8	179	0.014 (ns)	360	0.186 ($P < 0.001$)
TD9	178	0.169 ($P = 0.024$)	338	0.244 ($P < 0.001$)
TD10	103	0.072 (ns)	275	0.234 ($P < 0.001$)

Note: *TMY – total milk yield for the entire lactation; MY305 – 305 days milk yield; FP – fat milk percentage; PP – protein milk percentage; TD1-TD10 – average daily milk yield estimates for test days 1-10. Rs – Spearman's rank correlation coefficient estimate; P – significance level; ns –* $P > 0.05$
Source: *developed by the authors*

A high level of correlation between lactation length and total milk yield has already been noted in various studies. For example, in the research of D. Hunde *et al.* (2022) in crossbred cows between the Friesian and Jersey breeds with the local cattle breed Boran (Ethiopia), the corresponding estimate was 0.55 ($P<0.001$). In crossbred animals based on the Holstein-Friesian Crossbreds in India, it was 0.72 ($P<0.001$) (Kaur *et al.*, 2023). The article of D. Worku *et al.* (2022a) noted that in zebu-like cattle of the Sahiwal breed (Ethiopia), the correlation coefficient between lactation length and total milk yield was very high – 0.92 ($P<0.001$). The correlation estimates between lactation length and 305 days milk yield were significantly lower – for Friesian cows in Egypt, it was only 0.159 ($P<0.05$) (Sanad *et al.,* 2020).

Regarding the fat and protein milk percentage, a study by I. Boujenane (2019) on Holstein animals in Morocco obtained significant but positive correlation coefficient estimates with lactation length (0.425 and 0.768; $P<0.001$ in both cases), while in the current study, the corresponding estimates had a negative sign. In the research of A.S. Khattab *et al.* (2021) on Holstein-Friesian cattle in Egypt, no significant relationship was found between lactation length and fat milk percentage. Thus, for the qualitative traits of milk production, their relationship with lactation length is inconsistent for different breeds kept in different conditions.

Analysis of the effect of lactation length on cow lactation curves. Figure 5 shows the lactation curves for the first 305 days of lactation of cows from different subgroups depending on their lactation length. Among primiparous cows, daily milk yield estimates for TD1-TD10 did not differ significantly between animals with different lactation lengths, and accordingly, their lactation curves were similar in shape. At the same time, among multiparous cows, daily milk yield estimates for the last three months of lactation significantly depended on the lactation length subgroup. In general, with increasing lactation length, the corresponding daily milk yield estimates for TD8TD10 increased, which ensured an increase in the persistency of the lactation curve (Fig. 5B).

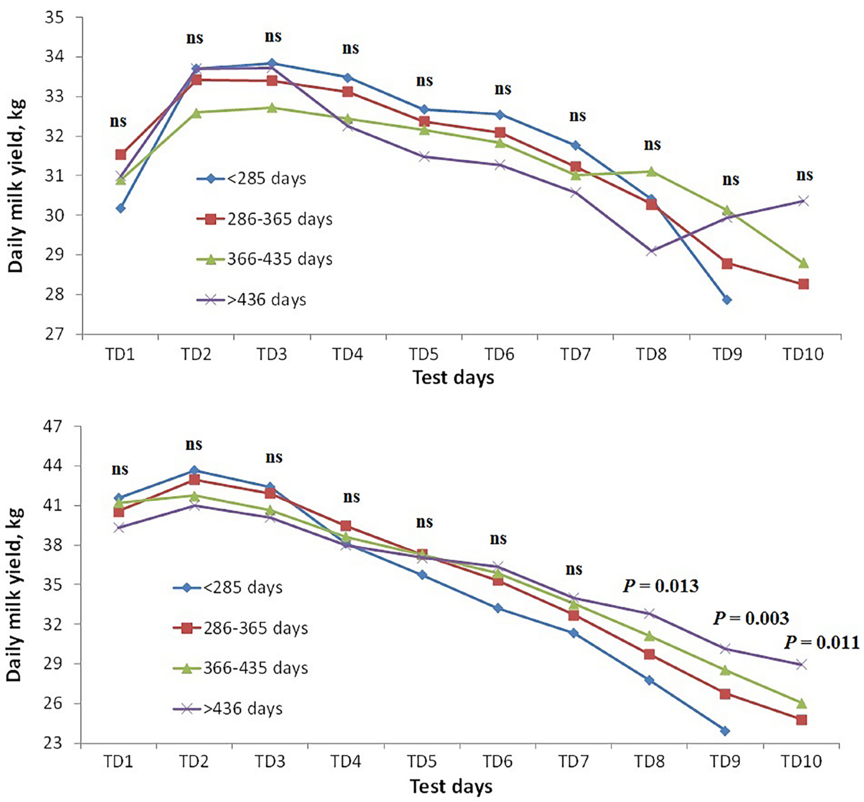

Figure 5. *Lactation curves for the first 305 days of lactation of cows from different subgroups depending on lactation length: A – primiparous cows; B – multiparous cows*

Note: *the results of the Fisher's test for homogeneity of subgroup means are shown. ns – P > 0.05. TD1-TD10 – average daily milk yield estimates for test days 1-10*

Source: *developed by the authors*

When approximating the lactation curves of the cows in the study group with the Wood's model, it was found that with increasing lactation length, the estimates of the Wood's model coefficient "*a*" increased, while the estimates of the coefficients "*b*" and "*c*", on the contrary, decreased (Table 7). The obtained patterns had a similar character in both primiparous cows and multiparous cows. This caused a gradual increase in the estimate of the persistency of the lactation curve of cows with increasing lactation length.

***Table 7**. Estimates of Wood's model coefficients and parameters of the lactation curve of primiparous cows and multiparous cows of different subgroups depending on lactation length*

Subgroup by lactation length	Wood's model coefficient			Wood's model parameter			
	a ± *SE*	*b* ± *SE*	*c* ± *SE*	R^2, %	*Ymax*, kg	*Tmax*, days	*Persistency*
Primiparous cow							
Short lactation	14.641 ± 1.629	0.2351 ± 0.0308	0.00239 ± 0.00027	93.73	34.0	98.4	-0.00988
Normal lactation	20.416 ± 0.830	0.1428 ± 0.0111	0.00164 ± 0.00009	98.73	33.5	87.1	-0.00410
Prolonged lactation	21.591 ± 1.150	0.1167 ± 0.0144	0.00121 ± 0.00012	95.33	32.7	96.4	-0.00265
Extremely prolonged lactation	24.916 ± 4.207	0.0809 ± 0.0461	0.00102 ± 0.00038	67.62	32.7	79.3	-0.00178
Multiparous cow							
Short lactation	21.120 ± 2.724	0.2392 ± 0.0366	0.00439 ± 0.00035	98.94	43.3	54.5	-0.01608
Normal lactation	20.164 ± 1.074	0.2400 ± 0.0148	0.00388 ± 0.00013	99.75	42.7	61.9	-0.01471
Prolonged lactation	25.974 ± 2.055	0.1599 ± 0.0219	0.00294 ± 0.00019	99.22	41.9	54.6	-0.00747
Extremely prolonged lactation	26.395 ± 1.997	0.1389 ± 0.0209	0.00233 ± 0.00018	98.78	40.5	59.6	-0.00541

***Note:** a, b, c – estimates of Wood's model coefficients of the lactation curve; R2 – coefficient of determination. Ymax – peak milk yield of lactation; Tmax – time to reach peak milk yield of lactation; Persistency – estimate of lactation persistency*
***Source:** developed by the authors*

From the point of view of the shape of the lactation curve, multiparous cows, unlike primiparous cows, show higher estimates of peak milk yield (*Ymax* = 40.5 to 43.3 kg for different subgroups by lactation length) with earlier achievement of peak milk yield (*Tmax* = 54.5 to 61.9 days for different subgroups by lactation length). Earlier, the research of T. Kopec *et al.* (2020) also found that the smallest value of parameter "*a*" (15.2317) of Wood's model of the lactation curve of Simmental primiparous cows was found for lactations lasting up to 305 days, in contrast to parameters "*b*" and "*c*", which had the highest estimates for these lactations (0.1029 and 0.0015, respectively). The maximum value of parameter "*a*" (17.4329) was found in animals with prolonged lactations (up to 640 days), in contrast to parameters "*b*" and "*c*", which had the minimum estimates for this lactation length (0.0603 and 0.0010, respectively).

Thus, the formation of a lactation curve shape specific to prolonged lactation manifests itself already during the 8^{th}-10^{th} months of lactation. In general, lactation length is determined by the influence of both genotypic (breed, crossbreed, bull sire) and environmental factors (lactation number, year and season of calving) and, in turn, affects the formation of a specific lactation curve shape and the level of milk production of dairy cows.

CONCLUSIONS

In Holstein cows at PJSC "Plemzavod "Stepnoi" (Zaporizhzhia Region, Ukraine), lactation length varied from 173 to 1,150 days and averaged 356.1 ± 4.1 days. The lactation length of multiparous cows significantly $P < 0.001$) exceeded the corresponding estimate for primiparous cows. Significant (P = 0.005) differences in lactation length estimates were found among the offspring of different bull sires only for multiparous cows. Environmental factors (year and season of calving) significantly affected the variability of lactation length in the study group of cows. The shortest lactation length was noted for multiparous cows that calved in the autumn months (332.9 days), and the highest estimates were for animals that calved in winter or autumn (386.3 to 397.0 days).

It was established that lactation length is significantly ($P < 0.001$) associated with total milk yield, but only for multiparous cows was a significant ($P = 0.036$) correlation established between lactation length and 305 days milk yield. On the other hand, a significant ($P \leqslant 0.001$ to 0.020) but negative correlation was established between lactation length and fat and protein milk percentage. Using Wood's model to approximate the lactation curve for TD1-TD10, it was found that with increasing lactation length, the estimates of the "*a*" coefficient increased, while the estimates of the "*b*" and "*c*" coefficients, on the contrary, decreased. In general, animals with prolonged lactation showed an increase in daily milk yield for TD8-TD10, which ensured an increase in the persistence of the lactation curve.

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CONFLICT OF INTEREST

None.

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Аналіз мінливості тривалості лактації та її зв'язок із молочною продуктивністю корів

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Анотація. Тривалість лактації є важливою ознакою, що тісно пов'язана як із рівнем продуктивності, так і відтворювальними якостями молочної худоби. Головною метою даного дослідження став аналіз факторів, що обумовлюють мінливість тривалості лактації та її вплив на формування лактаційної кривої, кількісні та якісні ознаки молочної продуктивності корів дійного стада. В роботі було використано дані щодо 604 повних лактацій корів, які отелилися у ПрАТ «Племзавод «Степной» (Запорізька область, Україна) протягом 2014-2017 років. У піддослідних корів тривалість лактації коливалася в межах від 173 до 1150 днів із середньою оцінкою 356,1 ± 4,1 днів. Вік корів (у лактаціях) вірогідно впливав на тривалість лактації ($P < 0,001$). Для корів-первісток не було встановлено вірогідного впливу бугая-плідника на тривалість лактації. Але при розгляді всіх лактацій разом, було доведено вірогідний вплив ($P = 0,005$) бугая-плідника на їх тривалість. Також встановлено, що мінливість тривалості лактації корів дослідної групи залежала від року та сезону їх отелення. В цілому, найнижчою LSM-оцінкою тривалості лактації характеризувалися повновікові корови, які отелилися в осінні місяці року (332,9 днів), а найвищі відповідні оцінки було відмічено серед тварин, які отелилися взимку або восени (386,3…397,0 днів). Тривалість лактації була вірогідно пов'язана із сумарним надоєм ($P < 0,001$), у той час як для надою за 305 днів лактації вірогідну кореляцію було встановлено лише для повновікових корів ($P = 0,036$). Вміст жиру і білка в молоці корів дослідної групи були також вірогідно ($P \leqslant 0,001…0,020$), але від'ємно пов'язані із тривалістю лактації. При апроксимації лактаційних кривих корів дослідної групи моделлю Вуда було встановлено, що зі зростанням тривалості лактації оцінки коефіцієнта "*a*" моделі Вуда збільшувалися, у той час як оцінки коефіцієнтів "*b*" та "*c*", навпаки, зменшувалися. В цілому, зі зростанням тривалості лактації відповідні оцінки добового надою за 8-10-й місяці збільшувалися, що забезпечувало підвищення сталості лактаційної кривої

Ключові слова: подовжена лактація; генотипові та паратипові фактори; сталість лактаційної кривої

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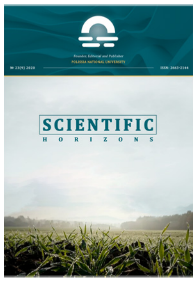

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Enhancing the productivity of honey bee colonies through the use of an immunomodulator

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Abstract. Providing honey bees with a diet enriched with biogenic metal compounds reduces the risk of infectious diseases, enhances resistance, improves the queen's reproductive capacity, and strengthens colonies. This study aimed to examine colony strength, productivity, brood development, and honey quality when using an immunomodulator. Colony strength was higher with the immunomodulator by 8.3% on 10 May, 7.1% on 15 May, 6.3% on 25 May, and 5.6% on 5 June. Pollen collection significantly increased by 11.9% on 10 May, 28.4% on 15 May ($P < 0.05$), 17.7% on

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25 May ($P < 0.05$), and 32.2% on 5 June ($P < 0.05$). Brood development increased by 5.3% on 10 May, 11.92% on 15 May, 19.6% on 25 May ($P < 0.05$), and 23.4% on 5 June ($P < 0.05$). Queens' live weight increased by 1.8% on 10 May, 2.5% on 15 May, 4.5% on 25 May, and 5.15% on 5 June in groups receiving the immunomodulator. When an immunomodulator was used for winter feeding, colony strength increased by 9.6%, honey production by 5.1%, pollen volume by 20.4%, brood quantity by 35.3%, and queens' live weight by 9.4% compared to the control. In October, colony strength increased by 18.7% ($P < 0.05$), honey production by 2%, pollen volume by 30.1%, and brood quantity by 50% in the experimental groups. The total honey weight increased by 14.4% and centrifuged honey by 15.5%. The use of the immunomodulator resulted in high quality honey, including a 20.9% increase in diastase activity and a 9.8% reduction in moisture content. A positive effect on the microscopic profile was noted, with increased adhesive and phagocytic activity of haemocytes against pathogens and an overall rise in immune cell count in bees. The practical significance of the study lies in enhancing the immune defences and productivity of honey bee colonies while ensuring high-quality and safe honey production

Keywords: immunomodulator; honey bee colony strength; honey yield; brood; queens live weight; pollen; honey quality

INTRODUCTION

Increasing the productivity of honey bee colonies is a crucial objective for beekeepers. Therefore, providing additional support to these insects during critical periods of their life is essential. Nutrient deficiencies within the bee's organism, particularly during overwintering, can lead to weakened immunity and increased susceptibility to diseases. Despite the numerous infectious diseases that can affect bees, researchers M. López-Uribe *et al.* (2020) identified a limited number of genes associated with genetically determined immune responses. This suggests that honey bees possess a unique species-specific mechanism for combating pathogens. However, the study did not specify the exact components responsible for the bees' natural immunity, nor the potential for their support and stimulation.

Scientists R. Underwood *et al.* (2023) conducted a study employing a systematic approach to assess the efficacy of three beekeeping management systems: traditional, organic, and chemicalfree. The research revealed that honey bee colony survival rates were 2.8 times higher in traditional and organic systems compared to chemical-free management. These results highlight the critical role of management system selection in colony preservation. However, the study primarily focused on parasitic diseases, leaving gaps in data concerning bacterial and fungal infections. Further research by L. Bataglia *et al.* (2022) demonstrated that the immunity of worker bees significantly declines with age and strenuous labour. This decline correlates with a reduction in juvenile hormone levels and an increase in haemolymph vitellogenin. Vitellogenin, a zinc-binding glycoprotein, plays a role in stimulating the bee's immune system. Consequently, the introduction of zinc into the bee's diet may support their resistance.

Field studies conducted by C. Rudelli *et al.* (2024) have demonstrated a correlation between pollen reserves, vitellogenin, and hexamerin levels in bees. In October, a decrease in iron and zinc levels coincided with an increase in *Varroa* mite infestation, negatively impacting bee overwintering success. Research into bee immunity and its relationship with the environment and nutrition is of paramount importance to both scientists and beekeepers. Consequently, there is ongoing research into safe immunomodulators to support bee immune defences throughout the honey flow season and during winter. The concentration of trace elements in honey bee haemolymph is linked to their prevalence in the surrounding environment (Fry *et al.,* 2023).

Studies by D. Fèvre and P. Dearden (2024) provide evidence that nutrition directly influences queen reproductive activity, colony productivity, overwintering, and overall health. The specific dietary components that are crucial remain to be determined. In a scientific review, H. Moura *et al.* (2020) identified essential biogenic metals for each animal species, which play a role in the functioning of organismal systems. It has been established that bees use magnetic iron oxide particles for their navigational system. There is a need to broaden the spectrum of biogenic metals that can be utilised to enhance honey bee colony strength and increase brood production. The application of plant-based and probiotic supplements has been shown to increase animal productivity. Calves were administered a premix of biogenic metal nicotinates (Shkromada *et al.* 2021). The results of these studies demonstrated a positive impact of biogenic metals on animal metabolism, productivity, and an increase in serum levels of zinc, iron, copper, and selenium. An immunostimulatory effect on young animals was also confirmed. This raises the need to investigate the effects of biogenic metals on honey bees (Fotina *et al.* 2024).

The enrichment of bee products (pollen) with biochemical components such as proteins, lipids, carbohydrates, carotenoids, and sporopollenins was determined by A. Kenđel and B. Zimmermann (2020) using infrared spectroscopy. The experimental results confirmed that the saturation of pollen with beneficial substances depends on bee nutrition. Research by

H. Shahid *et al.* (2023) has established the high antioxidant and anti-inflammatory properties of iron metal oxides obtained from honey. Honey bee pollen contains a rich array of trace elements, making it a viable bioindicator for environmental assessment, with demonstrated accuracy and precision (Erdoğan *et al.* 2023). Experimental results have identified key mineral components of pollen, including manganese, iron, zinc, selenium, and chromium. The mineral composition of pollen varies depending on the collection area and any supplemental feed provided to the bees.

Researchers R. Hussain *et al.* (2023) tested silver and zinc nanoparticles against fungal and bacterial infections in honey bees. Resistant honey bee pathogens, such as *Paenibacillus larvae*, *Melissococcus plutonius*, and *Ascosphaera apis*, exhibited sensitivity to Ag and Zn oxides. Bees obtain macro- and microelements from pollen, water, and nectar. A diverse pollen diet can positively influence honey bee health (Lee *et al.* 2024). However, the effects of phytochemicals and trace elements on honey bee physiology remain largely unexplored. Therefore, this study aimed to determine the impact of an immunomodulator on honey bee colony development, overwintering, productivity, and honey quality.

MATERIALS AND METHODS

Experiment design. The experiments were conducted in the "Innovative Technologies" laboratory of the Faculty of Veterinary Medicine at Sumy National Agrarian University and bee farms in the Sumy Region. In spring 2024, the following indicators characterising the development of honey bee colonies were examined: colony strength, brood development, pollen and honey production, and queen live weight. Ten honey bee colonies were selected for the study based on the principle of analogues, divided equally into experimental and control groups. The control group bees received a sugar solution (1:1). The experimental group bees received a sugar solution (1:1) supplemented with an immunomodulator based on germanium succinate, zinc, and cobalt, at a rate of 2.5 g of the preparation per honey bee colony in 0.5 L of syrup.

Honey quality analysis. Following the honey flow season, an inspection and preparation of honey bee colonies for overwintering were carried out. The honey underwent veterinary and sanitary examination according to DSTU 4497-2005 (2007). Honey quality and safety were assessed using organoleptic and laboratory methods. The organoleptic evaluation included assessments of consistency, colour, taste, aroma, and the presence of mechanical impurities. Laboratory methods were used to determine moisture content and diastase number.

Assessment of honey bee colonies' condition during winter preparation. Five spring feedings of the bees were conducted at 5-day intervals. The degree of honey bee colony development was determined using measurement frames.

Haemolymph analysis of bees following immunomodulator application. Following the application of the immunomodulator, haemolymph microscopy was performed using a scanning electron microscope to examine quantitative cellular changes and the haemocytes' immune response to bee pathogens. Haemolymph was extracted from the bee's heart. The obtained haemolymph was centrifuged at 1,500 revolutions per minute. A 2.5% glutaraldehyde solution was used for fixation. A buffer solution (NaH_2PO_4) was used to stabilise the resulting solution. Microscopy was conducted using a PEM 106 device (JSC SELMI, Sumy, Ukraine) at electronoptical magnifications ranging from 200 to 5,000 times, according to the methodology described by M. Bozhokin *et al.* (2021).

Statistical analysis. Experiments were conducted using Microsoft Excel 2010, and all obtained results were subjected to statistical analysis using the Fisher-Student method, considering statistical errors and a significance level of more than 95% ($p < 0.05$). During the study, the principles of humane treatment of experimental insects were followed, following DSTU EN ISO/IEC 17025:2019 (2021), adhering to the rules of bioethics and humane treatment of animals 2010/63/EU (Hartung, 2010), European Convention… (1986) Law of Ukraine No. 249 (2012)

RESULTS AND DISCUSSION

It was established that at the beginning of the experiment, the indicators of the control and experimental groups of honey bee colonies did not significantly differ. A gradual increase in colony strength was observed in both groups (Table 1).

***Table 1**. Indicators of honey bee colony development with immunomodulator supplementation, M ± m, n = 10*

Experiment	Groups	Colony strength, kg	Pollen volume, cm²	Brood, units	Queen bees' live weight, mg
10 May 2024	Control	1.1 ± 0.1	90.6 ± 15.5	3,410 ± 303.8	265.6 ± 7.5
	Experimental	1.2 ± 0.2	101.4 ± 21.4	3,590 ± 205.8	270.4 ± 4.7
15 May 2024	Control	1.4 ± 0.2	128.5 ± 24.9	6,070 ± 610.1	268.4 ± 7.6
	Experimental	1.5 ± 0.1	165.0 ± 24.7*	6,794 ± 665.4	275.1 ± 4.9
25 May 2024	Control	1.6 ± 0.1	200.0 ± 43.1	10,080 ± 653.6	272.4 ± 7.4
	Experimental	1.7 ± 0.2	235.5 ± 53.6*	12,060 ± 568.6*	284.6 ± 5.3
5 June 2024	Control	1.8 ± 0.2	248.5 ± 56.8	12,500 ± 836.8	273.6 ± 7.4
	Experimental	1.9 ± 0.1	328.5 ± 97.3*	15,420 ± 654.2*	287.7 ± 4.7

Note: **P < 0.05 – significant compared to the control*
Source: *compiled by the authors*

The experiment clearly demonstrates the difference in honey bee colony strength before and after immunomodulator supplementation. The strength of honey bee colonies in the experimental groups showed a non-significant increase during the following periods: 8.3% on 10 May, 7.1% on 15 May, 6.3% on 25 May, and 5.6% on 5 June. Pollen volume was higher in the experimental group: 11.9% on 10 May, 28.4% on 15 May (*P < 0.05), 17.7% on 25 May (*P < 0.05), and 32.2% on 5 June (*P < 0.05), compared to the control group without immunomodulator supplementation. A positive effect of the biogenic metal-based immunomodulator was observed on subsequent young bee generations. A trend towards increased reproductive activity of queen bees and an increase in sealed brood was observed in the experimental groups. The amount of brood was higher in the experimental groups compared to the control group without immunomodulator supplementation: 5.3% on 10 May, 11.92% on 15 May, 19.6% on 25 May (*P < 0.05), and 23.4% on 5 June (*P < 0.05). In the control group, larvae developed poorly, and some died before pupation. A nonsignificant trend of increased queen bees' live weight was observed with the use of the immunomodulator. It was found that in the immunomodulator-treated groups, the live weight of queen bees was higher: 1.8% on 10 May, 2.5% on 15 May, 4.5% on 25 May, and 5.15% on 5 June, compared to the control. The next study examined the development of honey bee colonies during preparation for overwintering (August) and during overwintering (October) (Table 2).

***Table 2**. Development of honey bee colonies during preparation for overwintering (August) and during overwintering (October) under the influence of immunomodulator, M ± m, n = 10*

Experiment	Groups	Colony strength, kg	Honey production, kg	Pollen volume, cm^2	Brood, units	Queen bees' live weight, mg
August	Control Experimental	2.1 ± 0.1 2.3 ± 0.1	11.7 ± 0.6 12.3 ± 0.8	131.6 ± 20.6 158.5 ± 24.1	5,780 ± 556.8 7,820 ± 406.7*	234.8 ± 7.5 256.8 ± 4.8
October	Control Experimental	1.6 ± 0.2 1.9 ± 0.1*	9,432 ± 0.57 9,620 ± 0.43	101.1 ± 5.5 131.5 ± 4.1	60 ± 33.1 90 ± 22.3	-

***Note:** *P < 0.05 – significant compared to the control*
***Source:** compiled by the authors*

It was demonstrated that at the end of the honey flow season, honey bee colonies in the experimental group exhibited higher levels of colony strength, queen bees' live weight, and brood quantity compared to the control group. It was found that honey bee colony strength in the experimental groups was higher in August by 9.6% and in October by 18.7% (*P < 0.05) compared to the control. Honey production was higher in the experimental group by 5.1% in August, at the time of feeding, and by 2% in October, during overwintering. Pollen volume in August was 20.4% higher, and in October, 30.1% higher than in the control. The greater amount of brood in the experimental colonies indicates that these groups have younger bees or bees with enhanced immunity. Such bees are better equipped to survive overwintering. It was established that the brood quantity in the experimental groups was higher in August by 35.3% and in October by 50% compared to the groups without immunomodulator supplementation. A non-significant increase in queen bees' live weight was observed at the beginning of feeding in August, by 9.4% in the experimental honey bee colony groups. Studies have shown that the experimental group produced more honey than the control group (Table 3).

***Table 3**. Average honey yield per honey bee colony per season, M ± m, n = 10*

Groups	Total honey weight, kg	Centrifuged honey, kg
Control	75.30 ± 3.45	55.18 ± 3.20
Experimental	86.12 ± 2.56*	63.75 ± 2.34*

***Note:** *P < 0.05 – significant compared to the control*
***Source:** compiled by the authors*

At the end of the honey flow season in August, an increase in total honey weight of 14.4% and centrifuged honey of 15.5% was observed in the experimental groups compared to the control. The potential impact of immunomodulator application on honey quality was also assessed (Table 4).

***Table 4**. Honey quality determination results following immunomodulator application, M ± m, n = 10*		
Indicator	**Groups**	
	Experimental	**Control**
Moisture, %	15.7 ± 0.5	17.4 ± 0.4
Diastase number, Gothe units	17.9 ± 0.1*	14.8 ± 0.2
Inverted sugar, %	73.8 ± 0.2	72.9 ± 0.1
Honeydew	Not detected	Not detected
Consistency	Liquid	Liquid
Consistency	Light amber	Light amber
Aroma	Pleasant	Pleasant
Taste	Pleasant	Pleasant
Mechanical impurities	Absent	Absent

Note: **P* < 0.05 – significant compared to the control*
Source: *compiled by the authors*

During the veterinary and sanitary examination of honey samples, it was found that honey from both experimental and control groups exhibited high-quality indicators. However, the experimental group's honey had a higher diastase number (20.9% increase) and a lower moisture percentage (9.8% decrease), which positively affected honey storage and quality. Haemolymph examination using scanning electron microscopy revealed that no infectious disease pathogens were found in the haemolymph of bees treated with the immunomodulator (Fig. 1). In the haemolymph of control group bees, phagocytosis of the Nosema pathogen was observed (Fig. 2). When examined under a scanning electron microscope, no disease-causing pathogens were observed in the haemolymph of bees treated with the immunomodulator, compared to the group of bees that did not receive the supplement. In the experimental haemolymph, a haemocyte, acting as an immune cell, exhibited signs of phagocytosis, specifically attracting and destroying the Nosema pathogen (Fig. 3). Additionally, there was a trend towards an increased number of haemocytes following immunomodulator application.

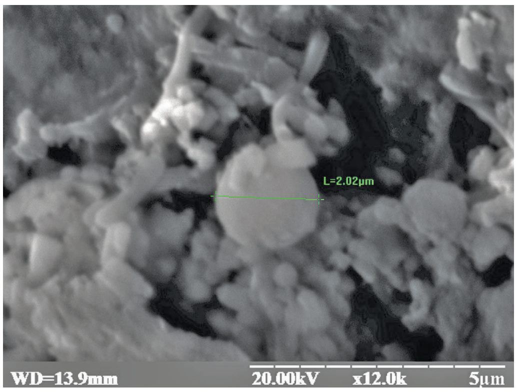

***Figure 1**. Haemocyte activity in bee haemolymph*
Source: *authors' photo*

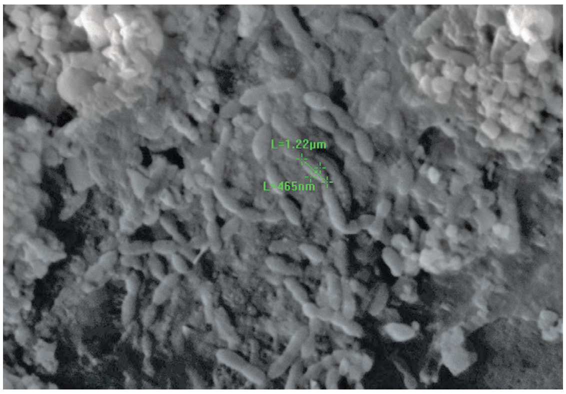

***Figure 2**. Nosema apis pathogen in the haemolymph of control bees*
Source: *authors' photo*

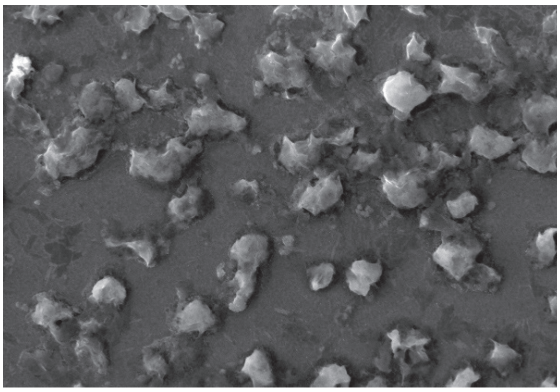

***Figure 2**. Destruction of Nosema apis after phagocytosis by haemocytes in the lymph of control bees*
Source: *authors' photo*

Field studies demonstrated that immunomodulator application increased bee productivity, resistance, and fecundity. The immunomodulator had no negative impact on honey quality. Honey bee colony strength significantly increased by 5.6-8.3% in the immunomodulator-treated groups from May to June. Pollen volume significantly increased by up to 32.2% in the experimental groups. Brood quantity increased by 23.4% in June in honey bee colonies treated with the microelement-based immunomodulator. Researchers G. Zhang *et al.* (2015) investigated whether bees obtain sufficient zinc from their environment. They confirmed that supplemental zinc enhances bee survival, royal jelly production, and larval health.

Studies have shown that the live weight of queen bees was higher in groups supplemented with microelements (Table 1). Similar results were obtained by researchers T. Fotina *et al.* (2022) when using mineral microelement supplements of zinc, copper, and manganese in poultry diets, which resulted in increased poultry live weight and enhanced immunity. Measurements taken in honey bee colonies during preparation for overwintering and during overwintering (Table 2) showed that honey bee colony strength was higher in the experimental groups compared to the control. When feeding honey bee colonies for overwintering, honey bee colony strength increased by 9.6%, honey production by 5.1%, pollen volume by 20.4%, brood quantity by 35.3%, and queen bees' live weight by 9.4%.

At the beginning of overwintering, the experimental groups showed higher values compared to the control group: colony strength was 18.7% higher (*$P < 0.05$), honey production was 2% higher, pollen volume was 30.1% higher, and brood quantity was 50% higher. Research by G. Glavan *et al.* (2024) demonstrated that zinc supplementation in bees did not cause toxic effects, even at high doses. However, as the results of this study show, therapeutic doses of a mineral-based immunomodulator positively influenced bee productivity and brood development in August. Researchers G. Ribeiro *et al.* (2023) confirmed experimentally that zinc supplementation in bee feed stimulates royal jelly production, which promotes brood survival. Additionally, the study of G. Cullen *et al.* (2023) supports that the diet composition of nurse bees influences larval development, reproductive potential, and disease resistance.

It was established that the average honey yield per honey bee colony at the end of the honey flow season was 14.4% higher in the experimental groups (Table 3). Furthermore, the amount of centrifuged honey increased by 15.5% compared to the control group. Research by M. Behjatian Esfahani *et al.* (2023) supports that adding microelements to bee diets increases their productivity and brood development. It was experimentally proven that the immunomodulator application had no negative impact on honey quality (Table 4). On the contrary, the diastase number was 20.9% higher compared to the control, and the moisture content was 9.8% lower. The physicochemical properties of honey are important as they determine the product's value in comparison to international standards (Sęk *et al.* 2023; Nikitina & Zasiekyn, 2024).

Researchers R. Pavlović *et al.* (2024) have established that micronutrient deficiencies in bee diets can lead to bacterial and fungal diseases. Therefore, the immune response of bees is affected by micronutrient shortages, which results in an increase in infectious diseases. As demonstrated in this study, infectious disease pathogens were not detected in the haemolymph of bees treated with the immunomodulator (Fig. 1). In the haemolymph of control group bees, phagocytosis of the Nosema pathogen was observed (Fig. 2). An increase in the number of haemocytes was observed in bees treated with the immunomodulator. Thus, to enhance the defensive capabilities of honey bee colonies, their productivity, and obtain high-quality and safe honey, it is advisable to use the immunomodulator at a rate of 2.5 g of the preparation per honey bee colony in 0.5 L of syrup.

CONCLUSIONS

Studies have demonstrated that the use of an immunomodulator resulted in increased honey bee colony strength during the following periods: 8.3% on 10 May, 7.1% on 15 May, 6.3% on 25 May, and 5.6% on 5 June. Pollen production significantly increased: 11.9% on 10 May, 28.4% on 15 May (*$P < 0.05$), 17.7% on 25 May (*$P < 0.05$), and 32.2% on 5 June (*$P < 0.05$). Queen reproductive capacity increased: 5.3% on 10 May, 11.92% on 15 May, 19.6% on 25 May (*$P < 0.05$), and 23.4% on 5 June (*$P < 0.05$). Additionally, queens live weight increased in the immunomodulator-supplemented groups: 1.8% on 10 May, 2.5% on 15 May, 4.5% on 25 May, and 5.15% on 5 June. When feeding honey bee colonies for overwintering, the immunomodulator increased honey bee colony strength by 9.6%, honey production by 5.1%, pollen volume by 20.4%, brood quantity by 35.3%, and queens bee live weight by 9.4% compared to the control. During overwintering in October, the experimental groups showed higher values: colony strength was 18.7% higher (*$P < 0.05$), honey production was 2% higher, pollen volume was 30.1% higher, and brood quantity was 50% higher. Furthermore, the experimental groups showed an increase in total honey weight of 14.4% and centrifuged honey of 15.5% compared to the control.

Veterinary and sanitary examination of the honey obtained using the immunomodulator demonstrated high quality, including a 20.9% increase in diastase number and a 9.8% decrease in moisture content. Scanning electron microscopy of bee haemolymph revealed the absence of infectious disease infections. The *Nosema apis* pathogen, undergoing phagocytosis, was detected in the haemolymph of the control group of bees. Future research will focus on determining the level of parasitic and bacterial infections in bees using the immunomodulator.

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CONFLICT OF INTEREST

None.

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Підвищення продуктивності бджолиних сімей за рахунок використання імуномодулятору

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Анотація. Забезпечення медоносних бджіл збагаченим раціоном на основі біогенних сполук металів зменшує ризик виникнення інфекційних захворювань, сприяє підвищенню резистентності, репродуктивної здатності матки та сили сімей. Метою дослідження було дослідити силу сімей, продуктивність, розплід, якість меду за використання імуномодулятору. Сила бджолиних сімей була більше у період 10 травня – на 8,3 %, 15 травня – на 7,1 %, 25 травня – на 6,3 %, 5 червня – на 5,6 % за використання імуномодулятору. Вірогідно збільшився видобуток пилку 10 травня на 11,9 %, 15 травня – на 28,4 % ($^*P < 0{,}05$), 25 травня – на 17,7 % ($^*P < 0{,}05$), 5 червня – на 32,2 % ($^*P < 0{,}05$). Розплід збільшився 10 травня – на 5,3 %, 15 травня – на 11,92 %, 25 травня – на 19,6 % ($^*P < 0{,}05$), 5 червня – на 23,4 % ($^*P < 0{,}05$). Жива маса маток збільшилась 10 травня – на 1,8 %, 15 травня – на 2,5 %, 15 травня – на 4,5 %, 5 червня – на 5,15 % у групах з додаванням імуномодулятору. При застосуванні імуномодулятора для підгодівлі сімей на зимування сила збільшилась на 9,6 %, видобуток меду – на 5,1 %, обсяг пилку – на 20,4 %, кількість розплоду – на 35,3 %, збільшення живої ваги маток – на 9,4 %, порівняно з контролем. У жовтні місяці сила сімей збільшилась на 18,7 % ($^*P < 0{,}05$), продукція меду – на 2 %, обсяг пилку – на 30,1 %, розплід – на 50 % у дослідних групах. Загальна вага меду збільшилась на 14,4 % та центрифугованого – на 15,5 %. За використання імуномодулятору отримали високу якість меду, в тому числі вище діастазне число – на 20,9 % та нижчий відсоток водності на 9,8 %. Відмічено позитивний вплив на мікрокартину, де спостерігається висока адгезивна та фагоцитарна активність гемоцитів до збудників хвороб та загальне збільшення кількості імунних клітин бджоли. Практичною цінністю роботи є підвищення захисних сил бджолиних сімей, їх продуктивності та отримання якісного та безпечного меду

Ключові слова: імуномодулятор; сила бджолиної сім'ї; видобуток меду; розплід; жива вага матки; пилок; якість меду

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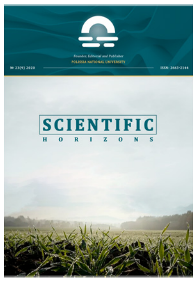

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Effectiveness of plant growth stimulants for winter wheat in the Left-Bank Forest-Steppe of Ukraine

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Abstract. The study aimed to determine the effectiveness of plant growth stimulants on yield and grain quality indicators of winter wheat grown on dark grey podzolic soil developed from loess-like loam. The research assessed the impact of seed treatment with the BioZern fertiliser for stimulating the growth and development of cereal crops, the Medax Top growth regulator, the Turbo micronutrient fertiliser, and $MgSO_4$

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in winter wheat cultivation under the conditions of Kyiv Region, at Biotech LTD. Seed treatment with BioZern in combination with Medax Top + Turbo + $MgSO_4$ resulted in a yield of 9.0 t/ha compared to 6.8 t/ha in the control. The application of plant growth stimulants (PGS) and micronutrients increased yield by 1.34-2.2 t/ha. The use of PGS in combination with $MgSO_4$ improved plant growth and development indicators, with an 8-10% increase in plant density, over a 20% rise in the number of productive stems per unit area, and a corresponding increase in the tillering coefficient. The application of PGS also significantly enhanced key indicators of wheat ear productivity. The number of spikelets, grains per spike, grain weight per spike, and total grain mass per spike increased in the studied crop. Growth ranged from 25% to 50% compared to the control. A key practical outcome of the study was the improvement of most indicators characterising product quality. In addition to an increase in the 1,000-grain weight, the test weight rose from 737 g/L in the control to 763-766 g/L in treatments with PGS. While vitreousness remained consistent across all treatments, PGS slightly reduced the grain protein content from 15.6% in the control to 14.0-14.2% in treated variants. The results confirm the high effectiveness of winter wheat seed treatment with the BioZern preparation, the application of the Medax Top growth regulator, the Turbo micronutrient fertiliser, and $MgSO_4$ under the conditions of Kyiv Region. These findings can be recommended for winter wheat cultivation

Keywords: plant growth regulators; grain quality; biometric growth indicators; yield; productivity

INTRODUCTION

Winter wheat is a crucial crop in Ukrainian agriculture, accounting for approximately 45% of the country's total sown area. Successful cultivation requires a series of precise agricultural practices that directly influence yield potential. However, in recent decades, growth-regulating substances or plant growth stimulants have become widely used in these operations. Manufacturers of these substances highlight their beneficial properties, which affect grain quality and yield indicators, resistance to adverse conditions, and the plant's ability to absorb organic and mineral nutrients. However, the effectiveness and practical implementation of combining different types of agrochemicals, including various forms of mineral fertilisers, growth regulators, and plant growth stimulants, remain insufficiently studied. Moreover, new types and formulations of agrochemicals are continually being developed and introduced to the market, cultivation conditions are evolving, and new varieties and hybrids are being introduced. This necessitates the development of recommendations for their effective use in production across different regions and conditions.

As highlighted by A. Panfilova *et al.* (2023), the implementation of modern agricultural technologies and high-yielding wheat varieties has the potential to significantly increase winter wheat production. However, the full potential of modern wheat varieties is not yet realised in production due to several limiting factors, including climatic conditions, soil properties, pests, and diseases. The future of the grain market heavily relies on the continued improvement of agricultural practices in winter wheat cultivation. In particular, more research is needed to understand the effects of new plant growth stimulants on crop development and yield in different varieties and hybrids. Achieving high yields is challenging, and adverse climatic conditions are a major cause of yield reduction. Addressing the impact of climate on winter wheat yield is a critical issue for researchers, as noted by S. Shylo *et al.* (2021).

V. Sarabi and E. Arjmand-Ghajur (2021) suggest that the use of plant growth stimulants allows for targeted regulation of key plant processes, enabling the full realisation of a variety's genetic potential. According to M. Korkhova *et al.* (2021), high-yielding winter wheat varieties have increased demands for soil fertility, moisture content, and weed control. When cultivating highyielding wheat varieties, proper fertilisation becomes crucial. Mineral fertilisers play a decisive role in achieving stable and high yields. The positive effects of mineral fertilisers applied to winter wheat are evident across various soil types and regions in Ukraine. This includes presowing (basic), at-sowing (row), and various top-dressing applications (surface, root, and foliar). A. Elkoussy *et al.* (2023) highlight that plant growth stimulants are an additional factor in increasing crop productivity, including winter wheat. They enhance the efficiency and return on investment of mineral fertilisers and pesticides. R. Kieloch and K. Marczewska-Kolasa (2022) note that plant growth regulators promote plant growth and development under both optimal and stressful conditions. They provide plants with resistance to abiotic stresses, mitigating the effects of herbicide stress and increasing plant tolerance. However, W. Miziniak and K. Matysiak (2023) indicate that the combined application of herbicides with mepiquat chloride only increases winter wheat grain yield in heavily weed-infested crops. The combined use of herbicides and growth stimulants requires careful timing, as herbicide application depends on the weed development stage, which may not coincide with the optimal timing for PGS application.

As D. Nsengiyumva *et al.* (2019) point out, the high effectiveness of plant growth regulators is due to their balanced composition of biologically active substances. These substances promote the rapid development of green mass and root systems. Researchers Z. Garban and G. Ilia (2024) and V. Kryzhanovskiy (2022) add that improved green mass and root activity lead to more efficient nutrient utilisation. This, in turn, enhances resistance to diseases, stresses, and adverse weather conditions. In addition to significantly increasing yield, plant growth stimulants, as highlighted by R. Babu *et al.* (2022), also shorten the maturation period, reduce nitrate, pesticide, and heavy metal content in plants, enhance the nutritional value of the harvested crop, and minimise losses during harvesting, transportation, and storage.

Therefore, this study aimed to determine the effectiveness of plant growth stimulants on the productivity and quality indicators of winter wheat grain in the Left-Bank Forest-Steppe region of Ukraine.

LITERATURE REVIEW

For the past few decades, Ukraine's agricultural sector has been a key driver of the country's economic development and a major source of foreign currency earnings (Kyfyak *et al.*, 2022). Winter wheat stands out as a crucial food and export crop. Winter wheat is one of the world's leading cereal crops, valued for its high nutritional and taste qualities, as well as its high productivity compared to other cereals (Tadesse *et al.,* 2020). Ukraine is a major agricultural exporter in Europe, with winter wheat playing a significant role (Kiforenko, 2023). While wheat is grown across various regions of Ukraine, the main cultivation areas are concentrated in the ForestSteppe zone, which provides the most favourable soil and climatic conditions for this crop (Lozinskiy & Samoilyk, 2023).

Many factors influence the yield and quality of winter wheat grain, and farmers use various methods to mitigate these factors. One common practice is the use of plant growth stimulants. The global market offers a wide range of these stimulants. However, there is a lack of information on their effectiveness in specific soil and climatic conditions. Winter wheat (*Triticum* L.) is the most valuable and high-yielding cereal crop. Its technological properties, including a high protein content (16%) and carbohydrate content (80%), make it suitable for use in the baking industry, pasta and confectionery production, and animal feed manufacturing (Kaplan Evlice, 2021; Ravshanov *et al.,* 2021).

Significant research has been conducted on the effects of plant growth stimulants applied either as foliar sprays or seed treatments on the development and productivity of agricultural crops. The application of growth regulators during seed preparation for sowing has been shown to increase seed germination energy and field emergence (Shalygina *et al.,* 2021; Tajdari *et al.,* 2024; Sethar *et al.,* 2024). Foliar application of products like the film-forming bioregulator Mars-ELBi, in conjunction with mineral fertilisers on typical chernozem soils, consistently increased winter wheat grain productivity when applied in spring after the resumption of spring growth (Yarchuk *et al.,* 2020). Under the influence of growth regulators, root system mass increased by up to 57% due to the formation of more secondary roots in cereals. This led to an increase in the number of spikelets per ear and the 1000-grain weight.

It is well-established that plant growth regulators facilitate plant growth and development under both optimal and stressful conditions. However, W. Miziniak and K. Matysiak (2023) found that the combined application of herbicides with mepiquat chloride only increased winter wheat grain yield in heavily weed-infested crops. The combined use of herbicides and PGRs requires careful timing, as herbicide application depends on the weed development stage, which may not coincide with the optimal timing for PGR application. I. Kosakivska *et al.* (2022) reported that treating winter wheat seeds with Fulvogumin and succinic acid increased germination energy to 9496%. Fulvogumin significantly increased root length. Pre-sowing application of Fulvogumin with succinic acid resulted in larger wheat seedlings (12.4 cm) and higher fresh weight (11.5 g/100 seeds). PGRs based on phytohormones are differentially distributed within plants.

Pre-sowing treatment of wheat seeds with exogenous phytohormones improves plant growth and development. According to O. Hordyna (2021), this treatment should be carried out simultaneously with seed dressing. It is recommended to reduce the dosage of seed dressing agents by 30% when used in a tank mixture with biostimulants. The author also found that biostimulants enhance metabolic processes in the plant and improve energy metabolism, contributing to higher field resistance of plants to abiotic and anthropogenic factors, including diseases. Treatment of winter wheat seeds of the Duma odeska variety with the natural growth biostimulant Azotofit-R, which actively fixes molecular and atmospheric nitrogen, improves seed germination and stimulates and improves root system development. Used alongside the biological fungicide Phytocide-R against fungi, it contributed to a yield of 6.09 t/ha. The use of growth regulators based on the metabolic products of micromycete fungi, a balanced complex of phytohormones of auxin and cytokinin nature, amino acids, carbohydrates, fatty acids, and micronutrients, increases germination energy and grain emergence. It also leads to a more branched root system and improved development of symbiotic microflora in the root growth zone (Tekaya *et al.,* 2022; Dymytrov *et al.,* 2023).

Anomalies observed in plants subjected to environmental stress include poor photosynthetic activity, the development of non-functional stomata, reduced wax deposition, poor root system development, and low resistance to pathogens (Pavlov *et al.,* 2021; Honchar *et al.,* 2023). The synthesis of natural antidepressants and anti-stress factors that confer resistance to drought, waterlogging, and other adverse environmental conditions in the soil and within the plant itself is promoted by the use of the biological inoculant PGPM. This can stimulate the improvement of plant vitality through various mechanisms, such as the production of plant growth hormones, nitrogen fixation, and the reduction of nitrate levels, among others. Furthermore, these PGPMs can act as biocontrol agents, helping plants develop resistance to pathogens at an early stage of development (Teraiya *et al.,* 2023). Biostimulants based on benzyladenine, kinetin, indole-3-butyric acid, and 1naphthaleneacetic acid are used to accelerate the breaking of seed dormancy in clonal production of forest crops (Dinçer, 2023).

MATERIALS AND METHODS

The field studies were conducted in the Kyiv Region, Ukraine, at the experimental field of "Biotekh LTD". The soil of the experimental plot is dark grey podzolic soil on loess-like loams. The agrochemical and physicochemical indicators are presented in Table 1. The climate of this area is temperate continental with a relatively mild winter. The duration of the growing season in this region ranges from 198 to 204 days, and the moisture coefficient is close to one.

***Table 1**. Agrochemical and physicochemical indicators of dark grey podzolic soil on loess-like loams*

Indicator	Depth of sample collection, cm	
	0-20	20-40
pH $_{KCl}$	5.4	4.8
Humus content,%	2.8	2.6
Absorption capacity, mg-equiv/100g	27.9	24.1
Hydrolytic acidity, mg-equiv/100g	2.6	3.1
Base saturation degree, %	86.3	87.1
Available N, mg/kg	37.8	18.8
$P_2O_{5,}$ mg/kg	305	201
K_2O_2 mg/kg	342	282

Source: *developed by the authors*

Morphological and biometric observations were carried out using the state variety testing method (Tkachyk *et al.,* 2017). The BBCH scale, which is currently the most common among professionals in Ukraine, was used to describe the phenological development of plants. The number of plants (plants/m^2), the number of stems (stems/m^2), the tillering coefficient – at BBCH 29, the height of winter wheat plants at BBCH 29, BBCH 59, BBCH 92, the number of grains in a spike (grains), the mass of the spike (g), the mass of grains in the spike (g), and the grain yield per unit area (t/ha) were determined.

Quality indicators were analysed according to the standards set out in DSTU 37682019 (2019): protein content in the grain was determined using the Kjeldahl method; crude gluten content was measured using the washing method; and the falling number was determined using the Hagberg-Perten method. The falling number is a unit of measurement for the activity of the α amylase enzyme in wheat grain. This enzyme breaks down starch into monosaccharides, releasing carbon dioxide, which contributes to the porosity of bread during baking. The value of the falling number can easily indicate the quality of future bakery products:

- a very high falling number indicates low α-amylase activity, resulting in insufficient carbon dioxide for dough leavening, leading to dry, low-volume bread;
- a low falling number indicates excessive enzyme activity, resulting in sticky dough and overly soft bread;
- the optimal falling number for wheat is 250 seconds (Gilissen & Smulders, 2021).

The test weight was determined using a grain tester. The 1000-grain weight was calculated. Grain translucency was measured using a DC3-3 diaphanoscope. Vitreosity (%) is an indicator that determines the hardness of the grain endosperm. Higher vitreosity indicates better baking properties and, consequently, higher wheat quality and value. The total area of the experimental plot was 50 m^2, with a recorded area of 26 m^2 and four repetitions. Statistical analysis was performed using the ANOVA method. The fertiliser and PGR application scheme is shown in Table 2.

***Table 2**. Experimental design*

Fertilisation variant	BBCH growth stage
1. Control (Background): N_{32} after previous crop harvest – UAN;N_{32} pre-sowing cultivation – UAN;LCF ($N_8P_{34)}$ – 150 kg/ha pre-sowing; KCl – 100 kg/ha pre-sowing	–
2. Background + Medax Top (1 L/ha) + Turbo (1 L/ha) + $MgSO_4$ (7 kg/ha)	BBCH 30-32 BBCH 37-39
3. Background + BioZern seed treatment 30 (2 L/t) + $MgSO_4$ (7 kg/ha)	BBC 37-39
4. Background + BioZern seed treatment 30 (2 L/t) + Medax Top (1 L/ha) + Turbo (1 L/ha) + $MgSO_4$ (7 kg/ha)	BBCH 30-32 BBCH 37-39

Source: *developed by the authors*

Medax Top (BASF) is a growth regulator that reduces plant lodging. It contains active ingredients: prohexadione calcium (50 g/L) + mepiquat chloride (300 g/L). The formulation is a concentrated suspension (CS). Turbo (TD Hermes) is a micronutrient fertiliser containing nitrogen (30%), potassium (3%), phosphorus (3%), magnesium (1.5%), sulphur (0.3%), and iron (0.2%), as well as humic substances, amino acids, and organic acids. $MgSO_4$ is a magnesium salt containing MgO (16%) and SO_3 (30%). BioZern is a fertiliser for stimulating the growth and development of cereal crops (wheat seed treatment): nitrogen (N) – 150 g/L, calcium (CaO) – 20 g/L, copper (Cu) – 10 g/L, manganese (Mn) – 20 g/L.

The experiment focused on the soft, awnless winter wheat (*Triticum aestivum* L.) variety Mulan, a German selection from Nordsaat Saatzucht GmbH. This variety is classified as a valuable, high-yielding, medium-ripening type, with a vegetation period of 275-280 days. It exhibits medium winter hardiness, increased resistance to drought, lodging, and diseases. The average plant height ranges from 80-90 cm. The seeding rate for winter wheat was 4.5 million seeds per hectare. The authors conducted the research following generally accepted methodological recommendations for crop cultivation. The experimental studies on winter wheat plants, including the collection of plant material, comply with the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

The productivity and quality of crops are significantly influenced by the conditions of plant growth and development in the early stages of organogenesis when the potential of the future harvest is established. Analysis of the results of observations of the effect of PGRs in combination with the application of magnesium sulphate showed that their application improved plant development indicators. While the number of plants in the control variant was 510 plants/m^2, the use of PGRs with magnesium sulphate increased this indicator to 554-566 plants/m^2, the number of stems increased from 915 to 1,210 stems/m^2, and the tillering coefficient increased from 1.79 to 2.14 (Table 3).

Table 3*. Effect of fertilisation during spring tillering (BBCH 29) on winter wheat growth indicators*

Variant number	Number of plants, plants/m^2	Number of stems, stems/m^2	Tillering coefficient
1	510	915	1.79
2	554	1,121	2.02
3	561	1,205	2.14
4	566	1,210	2.14

Source: *developed by the authors*

The highest indicators were observed in the variant with the combined application of Background + BioZern + Medax Top + Turbo + $MgSO_4$. This indicates an improvement in plant development when using PGRs on a high agricultural background. The largest winter wheat yield is obtained in the presence of a high stem density of productive shoots of plants per square meter of sown area and a high grain content in each ear (Zhuk & Stasik, 2024). The formation of the crop yield is significantly influenced by weather and climatic conditions, soil fertility, and the biological characteristics of the varieties being grown. Analysing the results, the tallest plants at the BBCH 29 stage (spring tillering) were observed in the treatment with Background + BioZern + Medax Top + Turbo + $MgSO_4$, measuring 29.1 cm (Fig. 1). This trend continued until the BBCH 92 stage (full maturity), with plants reaching 121 cm. The shortest plants were observed in the control group (N_{32} UAN + N_{32} + N_8P_{34} + KCl), ranging from 25.1 to 89.4 cm. In the treatment without BioZern, the difference compared to the control was 2.3 cm at the BBCH 29 stage, and this pattern persisted throughout the entire growing season.

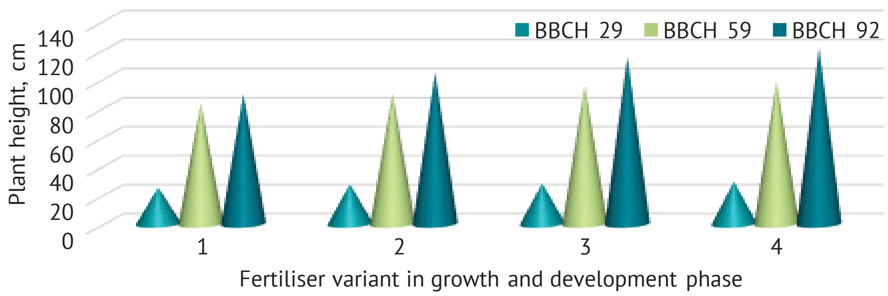

Figure 1*. Winter wheat plant height depending on fertiliser rates, cm*

Note: *LSD$_{0.05}$*
Source: *developed by the authors*

Better initial plant development conditions resulted in higher ear productivity. For example, the number of spikelets in the control variant was 11, while in the second variant, it was 15.1, in the third variant 15.9, and the fourth variant 16.2 (Table 4).

The grain content per ear increased from 12 grains in the control to 15.6-17.1 grains with the use of PGRs. This led to an increase in ear weight and grain weight per ear. In the control group, the test weight was 737 g/L, which contributed to an increase in the 1000-grain weight to 42.8 g (Table 5). With a gradual increase in fertiliser doses and the use of growth-stimulating products, the test weight increased to 763 g/L, and the 1000-grain weight to 45.4 g. The best results were observed in the treatment with Background + BioZern + Medax Top + Turbo + $MgSO_4$ compared to the control. In this treatment, the test weight was 766 g/L, and the 1000-grain weight was 45.5 g.

***Table 4**. Influence of fertilisation on the spike productivity of winter wheat*

Variant number	Number of spikelets per ear	Number of grains per ear	Ear weight, g	Grain weight per ear, g
1	11.0	12.0	4.0	3.15
2	15.1	15.6	4.5	3.8
3	15.9	16.8	5.7	4.1
4	16.2	17.1	5.8	4.0
$LSD_{0.05}$	0.01	0.01	0.02	0.01

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

***Table 5**. Physical indicators of winter wheat grain quality*

Variant number	Test weight, g/L	1000-grain weight, g	Vitreosity,%	Mass fraction of protein content, %
1	737	42.8	50	15.6
2	763	45.4	50	14.2
3	765	46.3	50	14.0
4	766	45.5	50	14.1

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

The vitreosity index was not influenced by fertilisation and remained at 50% across all treatments. This corresponds to the first-class grain according to the quality indicators of soft wheat grain. According to the conducted studies, the falling number ranged from 302 to 305 seconds across all treatments, which is an optimal indicator for winter wheat (Table 6). According to DSTU 3768:2019 (2019), the falling number for soft wheat ranges from 180 to 220 seconds depending on the class (the higher the class, the higher the falling number). For the bread-baking process, flour with a falling number of 250 seconds is most suitable. If the falling number exceeds 350 seconds, it means that the flour needs to be supplemented with some type of amylolytic enzyme or malt.

Analysing the combined data on wheat quality indicators across the fertilisation treatments, the treatment with Background + BioZern 30 + Medax Top + Turbo + $MgSO_4$ was the best across all studied parameters. The worst treatment was the background fertilisation, where the grain quality was classified as second-class grain. In all other treatments, the grain was classified as firstclass grain. The analysis revealed a pattern: as the protein content increased, the mass fraction crude gluten content also increased. The highest gluten content was observed in the control sample (32.9). However, an increase in gluten and protein content can negatively impact the baking properties of flour. Therefore, the treatment with Background + BioZern + Medax Top + Turbo + $MgSO_4$ was considered the best, as it had a gluten content of 28.8.

***Table 6**. Physical indicators of winter wheat grain quality*

Variant number	Mass fraction of crude gluten	Gluten quality: units of the gluten strain meter instrument	Falling number, s
1	32.9	82 II	302
2	29.0	75 I	302
3	29.7	69 I	303
4	28.8	73 I	305

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

Considering that the 1000-grain weight increased by 2.0-2.5 grams in the experimental treatments compared to the control, this was undoubtedly the main factor contributing to the increased winter wheat grain yield with the use of PGRs. In the control treatment, the background fertilisation provided a grain yield of 6.8 t/ha. The additional application of Medax Top + Turbo + $MgSO_4$ increased the yield to 8.23 t/ha (a 1.43 t/ha increase). The application of BioZern + $MgSO_4$ yielded 6.68 t/ha (a 1.88 t/ha increase) compared to the control. The application of BioZern + Medax Top + Turbo + $MgSO_4$ resulted in the highest yield of 9.0 t/ha (a 2.2 t/ha increase or 32.3% more than the control) (Fig. 2). It should be noted that all treatments with PGRs resulted in significant yield increases.

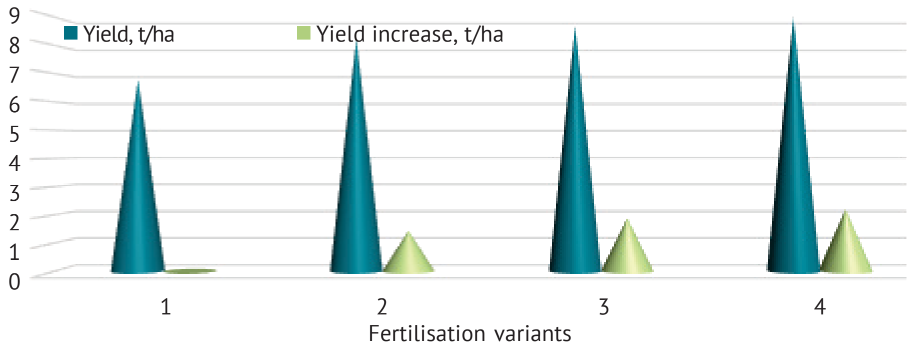

***Figure 2**. Winter wheat yield with the application of growth-stimulating products, 2020-2022*

***Note:** $LSD_{0.05}$ for yield – 0.36, for yield increase – 0.27*

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

The substantial increase in winter wheat yield with the use of PGRs, at relatively low additional costs, indicates the economic and agricultural efficiency of using PGRs in winter wheat crops in the Forest-Steppe region of Ukraine. However, there are publications that express scepticism and negativity regarding PGRs in the formation of grain productivity, not only in winter wheat but also in other cereal crops. Some researchers believe that most regulators do accelerate and enhance certain biochemical reactions in plant organisms (Zaiets & Onufran, 2021). However, such changes are usually unstable and short-lived. Enhancing one or two, even very important, biochemical reactions lead to a disruption of homeostasis, i.e., the stability of the organism, but soon the plant begins to quickly restore it. Hence, the effect of using this type of stimulant often does not exceed 10%. The complexity of using growth stimulants in agricultural production lies in the fact that the effectiveness of many of them can be limited by the peculiarities of the regulatory processes of plant growth and development at different stages of their ontogenesis. This is because the action of stimulants in ultra-low concentrations (e.g., hormones or other active compounds) can be compensated by other mechanisms in plants or by external factors, such as environmental conditions and nutrient availability (Hamoda, 2024).

The Ukrainian agricultural market is under pressure to reduce fertiliser costs, leading to an intensive search for alternatives to expensive mineral fertilisers. Physiologically active substances and preparations are gaining particular attention (Kraus *et al.,* 2021). Furthermore, unstable weather conditions, characteristic of the Forest-Steppe zone of Ukraine, which are approaching those of the Steppe zone, hinder the proper return from mineral fertilisers. Therefore, it is advisable to use various preparations to reduce stress on plants and increase the efficiency of using nutrients from mineral fertilisers, especially those that simultaneously increase yield and grain quality (Amjad Bashir *et al.,* 2021).

Effective cultivation of high-quality winter wheat varieties requires a sufficient micronutrient supply, which acts as a stimulant for macronutrients, particularly nitrogen. Winter wheat's sensitivity to micronutrient deficiencies in the soil, mainly copper and manganese, is higher than in other crops (Radzikowska-Kujawska *et al.,* 2022). The availability of micronutrients is limited by soil characteristics and no-till fertilisation systems. Therefore, foliar application of micronutrients appears to be more effective than soil application and is becoming increasingly popular. When plants were foliar-fed with "ROSTOK" Macro (2 L/ha) + "ROSTOK" Copper (1 L/ha), the number of grains per ear increased by 3.3-5.3 grains, the grain weight per ear increased by 0.22-0.33 g, and the 1000-grain weight increased by 3.1-5.0 g. Winter wheat plants developed well throughout the growing season, resulting in a yield that exceeded the control by 0.36 t/ha. The use of this type of preparation with manganese increased the grain yield by 0.45 t/ha, which is also significantly less than that obtained with the BioZern + Medax Top + Turbo + $MgSO_4$ treatment. The authors indicate that foliar feeding also contributed to an increase in technological indicators (vitreosity, protein content, gluten quantity and quality) and an improvement in the quality class of winter wheat grain (Yamkovy *et al.,* 2021)

Research on the effect of pre-sowing treatment of winter wheat seeds on biometric indicators of seedlings notes a positive effect from the biopreparation Azotofit at a dose of 0.5 L/t, which is prepared based on nitrogen-fixing bacteria *Azotobacter chroococcum* (Korkhova *et al.,* 2022). The application of micronutrients in winter wheat fertilisation allows for improved grain quality, especially when used in conjunction with foliar nitrogen fertilisation. In this case, the protein content can increase by 0.7%, and its amino acid composition is significantly improved (Zhilyak *et al.,* 2024).

Various growth stimulants are widely used in crop production, contributing to plant resistance to diseases and adverse environmental factors, affecting seedling uniformity, increasing the flag leaf area, and enhancing nitrogen uptake by plants. Their use in combination with plant protection products allows for reduced production costs and increased yield by 0.3-0.72 t/ha. Spraying crops with Emistim C, Agrostimulin, and Triman at a dose of 0.005 L/ha, or Vermistim (9 L/ha) during the spring tillering phase, increases plant resistance to septoria by 2.3-7.1%, thus increasing grain yield (Nepran *et al.,* 2021). High effectiveness of fumar was established at the level of 9-36% – a preparation that contains the active substance dimethyl ether of aminofumaric acid, which acts to activate the biosynthesis of all the most important phytohormones for crop growth in various cereal crops (Garcia-Molina *et al.,* 2021). The inclusion of humic stimulants in tank mixtures with seed dressings ensured an increase in winter wheat yield relative to the control variant for the Vyshyvanka, Pryvablyva, Obriad, Trudivnytsia Myronivska varieties by 0.88-1.32 t/ha (Gangur *et al.,* 2020)

Therefore, comparing the results of this study with the articles of other authors confirms the effectiveness of using PGRs in the cultivation of winter wheat in the Forest-Steppe region of Ukraine. The use of PGRs together with micronutrients can increase crop yields, reduce costs, and improve grain quality, which is important for food security and economic development of the country.

CONCLUSIONS

The conducted research has shown that under the conditions of the Left-Bank Forest-Steppe of Ukraine, on a sufficiently high agricultural background, the use of plant growth regulators ensures better development of the studied crop, high grain quality indicators, and an increase in yield to 9.0 t/ha, which is 32.3% higher than the control. The best indicators for 1000-grain weight, test weight, protein content, and gluten content were obtained with the treatment: Background + BioZern + Medax Top + Turbo + $MgSO_4$. This fertilisation regime resulted in first-class quality grain with optimal baking properties. The results of the field studies indicate the feasibility and effectiveness of using PGRs in combination with other types of agrochemicals in winter wheat cultivation. The treatment Background + BioZern 30 + Medax Top + Turbo + $MgSO_4$ provided the best results across all studied indicators and ensured first-class grain. In contrast, the treatment with background fertilisation had the lowest quality indicators, and the resulting grain was classified as second-class.

The study found a direct correlation between protein and crude gluten content. As protein content increased, so did crude gluten content, reaching 32.9% in the control sample. According to the research, excessive protein and gluten content negatively affect the baking properties of flour. The treatment with Background + BioZern + Medax Top + Turbo + $MgSO_4$ was deemed optimal, with a crude gluten content of 28.8%. Plant growth regulators increased the 1000-grain weight by 2.0-2.5 g compared to the control, contributing to higher yields. The application of Medax Top + Turbo + $MgSO_4$ increased the yield to 8.23 t/ha, 1.43 t/ha more than the control. The highest yield of 9.0 t/ha, which was 2.2 t/ha (32.3%) higher than the control, was achieved with the BioZern + Medax Top + Turbo + $MgSO_4$ treatment.

All treatments using PGRs demonstrated statistically significant yield increases. These results align with studies highlighting the importance of balanced fertilisation and growth regulator application for improving the quality and yield of winter wheat. Specifically, foliar feeding with complex fertilisers contributes to an increase in the number of grains per ear, spikelets per ear, ear weight, and 1000-grain weight, positively impacting overall crop productivity. Optimising fertilisation systems and implementing appropriate agricultural practices are key to achieving highquality and high-yielding winter wheat. Given the prospect of introducing new forms of agrochemicals, such as plant growth stimulants, it is important to continue in-depth research on their effectiveness in various soil and climatic conditions.

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CONFLICT OF INTEREST

None.

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Ефективність застосування стимуляторів росту рослин по пшениці озимій в умовах Лівобережного лісостепу України

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Анотація. Мета досліджень - визначення ефективності застосування стимуляторів росту рослин на урожайність та показники якості зерна пшениці озимої на темно-сірому опідзоленому на лесовидних суглинках ґрунті. У даній роботі на фоні стандартного удобрення досліджено вплив обробки насіння пшениці озимої добривом для стимуляції росту та розвитку зернових культур БіоЗерн, регулятору росту МедаксТоп, мікродобрива Turbo та $MgSO_4$ у посівах пшениці озимої в умовах Київській області, ТОВ «Біотех ЛТД». Обробка насіння БіоЗерн у поєднанні з препаратами МедаксТоп+Турбо+$MgSO_4$ забезпечило врожайність на рівні 9,0 т/га при 6,8 т/га на контролі. Підвищення врожайності за застосування стимуляторів росту рослин (СРР) та мікродобрив склало від 1,34 т/га до 2,2 т/га. Застосування СРР в поєднанні із $MgSO_4$ сприяло покращенню показників росту і розвитку рослин. Встановлено збільшення на 8-10 % кількості рослин у посівах, більш як на 20 % кількості продуктивних стебел на одиниці площі та коефіцієнту кущіння відповідно. Застосування СРР також суттєво покращило основні показники, які характеризують продуктивність колоса пшениці. Збільшилась кількість колосків, кількість зерен, вага зерен колосу досліджуваної культури та маса зерна в колосі. Ріст склав від 25 до 50 % відносно контролю. Важливим практичним результатом дослідження є покращення більшості показників, які характеризують якість продукції. Окрім збільшення величини маси 1000 зерен, зросла натура зерна з 737 г/л на контрольному варіанті до 763-766 г/л на варіантах внесення СРР. При однаковому значенні скловидності на усіх варіантах, СРР дещо знизили вміст білку в зерні з 15,6 % на контролі до 14,0-14,2 % на варіантах внесення СРР. Отримані результати доводять високу ефективність застосування обробки насіння пшениці озимої препаратом БіоЗерн, внесення регулятору росту МедаксТоп, мікродобрива Turbo та $MgSO_4$ у посівах культури в умовах Київській області і можуть бути рекомендовані при її вирощуванні

Ключові слова: регулятори росту рослин; якість зерна; біометричні показники росту; врожайність; продуктивність

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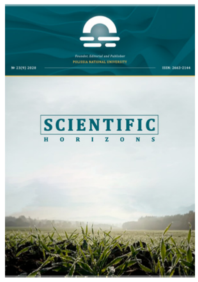

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Ecological stability, plasticity, and adaptability of asparagus pea (*Tetragonolobus purpureus* Moench) under different sowing dates

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Abstract. This study aimed to examine the response of asparagus pea grown under different sowing dates to abiotic factors characteristic of the Right-Bank Forest-Steppe of Ukraine, considering their impact on marketable bean yield. The research employed a comprehensive approach, incorporating field experiments and statistical analysis of the obtained data. Asparagus pea yield was largely dependent on sowing dates and weather conditions. The average yield of pods ranged from 2.0 to 6.4 t/ha, depending

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on the sowing date. The lowest amplitude of yield fluctuations (0.2-0.3 t/ha) was observed for sowing in the third ten-day period of April and the first ten-day period of May, whereas for other sowing dates, this indicator was significantly higher (up to 0.5-0.6 t/ha). It was established that yield positively correlated with temperature ($r = 0.88$) and precipitation ($r = 0.66$). An increase of these climatic factors by 10 units contributed to a yield increase of 0.703-0.877 t/ha. Plants sown in the third ten-day period of April and the first ten-day period of May exhibited the lowest regression coefficient b_i (0.77 and 0.40, respectively), indicating lower sensitivity to changes in growing conditions. In contrast, sowing in the third ten-day period of May and the first ten-day period of June resulted in greater sensitivity ($b_i = 1.55$ and 1.28, respectively). The optimal sowing dates were the first ten-day period of May and the third ten-day period of April, as they ensured the highest productivity and stability, along with a high content of dry matter (20.3-25.4%), sugars (5.56.8%), vitamin C (49.5-51.8 mg/100 g), and total nitrogen (3.5-3.7%). The poorest indicators were recorded for later sowing dates

Keywords: legumes; productivity; adaptive trait parameters; limiting factors; correlation

INTRODUCTION

Given the rapid growth of the global population, food and nutritional security has become one of the most pressing global challenges. Addressing this issue depends on increasing the productivity and resilience of agricultural crops. This requires a thorough understanding of how plants adapt to adverse conditions and the development of modern cultivation approaches. According to the Food and Agriculture Organization of the United Nations (FAO, 2023), approximately 730 million people (one in eleven globally) suffered from hunger in 2023. More than a third of the world's population cannot afford a healthy diet, particularly in low-income countries. The situation is projected to worsen, with hunger potentially affecting 582 million people by 2030, primarily in Africa.

The 20th century, with an average air temperature increase of approximately 0.6°C, has been the warmest of the last millennium. According to predictions by M. Muluneh (2021), future temperature increases are likely to be even greater, with expected rises of 0.1 to 2°C per decade. Specifically, global warming has numerous adverse effects on agricultural crops, including sharp temperature fluctuations, disrupted rainfall patterns, and the occurrence of floods and droughts, which in turn lead to outbreaks of numerous pests and diseases. These factors ultimately have a negative impact on crop production, reducing both the quality and quantity of agricultural output. As a result of climate change and rapid population growth, global food demand is significantly increasing (Zavadska *et al.*, 2021; Munaweera *et al.,* 2022; Natalchuk & RudnykIvashchenko, 2024)

To address this challenge, various approaches are being employed, including plant breeding, genetic engineering, microbial production, innovations in cultivation technologies, and the preservation of plant biodiversity. S. Kalenska (2022) and R. Bepary *et al.* (2023) argue that studying underutilised crops from a food and nutritional security perspective is an economically efficient and reliable method. For example, A. Aboltins *et al.* (2024) emphasise that cultivating underutilised protein-rich legumes is one of several crucial solutions to overcome protein deficiency. One such crop is asparagus pea, which, according to M. Raai *et al.* (2020), exhibits high adaptability to adverse conditions and contains a significant amount of protein.

The consumption of asparagus pea is primarily observed in Southern African and South Asian countries, as well as India and Malaysia. All parts of the asparagus pea, depending on the species, are edible, including the pods (which are eaten raw or pickled, particularly in India), flowers (added to salads and used to enhance the colour of dishes), leaves (prepared and consumed like spinach), tubers (eaten raw or cooked, mainly in Ghana, Papua New Guinea, Burma, Thailand, and Indonesia), and seeds. H. Bassal *et al.* (2020) and A. Mahobia *et al.* (2024) describe various culinary uses of asparagus pea. Immature seeds are used to prepare soups, while mature seeds are eaten roasted or dried and ground into flour. Oil can also be extracted from the seeds and used in cooking, for example, in the preparation of fried dishes.

As noted by A. Bhadmus *et al.* (2023), due to significant variations in yield and other agromorphological characteristics among asparagus pea samples, there is limited information on its adaptability to diverse soil and climatic conditions. Simultaneously, K. Laosatit *et al.* (2022) emphasise the importance of studying the genetic diversity of existing varieties across different regions to ensure stable yields and enhance cultivation efficiency.

This research was driven by the desire to explore how the agronomic practice of altering sowing dates influences the adaptability of asparagus pea to the abiotic conditions of the Right-Bank Forest-Steppe region of Ukraine, and how this, in turn, is reflected in plant productivity.

MATERIALS AND METHODS

Field studies were conducted over three years (2014-2016) at the "Fruit and Vegetable Garden" educational laboratory of the National University of Life and Environmental Sciences of Ukraine (NULES of Ukraine) in the Kyiv Region. The soil used for the studies is classified as dark grey, medium podzolic, and light loamy.

The acidity level of this soil is near neutral (pH 6.1). The humus layer reaches a depth of 24 to 28 centimetres. However, the organic matter (humus) content in this layer is relatively low, ranging from 1.5 to 2.2%. Additionally, the soil is characterised by a medium content of nitrogen (26-38 mg/kg), phosphorus (43-61 mg/kg), and potassium (28-34 mg/kg).

The experiment was replicated three times. Asparagus pea seeds were sown at four different times: 24 April (third ten-day period of April – control), 8 May (first ten-day period of May), 23 May (third ten-day period of May), and 5 June (first ten-day period of June). Seeds were sown at a spacing of 45×15 cm and a depth of 2-3 cm. The method for assessing the general and specific adaptive capacity of samples is based on studying *n* samples in *m* environments (locations, years) and *c* replications (Tyshchenko *et al*., 2023):

$$x_{ikr} = U + V_i + d_k + (Vd)_{ik} + e_{ikr}, \quad (1)$$

where x_{ikr} is the phenotypic value of trait *i* of the genotype when grown in environment *k* and replication *r*; *U* is the overall mean of the entire set of phenotypes; V_i is the effect of genotype *i*; d_k is the effect of environment *k*; $(Vd)_{ik}$ is the interaction effect of genotype *i* with environment *k*; e_{ikr} is the effect caused by random factors and associated with phenotype *ikr*.

Within this analysis, a series of constraints were imposed on the model elements:

$$\sum_i v_i = \sum_k d_k = \sum_k (vd)_{ik} = \sum_k (vd)_{ik} = \sum e_{ik} = 0. \quad (2)$$

Initially, dispersion factor analysis was employed to analyse the indicators of general adaptive capacity and sample stability.

The *F*-criterion was used to establish the significance of the influence of different samples, environments, and their interaction. In this case, the corresponding mean squares were compared with the mean square of random deviations *Me*:

For samples

$$F_{[n\text{-}1.nm(c\text{-}1)]} = \frac{M_n}{M_e}. \quad (3)$$

For environments

$$F_{[n\text{-}1.nm(c\text{-}1)]} = \frac{M_m}{M_e}. \quad (4)$$

For the interaction of samples and environments

$$F_{[n\text{-}1.nm(c\text{-}1)]} = \frac{M_{nm}}{M_e}. \quad (5)$$

When assessing the significance of individual differences, the standard error of the mean difference *Sd* was calculated:

For means

$$S_d = \sqrt{\frac{2Me}{c}}. \quad (6)$$

For samples

$$S_d = \sqrt{\frac{2Me}{mc}}. \quad (7)$$

For environments

$$S_d = \sqrt{\frac{2Me}{nc}}. \quad (8)$$

To compare individual means, samples, and environments, the least significant difference for the 5% significance level was found by multiplying the t_{05} criterion by the corresponding standard error of the mean difference *Sd*. The next stage of evaluation involved determining the general (GACi) and specific adaptive capacity (SACi) and stability of the samples. The effect of the general adaptive capacity of the sample GACi was *Vi*. In this case, the deviation from the sum *U*+*Vi* is the effect of the specific adaptive capacity of the variety in the *R* environment – SAC_{iR}. This effect includes a linear (effect of the *R* environment) and a non-linear part (effect of the interaction $(Vd)_{iR}$).

The specific adaptive capacity indicator was calculated using the following formula:

$$\sigma^2\ SAC_i = \frac{1}{m-1} * \sum_R (d_R + Vd_{iR})^2 - \frac{m-1}{m} * \sigma^2, \quad (9)$$

$$\sigma\ SAC_i = \sqrt{\sigma^2\ SAC_i}. \quad (10)$$

The relative stability index S_{gi} was used to compare the variability of different traits in the studied samples:

$$S_{gi} = \frac{\sigma_{SAC_i}}{U+GAC} * 100\ \%. \quad (11)$$

The regression coefficient b_i was determined using the formula:

$$b_i = \frac{\sum x_{iR} * d_R}{\sum_R d_R^2}. \quad (12)$$

The breeding value of the genotype (BVG_i) was used to select samples that combined productivity and stability:

$$BVG_i = U + GAC_i - p\sigma_{SAC_i}). \quad (13)$$

The calculation of the sum of effective air temperatures was carried out using the formula:

$$\sum t_{eff} = (t_{avg} - B) * n. \quad (14)$$

where Σt_{eff} is the sum of effective air temperatures over the period, °C; t_{avg} is the average air temperature for the period, °C; *B* is the value of the biological minimum, which in this analysis is taken to be 10°C; *n* is the number of days in this period.

The research results were processed using the *Statistica* 13.1 software (StatSoft, Inc., Tulsa, Oklahoma, USA). Tukey's test was also used to determine differences between sowing dates, with differences considered significant at $p < 0.05$ (accounting for the Bonferroni correction). To establish the direction and degree of correlation between the studied parameters, the correlation coefficient was calculated. The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

The yield of marketable pods of asparagus pea, when sown in the third ten-day period of April (control), the first ten-day period of May, and the first ten-day period of June, shows a non-normal distribution, although without any outliers. The mean, median, and mode are located at different points within the distribution (Fig. 1). The overall yield of marketable pods of asparagus pea when sown in the third ten-day period of May indicates a normal distribution, but with significant deviations: one case falls outside the lower line of the diagram. The mean, median, and mode of the overall yield are located almost at the same point, but do not quite, resemble a normal curve.

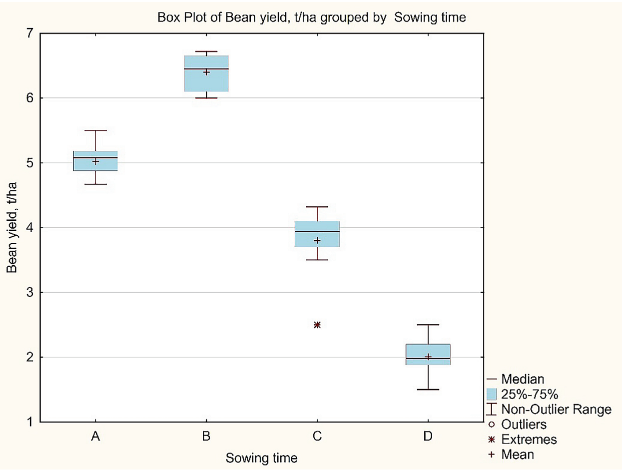

***Figure 1**. Box plot illustrating the yield of marketable pods of asparagus pea*

***Note:** the x-axis represents the sowing date: A) the third ten-day period of April (control); B) the first ten-day period of May; C) the third ten-day period of May; D) the first ten-day period of June (2014-2016)*

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

The average yield of pods of asparagus pea varied across different sowing dates, ranging from the lowest of 2.0 t/ha in the first ten-day period of June to the highest of 6.4 t/ha in the first ten-day period of May. The smallest amplitude of yield fluctuations over the years of research was observed in the first ten-day period of May (0.2 t/ha), followed by the third ten-day period of April (control) (0.3 t/ha), indicating their stable productivity across all studied years. In contrast, the largest amplitude of yield fluctuations was recorded in the third ten-day period of May (0.6 t/ha), followed by the first ten-day period of June (0.5 t/ha), indicating their variable yield and high sensitivity to changes in environmental conditions.

A strong positive linear correlation ($r = 0.88$) was found between the duration of the asparagus pea growing season and the yield of pods (Fig. 2). Based on the regression equations, it was established that an increase in the duration of the asparagus pea growing season by 5 days led to an increase in the yield of pods by 1.54 t/ha.

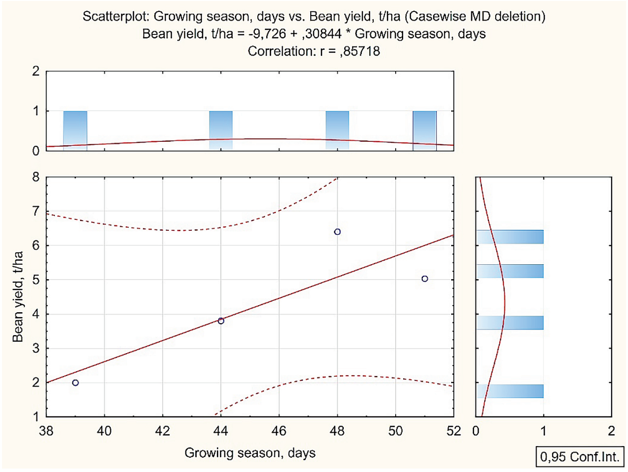

***Figure 2**. Analysis of the relationship between the yield of marketable green pods of asparagus pea at different sowing dates and the duration of the growing season, mm (2014-2016)*

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

During the 2014-2016 asparagus pea growing seasons, the sum of effective air temperatures (>10°C) ranged from 450.3 to 500.8°C, and the total rainfall ranged from 49.6 to 78 mm. A direct moderate correlation exists between the yield of marketable pods and the sum of effective temperatures ($r = 0.88$) and the sum of rainfall ($r = 0.66$) (Fig. 3).

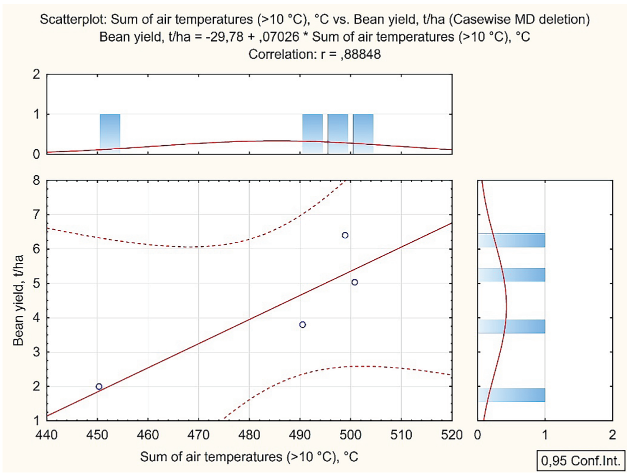

***Figure 3**. Analysis of the relationship between the yield of marketable pods of asparagus pea at different sowing dates and the sum of temperatures above 10°C during the growing season, °C (2014-2016)*

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

By substituting the values into the regression equations presented, it is possible to predict the yield of asparagus pea (Y) based on data on the sum of effective air temperatures (>10°C) and rainfall (X) during the growing season. An increase in the average sum of effective air temperatures during the growing season by every 10°C led to an increase in the yield of pods of asparagus pea by 0.703 t/ha. Simultaneously, every additional 10 mm of rainfall contributed to an increase in the yield of this crop by 0.877 t/ha (Fig. 4).

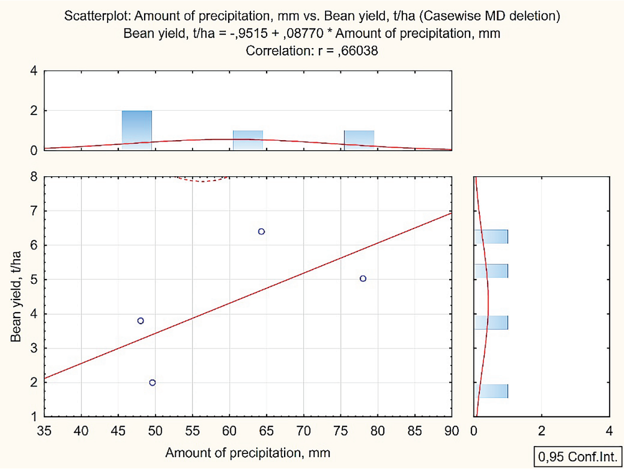

Figure 4*. Analysis of the relationship between the yield of marketable green pods of asparagus pea at different sowing dates and the sum of rainfall during the growing season, mm (2014-2016)*

Source: *developed by the authors*

According to the coefficient of variation in a pod of asparagus pea yield, it was established that the variation for sowing in the third ten-day period of April (control) (V = 3.03%) and the first ten-day period of May (V = 2.34%) is not significant, as the coefficient of variation is less than 10%. However, for sowing in the third ten-day period of May (V = 7.89%) and the first ten-day period of June (V = 13.23%), moderate variability was recorded, meaning the coefficient of variation is higher than 10% but less than 20% (Table 1). The term "adaptive capacity" is used to describe the ability of a genotype to maintain the phenotypic expression of a given trait in the presence of certain environmental conditions. The concept of general adaptive capacity is used to characterise the average value of a trait under different environmental conditions. Conversely, specific adaptive capacity represents a deviation from the general adaptive capacity in a specific environment.

The highest general adaptive capacity for asparagus pea productivity was observed when sown in the first ten-day period of May (GAC = 2.09), and the lowest in the first ten-day period of June (GAC = -2.31). However, in terms of specific adaptive capacity, the third ten-day period of May stood out (SAC = 0.079). All studied sowing dates of asparagus pea were characterised by variability in the stability of the studied trait (S_{gi} from 0.18 to 2.96) depending on growing conditions. However, overall, they exhibited high stability (S_{gi} < 25%) in pod yield.

Table 1*. Parameters of adaptive capacity and stability of asparagus pea at different sowing dates (2014-2016)*

Indicator		Sowing dates			
		Third ten-day period of April (control)	**First ten-day period of May**	**Third ten-day period of May**	**First ten-day period of June**
Yield of pods, t/ha	Min	4.9	6.3	3.5	1.8
	Max	5.2	6.5	4.1	2.3
	Range of variation	0.3	0.2	0.6	0.5
	Average	5.0 ± 0.088 [a]	6.4 ± 0.093 [d]	3.8 ± 0.185 [ac]	2.0 ± 0.111 [b]
Coefficient of variation (V), %		3.03	3.03	2.34	7.89
General adaptive capacity (GAC)		0.73	0.73	2.09	-0.51
Specific adaptive capacity (SAC)		0.013	0.013	0.012	0.079
Relative stability (S_{gi}), %		0.25	0.25	0.18	2.09
Plasticity (b_i), %		0.77	0.77	0.40	1.55
Homeostasis (*Hom*)		1.66	1.66	2.73	0.48
Selection value of genotype (SVG_i)		4.57	4.57	5.97	0.91

Note: *different letters (a, b, c, d) indicate values that were significantly different from each other within the same row of the table, according to comparisons using Tukey's test with Bonferroni correction*

Source: *developed by the authors*

The plasticity parameters (regression coefficient b_i) allow for predicting the behaviour of a variety under production conditions. In the asparagus pea cultivation variant sown in the third tenday period of April (control) and the first ten-day period of May, the regression coefficient for green pod yield was found to be less than one, 0.77 and 0.40, respectively. Cultivating the crop at these sowing dates results in a weak response to changes in environmental factors. While this approach may not achieve high yields under intensive farming, it leads to a smaller reduction in productivity under unfavourable conditions compared to sowing dates with a regression coefficient greater than one. Thus, for each 1 t/ha increase in the average yield of asparagus pea, there is only a 0.77 t/ha increase when sown in the third ten-day period of April (control) and a 0.40 t/ha increase when sown in the first ten-day period of May. Among the studied sowing dates, the third ten-day period of May and the first ten-day period of June showed the greatest sensitivity to changes in asparagus pea yield under experimental conditions. With an increase in the average yield of 1 t/ha, the yield when sown in the third ten-day period of May increased by 1.55 t/ha, and in the first tenday period of June, it increased by 1.28 t/ha.

It is known that one of the key indicators of adaptability is the homeostasis (*Hom*) of a genotype, which characterises the ability of an organism to exhibit minimal phenotypic variability when growing conditions change. This implies the ability to mitigate the effects of adverse environmental factors at various stages of plant growth and development. Accordingly, based on this indicator, two sowing dates stand out among the studied ones: the first ten-day period of May (*Hom* = 2.73) and the third ten-day period of April (control) (*Hom* = 1.66). The breeding value of the genotypes was determined to simultaneously select for general adaptive capacity and stability. The variants sown in the first ten-day period of May (BVG_i = 5.9) and the third ten-day period of April (control) (BVG_i = 4.57) demonstrated an optimal combination of high productivity and stable yield. The highest content of dry matter (25.4%) and total sugars (6.8%) in fresh asparagus pea beans was observed when sown in the first ten-day period of May, which is 5.1% and 1.3% higher than the control, respectively (Table 2). When sown in the third ten-day period of May, the dry matter content (20.1%) and total sugars (5.4%) were at the control level. The lowest dry matter content (18.5%) and total sugars (4.7%) were observed in asparagus pea beans when sown in the first ten-day period of June, which is 1.8% and 0.8% lower than the control, respectively. Regarding vitamin C content, a decrease was observed with later sowing dates and the lowest value of 30.3 mg/100g was obtained when sown in the first ten-day period of June, which is 21.5 mg/100 g less than the control. Additionally, the variants sown in the third ten-day period of April (control) and the first ten-day period of May, which accumulated a high vitamin C content (49.551.8 mg/100 g), can be highlighted. At the same time, the total nitrogen content also had the highest value of 3.7% when sown in the third ten-day period of April (control), gradually decreasing to 2.7% when sown in the first ten-day period of June.

***Table 2**. Qualitative assessment of fresh asparagus pea beans at different sowing dates (2014-2016)*

Experimental variant	Dry matter, %	Total sugars, %	Vitamin C, mg/100 g	Total nitrogen, % on air-dried matter
Third ten-day period of April – control	20.3 ± 0.199 ^{a}	5.5 ± 0.053 ^{a}	51.8 ± 0.507 ^{d}	3.7 ± 0.036 ^{d}
First ten-day period of May	25.4 ± 0.248 ^{c}	6.8 ± 0.066 ^{c}	49.5 ± 0.483 ^{c}	3.5 ± 0.034 ^{c}
Third ten-day period of May	20.1 ± 0.206 ^{a}	5.4 ± 0.055 ^{a}	35.7 ± 0.366 ^{b}	3.2 ± 0.032 ^{b}
First ten-day period of June	18.5 ± 0.528 ^{b}	4.7 ± 0.134 ^{b}	30.3 ± 0.866 ^{a}	2.7 ± 0.077 ^{a}

***Note:** different letters (a, b, c, d) indicate values that were significantly different from each other within the same row of the table, according to comparisons using Tukey's test with Bonferroni correction*
***Source:** developed by the authors*

Additionally, plants sown in summer were more severely affected by Fusarium wilt. Their growth and development were slower, and their fruits were smaller and of poorer quality. A direct correlation was established between the duration of the growing season and the biochemical indicators of fresh asparagus pea beans. The strength of the correlations was as follows: a strong correlation between the duration of the growing season and total sugars (r = 0.96), vitamin C (r = 0.99); a moderate correlation with total nitrogen (r = 0.63); and a weak correlation with dry matter (r = 0.53) (Fig. 5).

Based on the regression equations, it was established that an increase in the duration of the asparagus pea growing season by 5 days led to an increase in the dry matter by 1.53%, total sugars by 0.53%, vitamin C by 9.76 mg/100 g and total nitrogen by 0.42%. The best quality was demonstrated by asparagus pea beans sown in the third ten-day period of April and the first ten-day period of May. They contained high levels of dry matter (20.3-25.4%), sugars (5.5-6.8%), vitamin C (49.5-51.8 mg/100 g), and crude protein (3.5-3.7%). The results obtained indicate that the influence of year and genotype was significant for the yield of green beans, and that a better genotype and optimal environmental conditions are key elements in the successful production of asparagus pea. The presented experimental data are consistent with the results of S. Sriwichai *et al.* (2021), in which the genotype-environment interaction had an impact on the yield of *Psophocarpus tetragonolobus* (L.) DC., while samples *W*099 and *W*018 showed the most stable high bean yield, confirming their adaptability to various environmental conditions.

Plant architecture, as noted by X. Zhang *et al.* (2021), is an important factor for optimising crop management and achieving maximum bean yield. V. Kumar & R. Rajalekshmi (2021) emphasise that the hardness of asparagus pea seeds significantly limits their development, affecting germination rates. This is because the longer the seed storage period in cold, dry conditions, necessary for ensuring long-term seed viability during storage, the less its ability to absorb water when sown under optimal germination conditions. According to I. Fedosiy *et al.* (2022) and O. Litvinova *et al.* (2022), a sufficient level of soil moisture is a prerequisite for achieving high field seed germination.

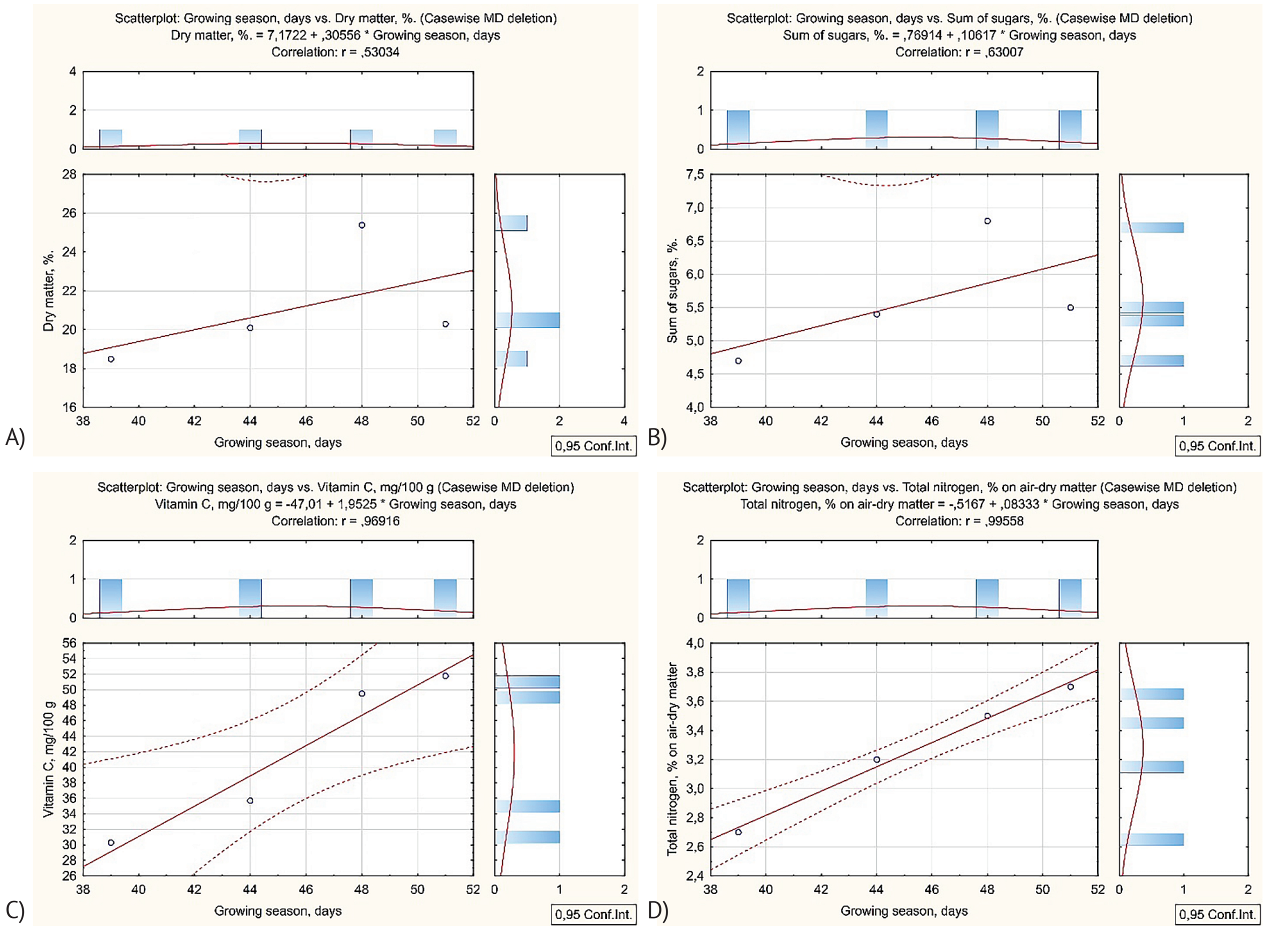

Figure 5*. Analysis of the relationship between the qualitative assessment of fresh asparagus pea beans and sowing dates*

Note: *A) Dry matter, %; B) Total sugars, %; C) Vitamin C, mg/100 g; D) Total nitrogen, % on airdry matter; (average for 2014-2016)*

Source: *developed by the authors*

Research I. Yulianah *et al.* (2020) indicates that in Indonesia, *Psophocarpus tetragonolobus* can be planted during both the rainy and dry seasons, producing beans in small to moderate quantities over several seasons. When *Psophocarpus tetragonolobus* is planted in the rainy season, it tends to produce more leaves rather than flowers and pods. In contrast, in Ukraine, where the climate is more continental, the optimal sowing times are the third ten-day period of April and the first ten-day period of May, when the soil is sufficiently warm. Subsequent sowing in the summer months can be problematic for plants due to pest damage, disease susceptibility, and moisture deficiency. P. Moorthy *et al.* (2022) report that a wide range of lepidopteran insects cause significant damage to flowers, leading to their premature drying and shedding without pod formation.

P. Singh *et al.* (2022) note that the asparagus pea is a short-day plant, with its flowering dependent on the length of daylight or photoperiod. This limits its year-round production, resulting in fluctuations in bean production volumes and prices. To ensure year-round production, as recommended by S. Sriwichai *et al.* (2022), it is advisable to use asparagus pea varieties with insensitive photoperiods. Thus, the significant genetic diversity of asparagus pea allows for the cultivation of plants in various geographical regions.

According to data from I. Bobos *et al.* (2022) and H. Slobodianyk *et al.* (2024), untimely harvesting can lead to a deterioration in crop quality due to adverse environmental conditions, including high temperature, high humidity, rainfall, drought, as well as damage from birds and animals, and infection by diseases and pests. Therefore, it is important to assess pod development and ripening by monitoring physical and physiological indicators. In a study by S. Sakthivel *et al.* (2020), three main stages of pod development were observed: rapid growth (5-30 days after the onset of pod formation, 57.9% moisture), slowed growth (30-50 days, 28.9% moisture), and ripening (50-60 days, 18.7% moisture). The fresh weight of the pods reached its maximum (27.84 g/pod) on the 30^{th} day, and a positive correlation with pod size was also noted. The timing of asparagus pea pod harvesting varies significantly: in Myanmar, it takes place in December-January (Maw *et al.,* 2023), and Italy, in June (Vargiu, 2021), whereas in Ukraine, it occurs in June-July.

Results published by G. Eagleton (2022) demonstrate that under Australian conditions, the *MYO*-01 variety produced an average of 93 mature pods per plant when sown on 5 October, 68 pods when sown on 3 November, and 44 pods when sown on 24 November. At the same time, the *CHIMBU* and *MYAN*-05 varieties had a significant number of full-sized green pods, but a negligible number of mature seed beans. Similarly, the *WAM*-07 variety had almost no mature beans or full-sized green pods by the end of the study on 30 June. The results of current research also revealed a significant difference between the influence of sowing dates and the number of pods per plant, which directly affected the overall yield. Climate change, accompanied by rising temperatures and droughts, requires new approaches from agriculture. The study of asparagus pea has shown that sowing dates significantly affect plant yield and adaptability. These data provide a basis for developing cultivation recommendations that take into account the characteristics of different varieties and the climatic conditions of the region.

CONCLUSIONS

The global food crisis, exacerbated by climate change, necessitates the search for sustainable solutions. Scientific research has confirmed that asparagus pea, due to its ability to adapt to changing conditions and its high nutritional value, can become an important component in ensuring food security. The yield of asparagus pea at different sowing dates significantly depended on climatic conditions ($r = 0.88$ with the sum of effective temperatures; $r = 0.66$ with the sum of rainfall). Sowing asparagus pea from the third ten-day period of April to the first ten-day period of May ensures an optimal combination of high homeostasis (*Hom* = 1.66-2.73) and breeding value of the genotype (BVG_i = 4.57-5.9) and productivity (5.0-6.4 t/ha). Late sowing dates, especially under conditions of insufficient moisture and high temperatures, led to a decrease in yield.

Sowing in the first ten-day period of May provided the highest content of dry matter (25.4%) and sugars (6.8%), while the lowest indicators were recorded when sowing in the first tenday period of June (18.5% and 4.7%, respectively). Vitamin C content ranged from 30.3 to 51.8 mg/100 g, decreasing with later sowing dates. Similar to other biochemical indicators, the highest amount of nitrogen was observed in pods sown in the third ten-day period of April (3.7%), and the lowest in the first ten-day period of June (2.7%). A strong positive correlation was found between the duration of the growing season and the content of vitamin C ($r = 0.99$), sugars ($r = 0.96$), dry matter ($r = 0.63$), and total nitrogen ($r = 0.55$) in asparagus pea beans. The regression analysis model made it possible to quantify the influence of the growing season duration on the biochemical composition of the crop's beans. Thus, every additional five days of vegetation increases the nitrogen content by 1.53%, dry matter by 0.53%, sugars by 9.76%, and vitamin C by 0.42 mg/100 g in asparagus pea beans. The combination of breeding, genetic engineering, and agricultural technologies, while increasing the added value of production, creates significant challenges and opportunities for intensifying the cultivation of asparagus pea in different ecological conditions, which requires further scientific research.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Екологічна стабільність, пластичність та адаптивність тетрагонолобуса (*Tetragonolobus purpureus* Moench) за різних термінів сівби

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Анотація. Метою даного дослідження було вивчення реакції рослин тетрагонолобуса, вирощених за різних строків сівби, на абіотичні фактори, характерні для Правобережного Лісостепу України, з урахуванням їхнього впливу на врожайність товарних бобів. Дослідження проводилося за допомогою комплексного підходу, який включає польові експерименти та статистичний аналіз отриманих даних. Врожайність тетрагонолобуса значною мірою залежить від термінів сівби та погодних умов. Середня врожайність бобів-лопаток змінювалася від 2,0 до 6,4 т/га залежно від терміну сівби. Найменшу амплітуду коливань врожайності (0,2-0,3 т/га) показала сівба в III декаді квітня та I декаді травня, тоді як для інших строків цей показник був значно вищим (до 0,5-0,6 т/га). Встановлено, що врожайність позитивно корелює з температурою (*r* = 0,88) та кількістю опадів (*r* = 0,66). Збільшення цих кліматичних факторів на 10 одиниць сприяло зростанню врожайності на 0,703-0,877 т/га. Рослини, висіяні в III декаді квітня та I декаді травня, мали найнижчий коефіцієнт регресії bi (0,77 та 0,40 відповідно), що свідчить про їхню меншу чутливість до змін умов вирощування. Натомість, сівба в III декаді травня та I декаді червня виявилася чутливішою (b_i = 1,55 та 1,28 відповідно). Оптимальними строками сівби є I декада травня та III декада квітня, адже вони забезпечили найвищу продуктивність і стабільність, а також високий вміст сухої речовини (20,3-25,4 %), цукрів (5,5-6,8 %), вітаміну C (49,5-51,8 мг/100 г) та загального азоту (3,5-3,7 %). Найгірші показники зафіксовано при пізніших строках сівби

Ключові слова: бобові; продуктивність; параметри адаптивних ознак; обмежуючі фактори; кореляція

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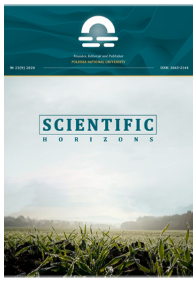

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Assessment of the economic efficiency of growing winter wheat using the resource-saving Mzuri-ProTil technology

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Abstract. The aim of the study was to investigate the economic efficiency of winter wheat cultivation of the Perlyna Odeska variety using the resource-saving Mzuri-ProTil technology. The results of the analysis showed that this technology has a significant impact on the yield and economic performance of production. In 2022-2024, research conducted at the Training and Research Centre of Mykolaiv National Agrarian University showed that the use of Mzuri-ProTil technology results in higher yields compared to conventional technology. In 2023, the yield of the classical technology was 6.30 t/ha, while the Mzuri-ProTil technology yielded 7.10 t/ha, which is 0.80 t/ha more. In 2024, the yield of the classical technology decreased to 4.17 t/ha, while the yield of the Mzuri-ProTil technology was 4.78 t/ha (+0.61 t/ha). This advantage demonstrates the more efficient use of resources and the ability of Mzuri-ProTil technology to deliver

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better results even in adverse weather conditions. The costs of Mzuri-ProTil technology in 2022-2023 amounted to 22373.70 UAH/ha, and in 2023-2024 – 1,5811.18 UAH/ha, which was lower compared to the costs of conventional technology (23,637.22 and 16,541.09 UAH/ha, respectively), due to optimised use of resources and reduced number of operations on the field. However, the increase in yields compensated for the additional costs, which helped to improve the overall economic efficiency of production. To assess profitability, we calculated the cost of production per unit of output. The cost of growing one tonne of wheat using the Mzuri-ProTil technology, taking into account costs and yields, was lower than using the classical technology due to higher yields, which reduced unit costs. Thus, the economic analysis shows the benefits of using Mzuri-ProTil technology, as it provides higher productivity and more products per hectare, which results in higher production revenues, even with higher input and machinery costs. Mzuri-ProTil technology is economically viable for farmers seeking to improve wheat production efficiency in the face of climate change and limited resources

Keywords: agriculture; profitability; resource-saving technologies; sustainable development; yield

INTRODUCTION

Agriculture is one of the main sectors of Ukraine's economy, which meets not only the country's domestic needs but also its export potential. Winter wheat, which remains one of the main grain crops due to its high productivity and stable demand on both domestic and international markets, plays a particularly important role in the agricultural sector. The issues related to optimisation of the export potential of cereals in the context of climate change were covered by K. Vasylkovska *et al.* (2021). In their study, they emphasise the need to introduce innovative technologies that can increase the efficiency of grain production and ensure Ukraine's competitiveness in the global market. The relevance of the study is due to the need to assess the economic efficiency of the latest wheat growing technologies that can help increase the productivity and sustainability of agricultural production in Ukraine. Climate change has a significant impact on agriculture, in particular on wheat growing, which requires adaptation of agricultural technologies to new conditions (Dolia & Shevchenko, 2024). In the context of global climate change, an important strategy is to introduce renewable energy sources that reduce dependence on fossil fuels and reduce greenhouse gas emissions. The use of technologies such as solar panels, wind turbines or biogas plants can not only ensure environmental sustainability but also reduce energy costs. According to a study by M.M. Rahman *et al.* (2022), the use of renewable energy sources in the agricultural sector can reduce the cost of machinery and soil cultivation, which in turn increases the economic efficiency of agricultural production. This is especially important in a context where efficient use of resources is key to ensuring sustainable agricultural development in the face of climate change.

The principle of operation of the Mzuri Pro-Til seed drill is based on precise strip tillage. A cutter bar on the front of the machine cuts through plant residues, after which a special tine loosens the seedbed, cleans it of residues and simultaneously applies fertiliser to the set depth. The press wheel compacts the soil to ensure optimum contact between the seed and the moist soil layer. Each furrow is processed separately, allowing for precise adjustment of the sowing depth and uniform seed distribution. According to a study by I. Koženiauskas (2021), such strip-till has a positive effect on soil structure, reducing energy costs for cultivation and reducing the negative impact on the environment, which confirms the effectiveness of this technology in increasing the productivity and sustainability of agricultural production. However, despite the widespread availability of various methods and technologies aimed at improving agricultural production efficiency, there is still a lack of sufficient research comprehensively comparing the cost-effectiveness of the latest technologies in wheat production. In particular, this applies to Mzuri-ProTil technology, which demonstrates significant potential for both increasing yields and reducing soil impact.

Current research tends to focus on agronomic aspects, including the impact of technologies on crop productivity, soil physicochemical properties and environmental sustainability. For example, I. Jaskulska *et al.* (2022) investigated the effectiveness of strip-till technology in pea and barley cultivation as a component of intercropping. Although their study confirmed the benefits of this technology for soil conservation and increased production sustainability, the issue of economic feasibility of its application was not addressed. It is known that traditional tillage and sowing technologies significantly reduce soil fertility and have a negative impact on the environment (Shakoor *et al.*, 2020). Frequent passes of machinery across the field lead to soil compaction, reduced aeration and water permeability, which ultimately negatively affects yields. At the same time, the latest technologies, such as Mzuri-ProTil, help to reduce machinery costs and improve crop performance. However, the question of the economic feasibility of their application remains open and requires more detailed research. The study by A. Panfilova *et al.* (2021) shows that optimisation of crop nutrition systems contributes to a significant increase in grain yield and quality, providing a 26-28% increase in productivity. This confirms the importance of precise fertilisation, which is a key aspect of the resource-saving Mzuri-ProTil technology.

In turn, K. Alekseieva *et al.* (2023) highlight the importance of state support for the introduction of innovative technologies in the agricultural sector, especially under martial law. The application of Mzuri-ProTil technology is consistent with the areas of support identified in the study, as this technology contributes to increased yields, efficient use of resources, and economic stability even under adverse conditions. In scientific works on the use of resource-saving technologies, authors such as Z. Ding *et al.* (2020), M. Habib-Ur-Rahman *et al.* (2022) have studied the impact of the latest technologies on increasing wheat yields, using specialised machinery, and reducing agronomic costs. They point to the possibility of reducing tillage and preserving soil structure, which contributes to increased fertility in the long term. However, most of these studies are limited to agronomic aspects only, and the issue of economic efficiency of Mzuri-ProTil technology remains insufficiently studied.

Thus, this study was aimed at determining the economic efficiency of growing winter wheat of the variety "Perlyna Odeska" using the Mzuri-ProTil technology in comparison with the classical technology.

MATERIALS AND METHODS

The research methodology included a comprehensive approach to assessing the economic efficiency of growing winter wheat of the variety "Perlyna Odeska" using the Mzuri-ProTil technology in comparison with the classical technology. The study was conducted during two agricultural seasons, 2022-2023 and 2023-2024, at the Educational and Research Centre of Mykolaiv National Agrarian University. The plots met the agronomic requirements for wheat cultivation. The soils of the experimental field are southern chernozems, residual slightly saline heavy loamy on loess. The humus content in the 0-30 cm layer is 3.1-3.3%. The reaction of the soil solution is neutral (pH 6.8-7.2). The topsoil contains 15-25 mg/kg of nitrates (according to Grandval Liege), 41-46 mg/kg of mobile phosphorus (according to Machigin), 389-425 mg/kg of exchangeable potassium mg/kg of soil (using a half-beam photometer). In 2022-2023, the weather conditions were favourable, which contributed to high yields, while 2023-2024 were characterised by periods of drought, which potentially affected the results. The Mzuri-ProTil technology used a specialised seed drill that provides simultaneous soil loosening, fertilisation and precision sowing. The classic technology included a full cycle of tillage using traditional approaches to seedbed preparation and crop care.

The variety selected for the study, Perlyna Odeska, is one of the most widespread in the region due to its adaptability to local climatic conditions. The results obtained may be relevant for other varieties with similar characteristics. The absence of significant fluctuations in the prices of fertilisers, fuel, and crop protection products during the study period minimised their impact on economic performance. To ensure the reliability of the results, statistical analysis was carried out, including estimation of average values and testing the significance of differences between methods. The choice of materials and the sample for the study covered 1-hectare plots divided into two equal parts of 0.5 hectares each. On one part, the Mzuri-ProTil technology was used, which involved the use of a specialised Mzuri Pro-Til 3T Select seeder, which ensured precise sowing, minimal soil tillage and fertilisation in the strip. John Deere 6R tractors with GPS navigation were used to ensure the accuracy of field operations. On another plot, we used the classic cultivation technology with traditional SZ-3.6 seeders and tractors without automated control systems, such as MTZ-82. This approach made it possible to compare the economic efficiency and agronomic performance of both methods on the same area with similar conditions.

The methodology for calculating economic efficiency is based on the identification and comparison of key economic indicators in 2022-2024, such as cost, gross margin, net profit, profitability, and payback period. For this purpose, data on production costs, crop yields, sales prices and costs of introducing new technology are used, in particular, based on statistical data on the grain market in Ukraine. According to the information available on the Statista platform (2024), grain prices and other important economic indicators in Ukraine in 2022-2024 showed certain fluctuations that could significantly affect the costs of agricultural enterprises and the effectiveness of new technologies in agriculture. This data served as the basis for assessing the financial feasibility of introducing technologies such as Mzuri-ProTil, which can reduce costs and increase production efficiency.

The production costs of winter wheat using Mzuri-ProTil technology were lower than those of conventional technology. For example, the costs in 2022-2023 and 2023-2024 were 22,373.70 and 15,811.18 UAH/ha for Mzuri-ProTil technology, respectively, while for the classical technology they were 23,637.22 and 16,541.09 UAH/ha. It should be noted that the cost of growing the crop in 2022-2023 was significantly higher than in 2023-2024, primarily due to the much higher price of mineral fertilisers. The results of the study took into account the specifics of winter crops, which require different approaches depending on agro-climatic conditions and economic situation in the analysed periods. This approach ensures that the economic performance of both technologies is correctly compared, as it eliminates the impact of cost changes on the assessment of their profitability and efficiency. This allows us to focus on analysing the impact of other factors, such as yield, net profit and payback period, and draw reasonable conclusions about the feasibility of using a particular technology in modern agricultural production conditions. The first step was to calculate the cost of winter wheat production. The cost of 1 tonne of grain (COG) is determined by dividing the production costs in UAH for growing the crop per 1 ha by the yield (1):

$$COG = \frac{PC}{y}, \tag{1}$$

where PC – production costs, UAH/ha; Y – yield, t/ha.

The second step was to calculate the value of gross production, which is defined as the product of yield and market price of grain. Comparing the value of gross production by different technologies allows us to assess the impact of Mzuri-ProTil technology on crop productivity and income (2):

$$V = Y \times Pm, \tag{2}$$

where V is the value of gross output, UAH/ha; Y is the yield, t/ha; Pm is the market price, UAH/t.

Based on the data on the value of gross output, net profit is calculated as the difference between the value of gross output and total production costs. Net profit is a key indicator for assessing the financial benefits of introducing a new technology (3):

$$P = V - PC, \tag{3}$$

where P – net profit, UAH/ha ; V – value of gross output, UAH/ha ; PC – production costs, UAH/ha.

Next, the production profitability was calculated, which shows the level of cost efficiency. To do this, the net profit is divided by the production costs and the result is multiplied by 100% to express the figure as a percentage. Comparison of profitability levels allows us to conclude that the Mzuri-ProTil technology is economically viable (4):

$$R = \frac{P}{PC} \times 100, \tag{4}$$

where R – production profitability, %; P – net profit, UAH/ha; PC – production costs, UAH/ha.

The final step was to estimate the payback period of the investment in the new technology. To do this, the total cost of implementation (including the cost of purchasing Mzuri-ProTil equipment and related costs) was divided by the net profit generated by using this technology. The result showed how long it would take for the initial investment to be fully recouped (5):

$$T = \frac{PC}{P}, \tag{5}$$

where T is the payback term, period; PC is production costs, UAH/ha; P is net profit, UAH/ha.

The collected data was processed to analyse the results, which allowed us to obtain accurate and substantiated conclusions regarding the cost-effectiveness of comparing different methods. The authors adhered to the standards of the Convention on Biological Diversity (1992).

RESULTS

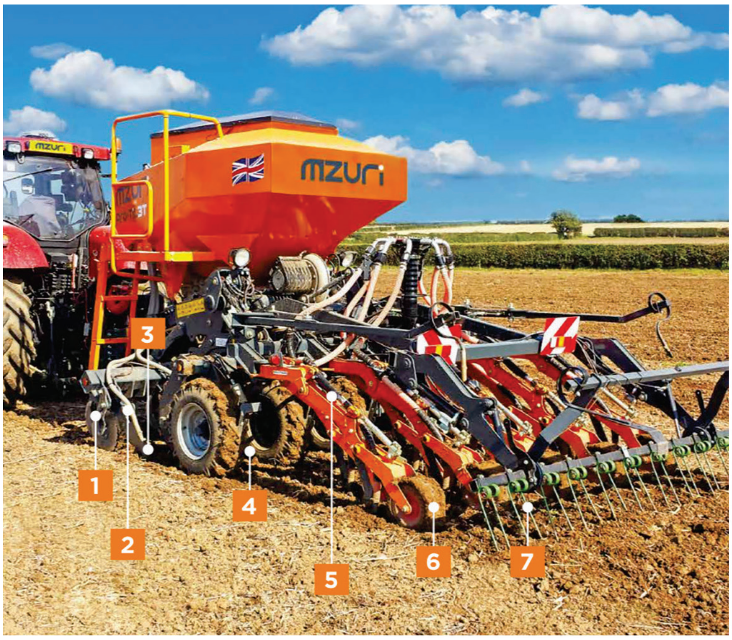
Classical wheat farming technology covers several key stages: soil preparation, sowing, crop care and harvesting. Soil preparation includes ploughing, cultivation and disking to create an optimal seedbed (Mayorov & Tsekhmeystruk, 2021). Sowing is carried out taking into account the timing, seeding rates and even distribution of seeds. Crop care includes fertilisation, weed, pest and disease control. The final stage is harvesting, aimed at minimising grain losses and maintaining its quality. The classical technology uses ploughing, disking, cultivation and levelling of the surface (Hakhula & Kiruta, 2023). These methods improve soil aeration, kill weeds, promote better moisture distribution and mix organic matter. However, intensive cultivation can reduce soil fertility, increase erosion processes and compact the lower layers of the soil, which affects the ecological state of the field.

The classical technology requires significant resources: tractors and tillage equipment for cultivating the field, sowing complexes for sowing, and combines for harvesting. Additionally, a significant amount of fuel is consumed for many field operations. The application of fertilisers and plant protection products also requires specialised equipment, which together increases production costs (Lysenko & Domushchi, 2021). The advantages of the classical technology include high efficiency in weed control, uniformity of crops and relative ease of implementation. However, it is resource-intensive, requiring high costs for machinery, fuel, and fertilisers. Compared to innovative technologies, the classical one has lower profitability and a greater negative impact on the soil due to intensive cultivation.

Crop care in the classical technology includes the application of mineral fertilisers to the soil to maintain fertility, as well as the use of herbicides to control weeds (Dubey *et al.*, 2020). Pesticides are used to protect against pests and diseases. All operations are carried out mechanically, with the use of modern machinery, which ensures efficiency but is costly. Classical technology has a positive effect on aeration and soil structure in the early stages due to loosening, but intensive cultivation reduces fertility due to the destruction of the humus layer and loss of organic matter. The water-holding capacity of the soil decreases due to partial degradation of the structure, which increases the risk of erosion and nutrient flushing, negatively affecting the ecological state of the agroecosystem (Pequeno *et al.*, 2021).

The application of Mzuri-ProTil technology has a significant impact on the yield of winter wheat compared to the classical cultivation technology. This technology provides a significant increase in yields due to a number of important factors, such as improved tillage management, precise fertiliser dosage and optimal seed contact with the moist soil layer. Thanks to these aspects, the technology contributes to the efficiency of winter wheat cultivation, making it an attractive alternative to traditional tillage methods. In 2023, using the classical winter wheat cultivation technology, the yield was 6.30 t/ha, while using Mzuri technology, this figure reached 7.10 t/ha. This means that the use of Mzuri led to a 13% increase in yield. In 2024, there is also a tendency to increase grain yields with the use of resource-saving technology: with the classical technology, it was 4.17 t/ha, while with Mzuri technology, this figure reached 4.78 t/ha, which is 14.6% more. This advantage confirms the effectiveness of Mzuri-ProTil technology in ensuring higher productivity even under adverse weather conditions.

One of the key reasons for this difference is the soil-preserving nature of Mzuri technology. It preserves soil structure, reduces soil compaction and erosion, which has a positive impact on soil fertility. The technology helps to retain moisture in the soil and create favourable conditions for plant growth. This makes it possible to obtain consistently high yields, even in the face of variable weather factors. In the growing season of 2022-2023, weather conditions were generally favourable for wheat production. The spring period was characterised by sufficient precipitation and moderate temperatures, which favoured active plant growth. In the summer, temperatures remained within normal limits, and short-term droughts did not have a significant impact on crop development. Thanks to these conditions, winter wheat was able to produce high yields, especially with Mzuri technology, which allows for the most efficient use of available soil moisture. In 2023-2024, the weather conditions were not favourable enough for winter wheat growing, especially compared to the previous periods. The spring was cool and prolonged, which delayed the start of active crop growth. During the growing season, precipitation was insufficient, resulting in a moisture deficit. The summer period was characterised by long periods of heat, which exacerbated the impact of drought. However, the Mzuri-ProTil technology allowed us to effectively retain moisture in the soil, which resulted in a higher yield compared to conventional cultivation. Mzuri technology involves the integration of several operations in one machine, which significantly optimises the tillage process. The main element is the specialised Mzuri-ProTil seeder, which performs several tasks at once. Figure 1 shows the Mzuri Pro-Til seed drill used for minimal tillage and simultaneous seeding.



1. Optional front disc to cut through surface residue
2. To auto reset leading tine ensures good root development and cleans the sowing strip of surface trash to produce a clean till of moist friable soil
3. Band placement of fertiliser below the seed reduces fertiliser requirement and ensures early nutrient accessibility
4. The staggered wheels remove air pockets and reconsolidate the tilled strips
5. Excellent soil to seed contact is achieved by hydraulic pressure exerted to each individual seed depth wheel
6. Individual depth adjustment to each of the semi-pneumatic coulter depth wheels accurately controls seed placement
7. Hydraulically operated adjustable pressure harrow ensures a level uniformed seed bed

***Figure 1**. Analysis of the design and functioning of the Mzuri-ProTil seeder*

***Source:** created by the authors based on Mzuri UK (2024)*

This image shows the design of the Mzuri-ProTil seed drill, which is the main element of the innovative strip tillage technology. The key feature of this technique is the combination of several operations in one pass, which ensures efficiency and precision of processing. The sowing machine is equipped with a number of working elements, each of which performs a specific function to achieve maximum yield. The design includes a front disc that cuts through plant residues and the surface layer of soil, preparing it for further processing. The deep loosening tine prepares the seedbed, helping to improve aeration and preserve soil structure. The innovative belt fertiliser application system ensures that fertiliser is placed directly under the seed, reducing costs and increasing efficiency. The adjustable pressure wheels ensure optimum contact between the seed and the soil, which contributes to uniform germination. The final step is precise sowing of the seeds to the desired depth with full control of the parameters. An important technical aspect is to minimise the impact on the soil by reducing the number of passes of the machinery. This preserves the natural structure of the soil, reduces compaction and promotes effective moisture management. The hydraulic and mechanical elements of the seed drill work in harmony to ensure uniformity and high quality of the field. The image clearly demonstrates how the Mzuri-ProTil works, highlighting technical innovations that not only reduce costs but also preserve the ecological stability of the soil. This diagram leads to a detailed analysis of the technology itself, its key advantages and potential for implementation in modern agriculture.

At the first stage, the sowing disc cuts through plant residues and the surface soil layer. The next working element, the deep-ripper, creates the seedbed, reducing soil compaction and improving soil aeration. At the same time, fertiliser is applied to the desired depth, ensuring precise and even plant nutrition. After processing the seedbed, the seed drill presses the soil in the strip using independently adjustable pressure wheels to ensure optimum contact between the seed and the soil. This ensures that the seeds germinate evenly and develop a strong root system. The final stage is sowing the seeds to the set depth with full control of the depth and density. The key technical innovation is the integration of GPS navigation in tractors, which ensures accuracy in all operations. Reducing the number of passes across the field minimises soil compaction, which is one of the main advantages of Mzuri-ProTil technology. Reducing the number of treatments not only reduces fuel and labour costs, but also preserves the natural structure of the soil, preventing soil degradation. This technology also contributes to the effective management of soil moisture retention properties, which is especially important in the context of climate change and uneven rainfall distribution. The costs per hectare of Mzuri-ProTil technology have changed compared to conventional winter wheat cultivation, and this is due to several factors that affect the cost structure.

The cost of growing winter wheat is an important indicator that reflects all the direct costs of producing 1 tonne of product (Kotlánová *et al.*, 2024). Formula 1 was used to calculate the cost of applying the classical technology and the Mzuri-ProTil technology. The analysis of the cost of the classical technology and the Mzuri-ProTil technology allows assessing their economic feasibility and impact on the final financial results. In 2022-2023, the cost of growing winter wheat using Mzuri-ProTil technology was 22,373.70 UAH/ha, which is lower than the classical technology, where these costs amounted to 23,637.22 UAH/ha. Due to higher yields, which amounted to 7.10 t/ha, the cost of one tonne of wheat decreased to 3,151.23 UAH/t, which is lower than the classical technology by 600.71 UAH/t. In 2023-2024, the cost of growing winter wheat using conventional technology was 16,541.09 UAH/ha. Given the yield of 4.17 t/ha, the cost per tonne of production was calculated as the ratio of total costs to the yield. Thus, the cost of winter wheat produced using conventional technology was approximately UAH 3,966.69 per tonne. The cost of growing winter wheat using Mzuri-ProTil technology in 2023-2024 was 15,811.18 UAH/ha, which is lower than the classical technology. The reduction in costs using Mzuri-ProTil technology is due to optimised use of technical resources, efficient application of materials and a reduction in the number of field operations. The yield of this technology was 4.78 tonnes per hectare. The cost of one tonne of production using Mzuri-ProTil technology decreased to 3,307.78 UAH/t, which is lower than the classical technology. This indicates that the increase in yields allowed reducing the cost per unit of production, compensating for the cost of implementing the technology. The results of the analysis show that Mzuri-ProTil technology provides economic benefits due to lower unit costs due to higher yields. This confirms its feasibility for agricultural producers seeking to optimise their costs and increase the competitiveness of their products on the market.

Firstly, Mzuri technology involves the use of specialised machinery that allows several operations to be performed simultaneously in the field: tillage, sowing, fertilisation and plant protection. Although the initial cost of purchasing and maintaining such equipment can be high, it can significantly reduce labour and fuel costs, as well as the number of tillage operations, which in turn reduces other operating costs. Secondly, thanks to the precise application of fertilisers and crop protection products, Mzuri technology ensures more efficient use of these resources. This reduces the total amount of chemicals used, thus reducing the cost of purchasing them. This approach also contributes to a more sustainable use of natural resources and reduces fertiliser costs, which is an important factor in improving economic efficiency. Gross margin is a key indicator of economic efficiency, as it is determined by the volume of products grown and their realizable value (Challoumis & Eriotis, 2024). Formula 2 was used to analyse the gross margin, and the results of two winter wheat cultivation technologies were considered: classical and Mzuri-ProTil. The calculations used statistical data on prices for winter wheat sales by agricultural producers in Ukraine for 2023 and 2024, which were adapted to real market conditions (State Statistics Service of Ukraine, 2024). In particular, the prices provided by official statistical sources were adjusted in accordance with the actual figures received from agricultural producers engaged in the cultivation and sale of winter wheat on the domestic market of Ukraine in order to accurately reflect the current market situation.

During the years of research, wheat yields using classical technology were 4.17-6.30 t/ha at a market price of 5,600-6,000 UAH/t. This resulted in a gross production value of 25,020-35,280 UAH/ha. This level of income demonstrates the potential of conventional technology to deliver stable financial results under favourable weather conditions, but costs and production costs remain critical factors in comparison with alternative approaches such as Mzuri-ProTil. Over the same period, Mzuri-ProTil technology delivered higher yields of 4.78-7.10 tonnes per hectare. At the market price of 5,600-6,000 UAH/t, the cost of gross production using this technology was 28,680-39,760 UAH/ha, which exceeds the classical technology by 3,660-4,480 UAH/ha. These results confirm the economic feasibility of Mzuri-ProTil technology due to its ability to use resources more efficiently even in adverse weather conditions.

The analysis shows that the Mzuri-ProTil technology demonstrates a stable advantage in gross income due to higher yields. Even in the unfavourable conditions of the 2023-2024 growing season, it remained more efficient, which underlines its potential to provide higher profitability compared to the classical technology. This makes Mzuri-ProTil technology an attractive option for farmers seeking to maximise their income by optimising yields. The increase in yields with Mzuri-ProTil technology has played a key role in compensating for the additional costs of machinery and inputs, and here are some of the main factors that explain how this happened. The increase in yields with Mzuri-ProTil technology has significantly increased the gross revenue per hectare. In the 2023-2024 season, Mzuri-ProTil technology yielded 4.78 t/ha, which is 14.6% more than the classic technology (4.17 t/ha). This led to an increase in gross income per hectare, as the products sold at UAH 6,000/t brought in more money. The increase in gross income helped cover the additional costs associated with the use of more expensive inputs, such as fuel, machinery maintenance and fertiliser. Secondly, the precise application of fertilisers and crop protection products using Mzuri technology significantly reduces excessive chemical costs. This means that part of the savings on fertiliser and pesticide application can be used to cover the cost of machinery and its maintenance. Net profit is a key financial indicator that demonstrates the difference between gross revenue and production costs (Devkota & Yigezu, 2020). The analysis of net profit calculated according to Formula 3 allows us to assess the economic efficiency of the classical winter wheat cultivation technology and the Mzuri-ProTil technology.

The cost of gross production in 2022-2023, depending on the technology of winter wheat cultivation, was 35,280-39,760 UAH/ha, which allowed obtaining 11,642.78-17,386.30 UAH of net income per 1 ha. In 2023-2024, according to the classical technology, the cost of gross production was 25,020 UAH/ha at a cost of 16,541.09 UAH/ha. This resulted in a net profit of 8,478.91 UAH/ha. Lower yields due to unfavourable weather conditions resulted in a decrease in net profit compared to favourable years, which highlights the vulnerability of the classical technology to climate change. In 2023-2024, Mzuri-ProTil technology provided a gross production value of 28,680 UAH/ha at a cost of 15,811.18 UAH/ha. This resulted in a net profit of 12,868.82 UAH/ha, which is 4,389.91 UAH/ha more than with the classical technology. The advantage of the Mzuri-ProTil technology is related to its ability to use moisture and other resources more efficiently, which ensured better results even in adverse weather conditions.

The analysis shows that the Mzuri-ProTil technology provides a consistently higher net profit than the classical technology, even under unfavourable conditions. This demonstrates its cost-effectiveness and potential to increase the profitability of agricultural enterprises. In addition, specialised tillage equipment based on Mzuri technology reduces the number of treatments and the cost of fuel and labour. The technology also reduces the risk of soil compaction, which ensures consistently high yields even in less favourable weather conditions. This not only increases yields, but also reduces the cost of additional agronomic measures, which also helps to maintain profitability. Thus, the increase in yields provided by Mzuri-ProTil technology compensates for the additional costs of machinery and resources, providing a higher gross income. This allows agricultural producers not only to cover the costs of implementing the new technology, but also to generate additional profits, making this method economically viable in the long term.

The higher yields provided by Mzuri-ProTil technology help to reduce unit costs due to several important factors. First, higher yields reduce unit costs through economies of scale. When yields per hectare increase, the total amount of product produced from the same field increases. This means that fixed costs, such as machinery, maintenance and other inputs, are spread over more units of output. Thus, the cost per unit of output (e.g., per tonne of grain) is reduced. Secondly, Mzuri technology reduces the overall cost of tillage and fertilisation through more efficient use of resources. The precise application of fertilisers and crop protection products and the reduction in the number of treatments reduce the cost of chemicals and fuel. This is important because higher yields mean more output with fewer inputs, which helps to reduce the cost per unit. Third, by reducing the number of treatments and using high-performance machinery, Mzuri technology reduces labour and fuel costs. The Mzuri-ProTil technology optimises the number of operations performed on the field by simultaneously performing several important agronomic activities, such as tillage, sowing, and fertilisation. This reduces the cost of machine maintenance and ensures more efficient use of resources. Overall, the higher yields achieved with Mzuri-ProTil technology help to reduce unit costs by increasing overall production and optimising resource use. This allows for greater profit from each unit of production and makes the technology more cost-effective for agricultural producers. The introduction of the Mzuri-ProTil technology has led to significant changes in the profitability of winter wheat production, in particular, to its growth compared to the classical cultivation technology. This is manifested in several aspects that indicate the increased economic efficiency of using this technology.

Yield growth is a key factor that contributes to increased profitability. The Mzuri-ProTil technology resulted in wheat yields of 4.78-7.10 t/ha in 2023 and 2024, which is 11.3-14.6% higher than the conventional technology (4.17-6.30 t/ha). Higher yields increase the gross income per hectare, which has a positive impact on the profitability and economic efficiency of the technology. Mzuri technology reduces unit costs by optimising growing processes, such as precise fertilisation and plant protection products, and reducing the number of operations on the field. Although the initial cost of machinery and its maintenance is higher, these additional costs are offset by the increase in yields, which reduces the overall cost per unit of production. Profitability is an important indicator that characterises the economic efficiency of a wheat production technology, as it reflects the ratio of net income to costs (De Andrade Ferrazza *et al.*, 2024). A high level of profitability indicates the ability of the technology to generate profit for every hryvnia spent. An analysis of the profitability of the classical technology and the Mzuri-ProTil technology allows us to assess which of these methods is more profitable for agricultural producers. Formula 4 was used to determine the level of profitability.

In 2022-2023, due to the high net income, the profitability of winter wheat cultivation was 49.3-77.7%. At the same time, using Mzuri-ProTil technology, the level of profitability of winter wheat cultivation was 28.4% higher compared to the classical technology of crop cultivation. In 2023-2024, the classic technology resulted in costs of 16,541.09 UAH/ha, while the net profit was 8478.91 UAH/ha. The decline in yields was a key factor that affected the economic performance of this technology. Profitability fell to 51.3%, which demonstrates the significant dependence of the classical technology's efficiency on weather conditions and yields. This demonstrates the need for adaptive and resource-saving technologies to ensure stable profits in the face of climate change. For the Mzuri-ProTil technology, in 2023-2024, the costs were 15,811.18 UAH/ha, and the net profit was 12,868.82 UAH/ha. The profitability level of winter wheat cultivation using this technology was 81.5%, which is higher than the same indicator of the classical technology. The efficiency of Mzuri-ProTil is ensured by greater resistance to adverse weather conditions and optimised use of resources, which allows for higher profit per unit of investment.

The Mzuri technology also reduces the negative impact of weather conditions through improved soil moisture retention and reduced soil compaction. This makes the technology more resilient to climate change and ensures consistently high yields, which also has a positive impact on profitability. Thus, after the introduction of the Mzuri-ProTil technology, the profitability of wheat growing has increased significantly due to higher yields, lower unit costs and improved resistance to adverse weather conditions. In general, this increases the economic efficiency of wheat cultivation and makes this method more profitable for farmers compared to conventional technologies. The payback period is an important indicator of the economic efficiency of a technology, which allows us to estimate how long it will take for the investment in the introduction of a new technology to be fully covered by the profit generated (Saquee *et al.*, 2024). Formula 5 was used to calculate the payback period. The payback period for the use of Mzuri-ProTil technology in 2022-2023 was 1.3 years, and for the use of conventional technology – 2 years. The cost per hectare of wheat cultivation in 2023-2024 was UAH 16,541.09 using the classical technology. The net profit was UAH 8,478.91. The payback period for this technology was calculated as the ratio of costs to net profit. According to the results of the calculations, the payback period was 1.95 seasons, which is equivalent to about two years. This indicates that in adverse weather conditions, investments are recovered more slowly, which reduces the economic attractiveness of the classical technology in such conditions. For the Mzuri-ProTil technology, the cost per hectare in 2023-2024 was 15,811.18 UAH, and the net profit was 12,868.82 UAH. The payback period was calculated using the same formula as for the classical technology. The results showed that the payback period for Mzuri-ProTil was 1.23 seasons, or approximately 1 year and 3 months. This indicates that the technology, despite its higher costs, provides a faster return on investment due to higher yields and optimised resources. Thus, in 2022-2024, Mzuri-ProTil technology proved to be more efficient than the classical technology, demonstrating a shorter payback period and a more stable financial result even in unfavourable climate conditions.

The Mzuri-ProTil technology is economically viable for farmers, especially in the face of climate change and limited resources. It offers several significant advantages that make it a profitable and efficient alternative to conventional wheat growing technology. Mzuri technology provides a significant increase in yields. Thanks to specialised machinery and precise application of fertilisers and crop protection products, farmers can achieve consistently high yields, even in adverse weather conditions. This is especially important in a changing climate, where extreme weather events such as droughts or excessive rain can significantly reduce yields. Mzuri technology mitigates the risks associated with such changes and ensures a stable income. The technology can significantly reduce unit costs. By optimising the costs of inputs such as fuel, fertiliser, pesticides and labour, farmers can achieve more efficient use of limited resources. Precise application of fertilisers and crop protection products can reduce their consumption, which not only reduces overall costs but also has a positive environmental impact. In this way, agricultural producers can not only maintain their profits but also make their production more sustainable and environmentally friendly.

The use of Mzuri technology helps to retain moisture in the soil, which is especially important in a changing climate where droughts are becoming more common. The technology helps to reduce soil erosion, improves soil structure and increases moisture retention, which allows plants to better withstand periods of drought. In addition, Mzuri technology helps to reduce tillage costs and reduces the number of treatments, which also has a positive impact on economic results. The use of multifunctional equipment allows for the simultaneous performance of several operations on the field, which reduces the need for additional equipment and labour. The results of a comparative analysis of the economic efficiency of two winter wheat cultivation technologies show significant differences between the classical technology and the soil-saving Mzuri-ProTil technology (Table 1). The main indicators such as yield, gross income, costs, net profit, profitability, and payback period were the key criteria for assessing the economic feasibility of both technologies. The soil-saving Mzuri-ProTil technology provided higher yields during the years of research, which directly influenced the increase in gross income compared to the classical technology. Despite the higher costs of implementing the Mzuri-ProTil technology, the increased productivity resulted in higher net profit and higher profitability. The payback period analysis showed that, although the classical technology is characterised by lower costs, it has limited prospects for long-term economic efficiency. The Mzuri-ProTil technology demonstrates economic viability in the medium term, providing better resistance to changes in weather conditions.

***Table 1**. Comparative analysis of the economic efficiency of using Mzuri-ProTil technology and classical technology for growing winter wheat*

Indicator	Technology			
	Classic		Mzuri-ProTil	
	Years			
	2022-2023	2023-2024	2022-2023	2023-2024
Yield (t/ha)	6.30	4.17	7.10	4.78
Production costs (UAH/ha)	23,637.22	16,541.09	22,373.70	15,811.18
Cost price (UAH/t)	3,751.94	3,966.69	3,151.23	3,307.78
Gross production value (UAH/ha)	35,280	25,020	39,760	28,680
Net profit (UAH/ha)	11,642.78	8,478.91	17,386.3	12,868.82
Profitability level (%)	49.3	51.3%	77.7	81.5%
Payback period (period)	2 years	1 year 11 months	1 year 3 months	1 year 3 months

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

In 2023-2024, the yield of Mzuri-ProTil technology was 4.78 t/ha, which is 0.61 t/ha higher than the result of the classical technology (4.17 t/ha). This resulted in a gross income of 28,680 UAH/ha compared to 25,020 UAH/ha with the conventional technology. Despite the fact that the costs of growing using Mzuri-ProTil technology were UAH 729.91 lower, the cost of production remained lower – 3,305 UAH/t, compared to 3,412 UAH/t for the classic technology. The net profit of Mzuri-ProTil technology in 2023-2024 was 12,868.82 UAH/ha, which is 4,389.91 UAH more than the classic technology. The profitability of cultivation using the Mzuri-ProTil technology reached 81.5%, which is also higher than the classical technology (51.3%). As for the payback period, Mzuri-ProTil requires 1 year and 3 months to recover costs, while the classical technology requires almost 2 years. In summary, the results of the analysis show that Mzuri-ProTil technology provides higher economic performance compared to the classical technology, even with a decrease in yields in 2023-2024. It remains more cost-effective and profitable, which confirms its feasibility for farmers seeking to improve the efficiency of their farms in the medium and long term. Thus, Mzuri-ProTil technology is economically viable for farmers due to its ability to increase yields, reduce costs, improve climate resilience and conserve natural resources. In the face of a changing climate and limited resources, this technology is a profitable and effective way to ensure sustainable agricultural development.

The Mzuri-ProTil technology demonstrates a significant increase in economic efficiency compared to conventional wheat growing technologies. It delivers higher yields, reduces unit costs by optimising inputs and facilitates adaptation to climate change. Higher yields and improved resource utilisation result in higher profits, despite higher initial costs for machinery and its maintenance. Sowing campaigns in a changing climate are becoming increasingly challenging for farmers

(Zhao *et al.*, 2022). Climate change, such as temperature fluctuations, changes in precipitation patterns and the frequency of extreme weather events, has a significant impact on agricultural production efficiency. This particularly applies to aspects such as sowing timing, variety selection and cultivation technology. In such circumstances, agronomists are forced to adapt their strategies to minimise the negative impact of climate change. In a changing climate, where droughts and extreme weather conditions are becoming more common, Mzuri technology is becoming an important tool for ensuring stable yields and economic sustainability for farmers. It reduces tillage costs, improves moisture retention and reduces the risks associated with unstable weather conditions, making it a profitable and viable option for modern agriculture.

DISCUSSION

Due to global climate change and growing demands on agricultural production efficiency, farmers are looking for new ways to increase productivity and reduce costs. Among the innovative methods that are gaining popularity are technologies aimed at preserving soil and minimising agronomic intervention. Mzuri-ProTil technology, compared to traditional No-till technology, provides better efficiency due to more precise control of sowing and fertilisation processes, which contributes to higher yields and economic efficiency. However, No-till also has the advantage of preserving soil structure and reducing erosion. Scientists such as H.S. Jat *et al.* (2020) emphasise that No-till is effective for sustainable agriculture, especially in the face of soil degradation, by maintaining soil health in the long term. However, in conditions where control over agronomic processes is important to achieve high yields, Mzuri-ProTil technology may have an advantage due to the ability to fine-tune fertilisation and seeding processes. On the other hand, while No-till provides significant soil conservation benefits, it does not provide the same level of control that can limit its effectiveness in optimising yields. Therefore, the choice between technologies depends on specific conditions and goals: No-till may be preferred for soil structure preservation and erosion control, while Mzuri-ProTil may be preferred for higher yields and economic efficiency.

Minimum tillage technology involves cultivating the soil to a shallow depth to improve sowing conditions, while keeping most of the organic residues on the surface (Pavlova & Litvinov, 2024). Compared to Mzuri-ProTil, minimum tillage uses less precise seeding and fertilisation management, which can reduce efficiency, especially in a changing climate. Scientists such as S.M. Junge *et al.* (2020) note that minimum tillage can be useful for conserving moisture and organic material, but its potential for increasing yields is less than that of more precise technologies. Mzuri-ProTil, on the other hand, allows for simultaneous precision seeding and fertilisation, which results in higher yields and better economic results. Thus, Mzuri-ProTil provides greater precision and control compared to minimum tillage, making it more effective when it is required to maximise productivity. Strip till technology involves cultivating only the strips of soil on which the seed is sown, leaving the rest of the field untilled. This helps to preserve organic residues on the soil surface, reduce erosion and retain moisture, similar to no-till technology. However, Strip till provides more precise soil management in the sowing area, which can be important for achieving high yields.

Compared to Mzuri-ProTil, Strip till also uses minimal tillage, but Mzuri-ProTil is even more precise as it allows for simultaneous sowing, fertilisation and plant protection products, which ensures even more efficient use of resources. Research, in particular the work of I. Jaskulska and D. Jaskulski (2020) show that strip tillage provides certain advantages over conventional tillage, but Mzuri-ProTil technology provides better yields due to additional opportunities for precise management of agronomic processes. Thus, Mzuri-ProTil delivers higher results in terms of yield and economic efficiency compared to Strip till. Conventional tillage technology involves complete loosening of the soil with a plough and other cultivation tools to prepare the field for sowing (Bulgakov *et al.*, 2019). This provides deep loosening, which facilitates the penetration of water and air into the soil, and kills weeds and organic residues. However, conventional tillage reduces soil organic matter, can cause erosion and moisture loss, and is costly in terms of fuel and technical resources (Zymaroieva *et al.*, 2021).

Compared to Mzuri-ProTil, Conventional tillage is less effective in terms of maintaining soil fertility in the long term. Mzuri-ProTil takes a more innovative approach by preserving organic residues on the soil surface, minimising erosion and retaining moisture. In addition, Mzuri-ProTil technology allows for precision sowing and simultaneous application of fertilisers and crop protection products, which increases resource efficiency and contributes to higher yields. Analysing the research of scientists such as M. Allam *et al.* (2022), it can be distinguished that Mzuri-ProTil technology has certain advantages over conventional tillage, in particular in a changing climate, due to better preservation of soil structure and more efficient use of water and nutrients. Ridge till technology involves tillage that creates ridges or raised strips on which to sow. This improves drainage, provides better air access to plant roots and reduces water erosion. At the same time, this technology allows preserving organic residues between the ridges and minimising erosion in the row spacing.

Compared to Mzuri-ProTil, Ridge till technology also retains a significant amount of organic residue on the soil surface, but it does not provide such high precision in seeding and fertilisation. Mzuri-ProTil allows for more precise control of sowing and plant nutrition, as it simultaneously applies fertiliser and plant protection products to the optimum locations for growth. Scientists such as O. Alagbo *et al.* (2022) note that Ridge till has advantages in conditions where it is important to improve drainage and soil structure, but Mzuri-ProTil gives better results in terms of yield and economic efficiency due to precise management of agronomic processes. Therefore, Mzuri-ProTil can be a more efficient option compared to Ridge till, especially in conditions that require high yields and conservation of resources. Aeration tillage technology involves tilling the soil to improve its aeration (Boiko & Kovalenko, 2024). Instead of deep loosening, this technology uses special tools that create small holes or cracks in the soil, improving oxygen access to the root system of plants and reducing soil compaction. This allows for increased water and air permeability of the soil, while retaining organic residues on the surface and minimising erosion.

Compared to Mzuri-ProTil, Aeration tillage technology is a less precise method for seeding and fertilisation control. Mzuri-ProTil not only aerates the soil, but also simultaneously performs precision sowing, fertilisation and plant protection products, which helps to increase yields and economic efficiency. Studies, such as those by G.O. Awe *et al.* (2023), show that while Aeration tillage improves soil structure, Mzuri-ProTil provides benefits through a more integrated approach to tillage and resource use, which leads to better production results. Drill till technology involves the use of special seed drills that combine tillage and sowing, ensuring precise seed placement in the treated strip. This method allows for minimal tillage, preserving organic residues on the surface, while preparing a separate strip for sowing, which increases the accuracy and uniformity of seed placement.

Compared to Mzuri-ProTil, Drill till technology has certain advantages in terms of sowing accuracy, but does not provide such high efficiency in the application of fertilisers and plant protection products. Mzuri-ProTil allows simultaneous precision sowing, fertilisation and crop protection in one operation, which reduces the cost of technical resources and improves the economic efficiency of production. Research, in particular the work of Y. Mykhaylichenko *et al.* (2023), show that Drill-Till technology is an effective method for reducing tillage costs and preserving soil structure, as well as ensuring precision in sowing, which contributes to stable yields and sustainable use of agricultural resources. However, this technology does not allow combining several operations into one, as implemented in Mzuri-ProTil.

In comparison with Drill-Till, Mzuri-ProTil demonstrates advantages through an integrated approach to sowing, fertilising and plant protection. This technology reduces the number of passes of equipment across the field, which not only saves resources but also minimises soil compaction. Thanks to the precision and synchronisation of operations, Mzuri-ProTil allows for better fertiliser use and reduces crop losses due to uneven nutrient distribution, which is especially important in a changing climate. Thus, Mzuri-ProTil is a technology that allows achieving higher economic results on fields with high productivity potential. Precision tillage technology involves the use of modern technologies such as GPS and sensors to precisely control soil cultivation, which reduces fuel and lubricant costs, preserves soil fertility and increases resource efficiency (Golub *et al.*, 2020). It allows for precise control of the depth and width of tillage, including soil conditions and plant needs.

Compared to Mzuri-ProTil, Precision tillage uses high-precision tillage methods, but Mzuri-ProTil is a more integrated technology as it simultaneously performs precision seeding, fertilisation and crop protection, which provides even greater cost-effectiveness. In studies such as those by Y. Sabouri *et al.* (2021), it is noted that Precision tillage provides significant benefits in terms of tillage accuracy, but Mzuri-ProTil provides an integrated approach that allows for higher yields and better economic results due to the simultaneous control of several processes of the agronomic cycle. Broadcast sowing technology provides for the uniform distribution of seeds over the soil surface without preliminary tillage or soil preparation. This method allows sowing large areas quickly and efficiently, but requires additional measures to improve seed contact with the soil, such as rolling or reverse tillage.

Compared to Mzuri-ProTil, Broadcast sowing technology does not have such high precision in sowing and fertilisation. Mzuri-ProTil provides more precise sowing due to the simultaneous application of fertiliser and plant protection products, which improves resource efficiency and increases yields. Studies such as those by K. LoPiccalo (2022) show that while Broadcast sowing can be a fast and economical method, Mzuri-ProTil offers advantages due to the high precision of seeding and plant nutrition management, which ultimately provides better economic and agronomic results.

In turn, V. Havrysh *et al.* (2020) emphasise the importance of introducing energy-saving technologies in the agricultural sector. These conclusions are consistent with the characteristics of the Mzuri-ProTil technology, which, by reducing the number of passes of machinery, contributes to the rational use of energy resources. This is a significant advantage compared to Precision tillage, which, although it provides high precision tillage, does not offer an integrated approach like Mzuri-ProTil. The complexity of the latter allows reducing cultivation costs and increasing yields at the same time, which confirms its economic feasibility.

CONCLUSIONS

The study revealed a significant economic efficiency of Mzuri-ProTil technology in the cultivation of winter wheat of the Perlyna Odeska variety compared to the classical technology. The Mzuri-ProTil technology has demonstrated advantages in the face of climate change, providing consistently higher yields and economic profitability even under adverse weather conditions. In 2022-2024, the profitability of Mzuri-ProTil technology was 77.7-81.5%, which exceeded the results of conventional winter wheat cultivation by 28.4-30.2%. The net profit of Mzuri-ProTil technology amounted to 12868.82-17386.3 UAH/ha, which is 33-34.1% higher than the classical technology of growing the crop, which provided a net profit of 8478.91-11642.78 UAH/ha, depending on the years of research. The payback period for the Mzuri-ProTil technology in the years of research was 1 year and 3 months, while for the classical technology it was 1 year 11 months – 2 years. This confirms the economic feasibility of introducing the latest technology, even in the face of adverse weather factors typical for this season.

The practical significance of the study was to identify the Mzuri-ProTil technology as an effective means of increasing yields and optimising costs. The latest technology has reduced the number of passes of machinery across the field, which has helped to reduce soil compaction, improve its structure and aeration. The rational use of fertilisers and crop protection products has saved resources and contributed to the environmental sustainability of production. An additional benefit was the reduction in fuel and equipment maintenance costs. Prospects for further research include adapting the Mzuri-ProTil technology to specific soil types, such as heavy clay soils, and analysing the long-term impact on soil fertility. It is also advisable to study the technology's effectiveness under conditions of limited irrigation and rising temperatures, which are characteristic of climate change. Particular attention should be paid to improving technical equipment and introducing automated control systems that can improve the accuracy of operations and reduce costs. The use of integrated digital platforms for monitoring agro-technological processes can significantly improve the efficiency and environmental friendliness of production, contributing to the sustainable development of agriculture.

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CONFLICT OF INTEREST

None.

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Оцінка економічної ефективності вирощування пшениці озимої за ресурсозберігаючої технології Mzuri-ProTil

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Анотація. Метою роботи було дослідити економічну ефективність вирощування пшениці озимої сорту «Перлина одеська» за ресурсозберігаючою технологією Mzuri-ProTil. Результати аналізу показали, що ця технологія має значний вплив на врожайність і економічні показники виробництва. За підсумками досліджень в умовах Навчально-науково-практичного центру Миколаївського національного аграрного університету у 2022-2024 роках було встановлено, що застосування технології Технологія Mzuri-ProTil забезпечує вищу врожайність порівняно з класичною технологією. У 2023 році врожайність за класичною технологією становила 6,30 т/га, тоді як за технологією Mzuri-ProTil – 7,10 т/га, що на 0,80 т/га більше. У 2024 році врожайність за класичною технологією знизилася до 4.17 т/га, а за технологією Mzuri-ProTil – склала 4,78 т/га (+0,61 т/га). Ця перевага свідчить про ефективніше використання ресурсів та здатність технології Mzuri-ProTil забезпечувати кращі результати навіть за несприятливих погодних умов. Витрати за технологією Mzuri-ProTil у 2022-2023 рр. склали 22373,70 грн/га, а у 2023-2024 рр. – 15811,18 грн/га, що було нижчим порівняно з витратами за класичною технологією (23637,22 і 16541,09 грн/га відповідно), завдяки оптимізації використання ресурсів і зменшенню кількості операцій на полі. Проте збільшення врожайності компенсувало додаткові витрати, що дозволило підвищити загальну економічну ефективність виробництва. Для оцінки рентабельності було проведено розрахунки вартості виробництва одиниці продукції. Вартість вирощування однієї тони пшениці за технологією Mzuri-ProTil, враховуючи витрати та врожайність, була нижчою, ніж за класичною технологією, завдяки більш високій врожайності, що дозволяє зменшити витрати на одиницю продукції. Таким чином, економічний аналіз свідчить про переваги застосування технології Mzuri-ProTil, оскільки вона забезпечує вищу продуктивність і більшу кількість продукції на один гектар, що в результаті дозволяє забезпечити більш високі доходи від виробництва, навіть за умови збільшення витрат на ресурси та техніку. Технологія Mzuri-ProTil є економічно доцільною для фермерів, які прагнуть підвищити ефективність виробництва пшениці в умовах зміни клімату та обмежених ресурсів

Ключові слова: сільське господарство; рентабельність; ресурсозберігаючі технології; сталий розвиток; урожайність

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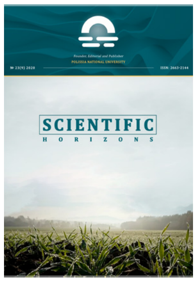

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Justification of the impact of complex melioration on the fertility of compacted sierozem soils of irrigated lands of the Zhambyl region

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Abstract. The aim of the study was to develop effective methods of improving physical, chemical and biological properties of soil to increase its productivity and resistance to degradation under conditions of intensive agricultural use. The article presented a study of the impact of complex reclamation measures on the restoration of compacted grey soils in the conditions of irrigated lands of Zhambyl oblast. The experimental part included application of deep loosening and organic fertilizers, as well as water

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regime management using drip irrigation. The results of the study showed that ameliorative measures allowed reducing soil density by 15-20%, which provided improvement of its structure and increased water permeability by 300-400%. This created conditions for a more uniform distribution of moisture in the root-inhabited layer, which minimised surface run-off by 60-70% and prevented nutrient losses. The application of organic fertilizers increased the humus content by 15-20%, which improved the chemical composition of the soil and increased its ability to retain nutrients. Special attention was paid to the biological activity of the soil, which increased by 25-30% due to the activation of microbial communities. These changes improved the decomposition of organic matter and increased the availability of nitrogen, phosphorus, and potassium for plants. As a result of application of complex measures, an increase in wheat and maize yields by 15-20% was observed, which confirmed the effectiveness of the proposed approaches. The made conclusions demonstrate that the use of deep loosening, organic fertilisation and drip irrigation in complex is an effective method of restoration of degraded grey soils. The results of the study have significant practical value and can be recommended for implementation in agricultural production in arid regions

Keywords: land irrigation; soil fertility; crop yields; deep loosening; ecological technologies; agricultural productivity; water permeability

INTRODUCTION

The relevance of this study is conditioned by the need to improve the efficiency of land resources use in Zhambyl oblast, where grey soils are characterised by low natural fertility and high susceptibility to degradation processes. The arid climate of the region, limited water resources and intensive farming lead to soil compaction, deterioration of soil structure and reduction of wheat and maize yields. Ameliorative measures, including deep loosening and application of organic fertilizers, allow not only to improve physical and mechanical properties of soil, but also to increase its water permeability, humus content and biological activity. This creates a basis for increasing soil productivity and sustainable development of the agrarian sector of the region, which makes this area of research particularly relevant.

The problematics of the research is related to the deterioration of grey soils caused by compaction, lack of organic matter and low biological activity. These factors lead to a decrease in water-holding capacity and deterioration of plant access to nutrients, which in the conditions of arid climate leads to significant yield losses. The situation is aggravated by intensive tillage methods and irrational irrigation, which contribute to the leaching of nutrients, development of erosion processes and deterioration of soil structure. Insufficient study of the influence of complex melioration on fertility of compacted grey soils in conditions of Zhambyl oblast underlines the necessity of this research. Analysing the works of other authors, it can be noted that A. Rau *et al.* (2023) justified the necessity of introducing reclamation measures, such as deep loosening and application of organic fertilizers, to increase water permeability and moisture retention in the soil. According to the findings of A.T. Aimen *et al.* (2022) low humus levels and soil compaction in Central Asia significantly reduce crop yields. And emphasised that organic matter application and water regulation effectively increase soil biological activity. Researchers D. Raiymbekov *et al.* (2023) indicate that agronomic measures such as loosening and water table regulation help to reduce soil density and prevent erosion.

As noted by S. Razanov *et al.* (2022), standard intensive farming practices reduce soil fertility, but the introduction of a systematic approach including improvement of soil structure and chemical composition can achieve significant results. In the studies of Y. Kenjaev and A. Tursunkulova (2021), the authors draw attention to the fact that improper irrigation aggravates soil compaction, but the introduction of drip irrigation and reclamation measures contributes to the restoration of soil fertility. According to N.S. Mustakimovna (2021), the increase in the content of organic matter in the soil contributes to the increase of its biological activity and resistance to degradation, which confirms the need to apply organic fertilizers.

As noted by A. Tadesse and W. Hailu (2024), land degradation in arid regions requires an integrated approach, including physical and chemical methods of soil restoration. As the results of I.J. Roziyeva and K.U. Turabayeva (2022), in irrigated soils, the reduction of biological activity and nutrient deficiency are compensated by organic matter application and improvement of water regime. W.T. de Vries and I. Rudiarto (2023) emphasise successful soil rehabilitation strategies, including measures to reduce compaction and increase humus content, which is important for degraded soils. As indicated by I. Plisko *et al.* (2021), the use of spatial diagnostics of soil degradation allows to accurately identify problem areas and effectively plan reclamation measures, emphasising their importance for fertility restoration. Authors V. Gamayunova *et al.* (2024) highlight the key role of resource-saving technologies, including the use of straw to improve soil fertility. Studies show that the application of organic material contributes to humus recovery and increased yields, which confirms the effectiveness of organic approaches to the reclamation of grey soils. As noted by N.S. Kaya and O. Dengiz (2024) soil quality assessment using neutrosophic logic and machine learning techniques can accurately identify factors limiting agricultural land productivity. These studies emphasise that rehabilitation of compacted grey soils requires an integrated approach combining traditional reclamation methods with innovative technologies and biological approaches.

Thus, the aim of the study was to justify reclamation measures to improve the properties of compacted grey soils in Zhambyl oblast and increase their productivity.

MATERIALS AND METHODS

The study was conducted in 2024 (June-August) on the basis of experimental fields of Taraz Regional University named after M.Kh. Dulaty in Taraz city, Zhambyl region. The study covered the summer period (vegetation period from 1 June to 31 August, 92 days), because at this time the most active processes of soil formation, dynamics of moisture and temperature regime, as well as the maximum vegetative activity of wheat and maize are observed, which allows the most complete assessment of the impact of reclamation measures. The climate of the region was characterised by sharply continental conditions, including hot and dry summers, with daytime temperatures of +22-30°C and nighttime temperatures of +15-18°C. The average annual precipitation was 120-200 mm, most of it falling in spring, which required the use of effective moisture conservation methods to maintain wheat and maize productivity. The object of the study was compacted grey soils, on which ameliorative measures were carried out to improve their physical and chemical characteristics.

The soils of the experimental plot were typical grey soils with low humus content (1.3-1.4%) and limited reserves of available nitrogen, phosphorus, and potassium. Before the experiment, soil samples were analysed, which revealed neutral acidity (pH 6.8-7) and low biological activity. The experiment was conducted on one plot of 1 ha with the use of ameliorative measures, including deep soil loosening (to a depth of 30-35 cm) in combination with the application of organic fertilizers (over-fermented cattle manure at a dosage of 30 t/ha). The study was conducted in three repetitions. Watering was carried out by drip irrigation for uniform moisture distribution and prevention of erosion processes. Soil water regime was evaluated by infiltration, water-holding capacity and evaporation. Infiltration rings were used to measure water permeability, and field water retention was determined based on the difference in soil moisture immediately after irrigation and after a certain time interval. Moisture evaporation was monitored by hydrometric methods. On the basis of the obtained data, the influence of land reclamation on soil water balance and its ability to maintain optimal moisture level for plants was analysed.

Complex application of loosening and organic fertilizers provided improvement of soil physical and chemical properties. It was expected that loosening would reduce soil density, increase its aeration and water permeability, and the application of organic matter would increase humus content, increase nutrient element availability and soil water-holding capacity. The change in the number of soil microorganisms was evaluated as an indicator of soil biological activity. Numbers were determined by culturing on selective nutrient media, which made it possible to trace the dynamics of microbial activity change. Measurements were carried out during the vegetation period. Changes in soil physical properties, dynamics of water regime, humus and nutrient elements content, as well as activity of soil microbiota were analysed. The obtained data allowed objectively assessing the efficiency of applied ameliorative measures and their impact on soil fertility restoration. Changes in soil physical properties were assessed by measuring its density, porosity, and water permeability. Density was determined by taking cylindrical samples, which were weighed to calculate volumetric weight. Water permeability was analysed using infiltration rings to determine the rate of water infiltration into the soil. Filtration coefficient was calculated using the Darcy formula (1):

$$K = \frac{V}{F \times t}, \tag{1}$$

where K is the index of soil filtration capacity expressed in centimetres per hour (cm/h); V is the total volume of water that passed through the soil during the experiment (cm^3); F is the cross-sectional area of the infiltration ring through which infiltration occurred (cm^2); t is the duration of the infiltration process measured in hours (h).

Soil chemical condition was studied on the basis of organic matter, nitrogen, phosphorus, and potassium content. The humus content was determined by the Turen method (DSTU 4289:2004, 2005), nitrogen was estimated by the Kjeldahl method (DSTU ISO 11261:2001, 2003), mobile forms of phosphorus were analysed by the standard colorimetric method (DSTU 4729:2007, 2008), and potassium content was determined by the flame photometric method (DSTU 7863:2015, 2016). All data were processed statistically using analysis of variance. The results were presented in the form of mean values with indication of standard errors, which provided reliability of data interpretation and allowed identifying reliable differences between control and treated plots.

RESULTS

Changes in soil density and porosity before and after melioration measures

Before the experiment, compacted grey soil showed high density in the range of 1.45-1.6 g/cm^3, which is critical for plant growth. The pre-intervention soil density was 1.45-1.6 g/cm^3 and water permeability was extremely low (0.05-0.1 mm/min). A drip irrigation system was applied to maintain a stable soil moisture level.

Such density values limited soil permeability for water and air, creating unfavourable conditions for the development of the root system of wheat and maize. This problem was especially acute in areas with intensive irrigation, where insufficient water permeability led to stagnation and erosion processes (Yeraliyeva *et al.*, 2017). After reclamation measures, including deep loosening, application of organic fertilizers, as well as improvement of drainage system, soil density on the studied plots decreased on average by 15-20%. Final density values varied in the range of 1.2-1.35 g/cm^3, which corresponds to optimal conditions for most wheat and maize cultivated under irrigated farming conditions. This indicates a significant improvement of soil agrophysical properties, which is confirmed by both quantitative and qualitative indicators.

The decrease in soil density was accompanied by an increase in porosity, which is important for water and air permeability. Before reclamation, the total soil porosity was about 40-42%, which is obviously insufficient to ensure a normal regime of moisture storage and aeration. After the measures this indicator increased up to 50-55%, and active porosity, responsible for gas exchange and water availability for plants, increased by 25-30%. Particularly noticeable changes occurred in the upper soil layer (0-30 cm), where the bulk of plant roots are concentrated. This increase in porosity contributes not only to a better supply of moisture to plants, but also to an increase in the biological activity of the soil.

Reduction of soil density also had a positive effect on water permeability. Before reclamation measures, soil filtration coefficient was extremely low – from 0.05 to 0.1 mm/min, which led to frequent stagnation of water on the surface and reduction of irrigation efficiency. After the introduction of reclamation measures, this indicator increased to 0.25-0.35 mm/min. This allowed significantly improving moisture distribution over the soil profile, reducing the volume of surface run-off and minimising erosion risks. Moreover, the water-holding capacity of the soil increased, which is especially important in the arid conditions of the region, where regular moisture supply plays a key role for wheat and maize growth (Kamzina *et al.*, 2022).

The findings confirm that reducing soil density improved the mechanical structure of the soil. Soil aggregates with a diameter of 1-3 mm became more stable and their number increased by 30%. Before the measures, the stability of aggregates was 30-35%, whereas after reclamation this indicator increased to 50-55%. Soil structure stability is an important factor, preventing reconsolidation and ensuring its stability under mechanical impact such as tillage or irrigation (Fedoniuk *et al.*, 2019; Panchenko *et al.*, 2024). Changes in soil density and structure resulted in improved conditions for plant growth and higher yields. The reclaimed plots showed an increase in wheat and maize yields by 15-20% compared to control plots. This is due to improved water-air regime, increased availability of nutrients and creation of more favourable conditions for root system development. In addition, the reduction in soil density reduced energy inputs for mechanical cultivation of fields, which increased the overall profitability of agricultural production (Table 1).

***Table 1**. Changes in soil density and porosity before and after reclamation activities*

Parameter	Before reclamation	After reclamation	Change (%)
Soil density (g/cm^3)	1.45-1.6	1.2-1.35	-15-20
Total porosity (%)	40-42	50-55	+20-30
Filtration coefficient (mm/min)	0.05-0.1	0.25-0.35	+300-400
Aggregate stability (%)	30-35	50-55	+30-50
Yield (c/ha)	25-30	35-40	+15-20

Source:developed by the authors*

These results demonstrate the significance of application of complex reclamation for restoration and improvement of physical and mechanical properties of grey soils in conditions of irrigated farming in Zhambyl oblast. The obtained data highlight the practical benefits of measures aimed at reducing soil density, which in the long term contributes to reducing the need for fertilizers by improving the availability of nutrients, increasing soil resistance to drought due to improved water-holding capacity, as well as stabilising soil structure, reducing its susceptibility to erosion and compaction. These changes ensure sustainable development of the region's agricultural sector and increase the efficiency of farming in an arid climate.

Change of soil water regime indicators before and after reclamation measures

The results showed significant improvement of soil physical characteristics, its water permeability and resistance to erosion. Soil filtration coefficient increased by 300-400%, which provided significant improvement of water distribution in the soil profile. Before reclamation, the soil was characterised by extremely low water permeability, due to which a significant part of irrigation water remained on the surface, causing stagnation, water erosion and nutrient leaching. After the introduction of measures, water began to penetrate deeper, evenly distributed over the root layer, which contributed to improved conditions for plant growth.

A 60-70% reduction in surface run-off was also a key result. Before the measures, about 30-40% of irrigation water was lost as run-off, carrying away fertile topsoil and nutrients. After reclamation, this figure was reduced to 10-15%, which significantly reduced moisture losses and minimised soil degradation. Improved water-holding capacity, which increased by 20-25%, played an important role in stabilizing the water regime. This allowed the soil to retain moisture longer during dry periods, which was particularly important for the agricultural sector in Zhambyl province, where irrigated agriculture depended on the rational use of water resources.

Total soil porosity increased by 20-25%, which improved conditions for gas exchange and moisture retention, promoting the development of plant root systems. This directly influenced the efficiency of irrigation water use, allowing crops to receive moisture evenly even at minimum irrigation volumes. This effect was especially significant in conditions of intensive irrigation, where excessive saturation of soil with water previously caused its compaction and reduced productivity. Reduction of soil erosion losses by 70-80% was another significant achievement. Before reclamation, annual soil losses due to water erosion were 4.5-5 tonnes/ha, which worsened its fertility. After implementation of measures, this indicator decreased to 1-1.5 tonnes/ha. This improvement was explained by increased soil resistance to surface water flows due to improved soil structure and increased organic matter content. Organic matter, the content of which increased by 15-20%, contributed to the formation of water-resistant aggregates, making the soil more resistant to erosion and leaching. The 15-20% increase in wheat and maize yields confirmed the positive impact of reclamation on soil productivity. Improvement of water regime created favourable conditions for plant growth, providing their access to water and nutrients. Especially it was reflected on grain crops yield, which increased from 25-30 c/ha to 35-40 c/ha.

The increase in the number of soil microorganisms by 25-30% also confirmed the positive impact of reclamation on the soil. Biological activity increased due to improvement of its moisture and structure, which created favourable conditions for microbiological activity. Microorganisms played a key role in the processes of organic matter decomposition and transformation of nutrients into forms available for plants. The growth of their number contributed to the increase of natural fertility of soil, making it more resistant to degradation (Table 2).

***Table 2**. Changes in soil water regime indicators before and after reclamation activities*

Parameter	Before melioration	After melioration	Change (%)	Notes
Filtration coefficient (mm/min)	0.05-0.1	0.25-0.35	+300-400	Improved infiltration and moisture redistribution
Surface run-off (% of volume)	30-40	10-15	-60-70	Reduction of water loss and erosion processes
Total porosity (%)	40-42	50-55	+20-25	Increasing pore volume for water and air
Water holding capacity (%)	18-20	23-25	+20-25	Preserving moisture during dry periods
Soil erosion losses (t/ha)	4.5-5	1-1.5	-70-80	Reducing the risk of fertile soil layer washout
Grain yield (c/ha)	25-30	35-40	+15-20	Improving conditions for plant growth and development
Organic matter content (%)	1.2-1.4	1.6-1.8	+15-20	Increasing the water-retaining properties of the soil
Number of soil microorganisms (thousand/g of soil)	2.5-3	3.8-4.2	+25-30	Increased activity due to optimal water regime

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

The complex effect of reclamation measures was manifested in the improvement of all key soil characteristics. Increase in filtration coefficient, decrease in surface run-off and erosion losses, increase in water retention capacity and total porosity – all this contributed to a significant increase in fertility of sierozem soils. These results confirmed that integrated land reclamation was an effective tool for improving soil physical and chemical properties and an important factor for sustainable development of the agricultural sector under irrigated farming conditions.

Changes in organic matter and nutrient content

Before reclamation activities, the content of organic matter in the soil was at a low level – on average 1.2-1.4%. This limited the soil's ability to retain moisture and nutrients and reduced its biological activity. Low organic matter content also worsened the structural characteristics of the soil, making it prone to compaction and erosion. After the implementation of a set of measures including organic fertilizers, siderates and improved drainage system, the organic matter content increased by 15-20%, reaching 1.6-1.8%. This significant increase in organic matter improved the physical, chemical and biological properties of the soil, making it more resilient and more productive. The increase in organic matter content was accompanied by an increase in available nutrient elements such as nitrogen, phosphorus, and potassium. Before reclamation, the level of available nitrogen in the soil was about 40-50 mg/kg, which was insufficient to ensure normal plant growth. After the measures, this indicator increased by 25-30%, reaching 60-65 mg/kg. Similar changes were recorded for phosphorus: its content increased from 15-20 mg/kg to 25-30 mg/kg. Potassium availability also increased by 20-25%, which strengthened the overall nutrient balance of the soil. These changes were related both to the application of organic fertilizers and to the activation of soil microorganisms, which accelerated the decomposition of organic matter and the transformation of nutrient elements into available forms.

Chemical changes in the soil were also due to the improvement of its structure and water regime. The increase in organic matter content favoured the formation of water-stable aggregates, which prevented the leaching of nutrients and increased their availability to plants. Due to this, the balance of nitrogen, phosphorus, and potassium in the soil became more stable, which created conditions for uniform nutrition of plants throughout their vegetation period. The increase in available nutrient elements directly contributed to higher yields, which increased by 15-20% compared to control plots. The research also revealed an increase in the number of soil microorganisms, which is an indicator of soil biological activity. Their numbers increased by 25-30%, which indicated the creation of favourable conditions for microbiological processes such as mineralisation of organic matter and nitrogen fixation. This growth additionally contributed to the increase of available nutrients and strengthening of natural soil fertility (Fig. 1).

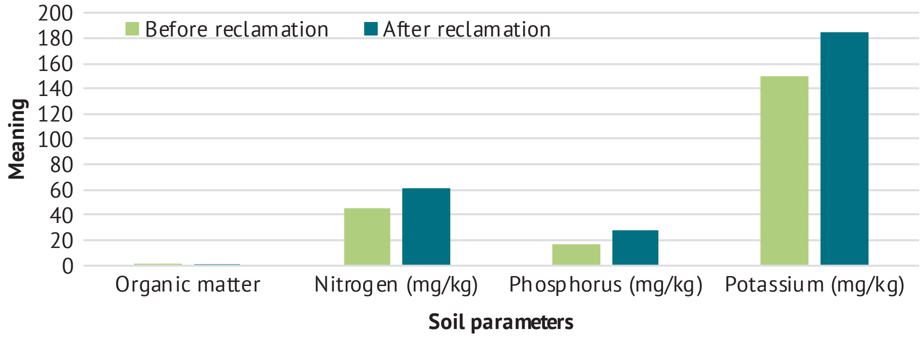

***Figure 1**. Changes in organic matter and nutrient content*

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

The increase in the content of organic matter and nutrient elements had a complex positive impact on the ecological sustainability and productivity of the studied soils. These changes made the soil more resistant to degradation processes, such as compaction and erosion, and improved its ability to withstand external stresses, including intensive irrigation and mechanical cultivation.

Changes in the number of soil microorganisms and their impact on soil parameters

Before reclamation, the number of microorganisms was at low level – on average 2.5-3 thousand/g of soil. This limited the processes of organic matter mineralisation and worsened biological productivity of soil. The reason for low activity was both insufficient moisture and availability of organic matter and compacted soil structure, which prevented oxygen access. After a set of reclamation measures, including deep loosening, application of organic fertilizers and improvement of water regime, the number of microorganisms increased by 25-30%, reaching 3.8-4.2 thousand /g of soil. This increase was attributed to improved conditions for microbial activity, including higher moisture levels, increased organic matter content and improved gas exchange in the soil.

The restoration of soil biological activity was also manifested in the acceleration of organic matter decomposition processes. Increased microbial populations contributed to more efficient mineralisation, making nutrients such as nitrogen, phosphorus, and potassium available to plants. This in turn contributed to higher yields of wheat and maize. The increase in soil biological activity also had a positive effect on its resistance to degradation processes. The increase in the number of microorganisms favoured the formation of water-stable aggregates, which increased the structural stability of the soil. This reduced the risk of compaction and erosion, especially under conditions of intensive irrigation (Table 3).

***Table 3**. Changes in the number of soil microorganisms and their impact on soil parameters*

Parameter	Before reclamation	After reclamation	Change (%)
Number of microorganisms (thousand/g)	2.5-3	3.8-4.2	+25-30
Rate of organic decomposition (%)	50-55	65-70	+20-25
Humus content (%)	1.2-1.4	1.6-1.8	+15-20
Nitrogen availability (mg/kg)	45-50	60-65	+25-30
Soil structure stability (%)	30-35	50-55	+40-50

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

The restoration of biological activity played a key role in maintaining ecological balance. Microorganisms, decomposing organic matter, not only provided plants with nutrients, but also contributed to the accumulation of humus, which improved the physical and chemical properties of the soil. The increase in the number of microorganisms confirmed the effectiveness of reclamation measures in increasing the natural fertility of grey soils.

Distribution of yield before and after melioration

The results of the research showed that complex reclamation significantly increased the yield of wheat and maize on the studied plots. Before reclamation measures, grain yields were 25-30 kg/ha, which was below the average level for irrigated farming conditions in Zhambyl oblast. The main limiting factors were compacted soil structure, low water permeability, weak biological activity and lack of available nutrients. After reclamation measures, yields increased to 35-40 kg/ha, which corresponded to an increase of 15-20%. Such increase was explained by improvement of water regime, chemical and biological properties of soil. Due to the decrease in soil density and increase in its porosity, the access of plant roots to water and air improved. In addition, the increased content of organic matter and available nutrients provided plants with everything they needed for active growth and yield formation. The even distribution of moisture throughout the soil profile helped to minimise the risk of drought, which is particularly important in a hot climate region. Increased water permeability and reduced surface run-off helped to reduce water and nutrient losses, providing plants with optimal nutritional conditions throughout the growing season. This played a key role in increasing yields.

An additional factor in yield growth was the activation of soil microflora. The increase in the number of microorganisms improved the decomposition of organic matter, accelerated the transformation of nutrients into available forms and contributed to the accumulation of humus. All this created more favourable conditions for root system growth and efficient resource assimilation (Fig. 2).

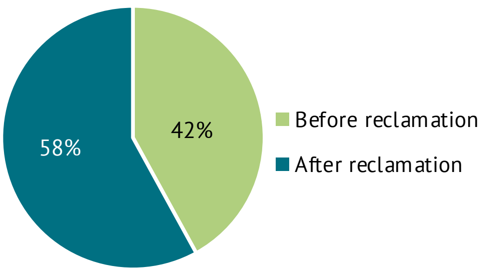

Figure 2*. Yield distribution before and after reclamation*
Source: *developed by the authors*

As a result of reclamation measures, the efficiency of crop cultivation has also increased. The increase in crop yields led to an increase in the profitability of agricultural production, while the reduction of fertilizer and irrigation costs due to improved soil properties allowed optimizing costs. These results confirmed the feasibility and efficiency of application of integrated land reclamation to increase the productivity of irrigated lands.

DISCUSSION

The results of the study showed that complex ameliorative measures effectively improve physical, chemical and biological properties of compacted grey soils of Zhambyl oblast. Reduction of soil density by 15-20% after deep loosening was accompanied by a significant increase in water permeability, which increased by 300-400%. These changes ensured improvement of soil water regime, promoted uniform distribution of moisture in the root layer and reduced erosion risks. The application of organic fertilizers increased the humus content of the soil by 15-20%, which had a positive effect on its fertility. Organic matter improved soil structure, increased its water-holding capacity and provided nutrients necessary for plant growth. The biological activity of the soil also increased, as evidenced by a 25-30% increase in the number of microorganisms. This indicates the activation of microbiological processes that play an important role in decomposition of organic matter and increasing the availability of nutrient elements (Kravchuk *et al.*, 2024).

Studies by C. Kimani (2021) and L.M. Giuliani *et al.* (2024) emphasise the need for an integrated approach to address soil degradation caused by intensive land use and anthropogenic factors. C. Kimani notes that increasing population density leads to increased pressure on soil resources, which contributes to their compaction, loss of organic matter and reduction of overall productivity. This creates additional difficulties for land rehabilitation, especially under intensive farming conditions. L.M. Giuliani *et al.* point out the importance of introducing systematic monitoring of soil conditions. The authors argue that regular monitoring of key characteristics such as density, humus content and water permeability allows timely identification of degradation zones and the development of effective restoration strategies. This study similarly demonstrates that reducing soil density and improving its water regime play a crucial role in restoring fertility. The use of reclamation measures such as deep loosening and organic enrichment significantly improved soil physicochemical properties.

The works of T.S. Telles *et al.* (2022), and D.C. Reicosky and A. Kassam (2021) highlight conservation agriculture as a key approach to the restoration of degraded soils. T.S. Telles *et al.* emphasise that minimum tillage and conservation of crop residues improve soil structure, reduce erosion and increase resilience. D.C. Reicosky and A. Kassam highlight maintaining carbon balance in the soil to improve its chemical properties and reduce carbon dioxide emissions. These approaches focus on maintaining the natural balance of the soil and minimizing its mechanical impact. The present study also demonstrated the importance of soil organic enrichment, but the approach taken was more comprehensive. The use of deep loosening has significantly improved the physical characteristics of the soil, including its porosity and water-holding capacity. This is particularly important in the arid climate of Zhambyl Oblast, where soils are prone to compaction and moisture loss. In contrast to methods based on minimum tillage, in this study it was shown that deep loosening in combination with organic fertilizers creates favourable conditions for soil regeneration.

A. Rivera *et al.* (2023) and R.G. César *et al.* (2021) emphasise the influence of the surrounding landscape and soil chemistry management on soil recovery. A. Rivera *et al.* point out the application of microfertilizers to improve soil chemical properties and productivity. R.G. César *et al.* emphasise the role of vegetation cover and landscape context in maintaining soil resilience and preventing erosion, noting that the use of natural mechanisms contributes to long-term land restoration. This study shows that water management, including drip irrigation, promotes even distribution of moisture, which improves its availability to the plant root system and prevents surface run-off. In contrast to the above studies, the main focus is on internal soil changes, such as reduction of density and improvement of structure, which creates favourable conditions for microbiological activity. The activation of microbial communities helps to accelerate the decomposition of organic matter and increase the availability of nutrient elements for plants (Onopriienko *et al.*, 2023). This approach makes the proposed measures not only effective, but also adapted to the conditions of intensive agricultural use, especially in regions with arid climate.

In the studies of A. Kırcı and F. Türkmen (2023) and J.C. Nwite (2021), the authors emphasise on changes in land use and their effects on soil physical and chemical properties. A. Kırcı and F. Türkmen point out that long-term land use without considering erosion factors leads to loss of organic carbon and deterioration of soil structure. The authors point out that soil restoration is possible by improving organic matter management and erosion control. J.C. Nwite, on the other hand, focuses on the importance of nutrient replenishment through fertilizer application to improve soil fertility and productivity. In this study, as in these studies, it is demonstrated that the application of organic fertilizers improves soil chemical properties. However, unlike these studies, here we additionally consider the impact of reclamation measures on soil physical characteristics, including reducing density and increasing water retention capacity, which makes the approach more comprehensive and effective for intensive agriculture.

In the works of S. Lieder and C. Schröter-Schlaack (2021), and M. Jafari *et al.* (2022), the authors discuss modern approaches to soil management, including the use of technology and vegetation to restore soil properties. S. Lieder and C. Schröter-Schlaack highlight smart farming as a tool to improve soil management accuracy, minimise water loss and improve soil productivity. M. Jafari *et al.* emphasise the role of vegetation cover in preventing erosion and restoring degraded land. In this study, the use of drip irrigation has effectively managed the water regime by providing uniform moisture distribution. However, the difference lies in the study of internal soil changes, such as activation of biological processes and improvement of its structure, which makes the proposed measures more adapted to the conditions of arid climate and intensive land use.

Studies by Y. Ulko (2022) and S. Laiskhanov *et al.* (2023) focus on approaches to fertility restoration and land reclamation. Y. Ulko emphasises that innovative agro-ameliorative approaches, including soil structure improvement and soil fertility management, play an important role in improving the productivity of agricultural land. S. Laiskhanov *et al.* consider the rehabilitation of abandoned land through ecological and reclamation measures, emphasizing the importance of improving organic matter content. This study similarly finds that a combination of deep loosening and organic fertilizer application contributes to the restoration of soil structure. However, additional attention is paid to improving water regime and biological activity, which makes the proposed measures more universal and adapted for use in the conditions of Zhambyl oblast.

In the studies of S. Kaldybaev *et al.* (2022) and Z. Mazhitova *et al.* (2022), the authors emphasise the need for adaptive approaches to land reclamation in Central Asia and Kazakhstan, taking into account the ecological conditions of the region. S. Kaldybaev *et al.* focus on landscape solutions, such as regulating water flows and minimizing erosion, to rehabilitate degraded lands. Z. Mazhitova *et al.* analyse the environmental impacts of virgin and fallow land development, including soil degradation caused by intensive farming. Both studies agree that restoration of soil structure and chemical composition is the basis for sustainable land use. This study supports these conclusions by demonstrating that reclamation measures, including deep loosening and application of organic fertilizers, effectively restore soil structure, improve its water-holding capacity and reduce erosion risks. However, the difference is that this study additionally considers biological aspects, including the activation of microbial communities, making the approach more comprehensive and versatile. S. Kaldybaev *et al.* also draw attention to the importance of water management to prevent overuse. This aspect echoes the results of this study, where the use of drip irrigation reduced surface run-off and ensured uniform moisture distribution, contributing to the restoration of the soil water regime.

In studies by P. Smith *et al.* (2024) and F.B. Baloch *et al.* (2024), the authors examined the influence of soil characteristics on the sustainability of agricultural ecosystems. P. Smith *et al.* emphasised the global state of soils, stressing the importance of maintaining soil structure and fertility to prevent degradation. At the same time, F.B. Baloch *et al.* analysed the effects of volatile organic compounds produced by rhizobacteria on plant nutrition and soil health. Both studies confirmed that active management of soil properties significantly increased its productivity and tolerance to stress conditions. This study similarly demonstrated that reclamation improved the physical and chemical characteristics of the soil, but additional attention was paid to its biological activity, including microbial abundance and its role in organic matter decomposition.

New approaches to the study of soil stability were presented in the works of G. Ntsomboh-Ntsefong *et al.* (2024), Z. Haj-Amor *et al.* (2022) and W.-P. Zhang *et al.* (2024). G. Ntsomboh-Ntsefong *et al.* considered innovative technologies to improve soil productivity, including conservation agriculture and biofertilizers. Z. Haj-Amor *et al.* analysed the effect of salinity on microbial communities and yields, proving that high salt concentration impaired soil regeneration capacity. W.-P. Zhang *et al.* studied agronomic systems with different rooting strategies, confirming that integrated practices increased water-holding capacity and improved soil physical structure. This study supported the findings of these works, demonstrating the significant effect of reclamation on improving soil properties. However, the main difference was the combination of mechanical loosening with biological enrichment of soil with organic fertilizers, which provided sustainable results under arid climate conditions. In contrast to W.-P. Zhang *et al.*, not only the influence of agronomic strategies, but also the dynamics of soil microorganisms involved in organic matter decomposition were studied here.

Thus, these studies support the need for an integrated approach combining landscape, chemical and biological measures to restore degraded land. However, the methods proposed in this study stand out for their application and effectiveness in arid climate conditions.

CONCLUSIONS

The study was aimed at development and justification of effective reclamation measures to improve the condition of compacted grey soils of irrigated lands in Zhambyl oblast. An integrated approach including physical, chemical and biological methods of soil rehabilitation allowed studying in detail the impact of reclamation measures on its key properties. The main focus was on reducing soil density, improving its water regime, increasing the content of organic matter and activating biological processes.

The results of the experiment showed that the use of deep loosening reduced soil density by 15-20%, which improved its porosity and promoted better air and water penetration. Soil water permeability increased by 300-400%, which was the basis for uniform moisture distribution in the soil profile. This minimised water losses through surface run-off by 60-70%, which is particularly important for erosion prevention and nutrient conservation. The application of organic fertilizers provided a significant increase in humus content by 15-20%, which improved the chemical composition of the soil. The increase in organic matter improved its water-holding capacity and the availability of key nutrients such as nitrogen, phosphorus, and potassium. These changes were directly reflected in improved conditions for plant growth and productivity. Special attention in the study was paid to the biological activity of the soil. The analysis showed that the number of microorganisms increased by 25-30%, which indicates the activation of microbiological processes. This improved decomposition of organic matter and increased availability of nutrient elements for plants, which plays a key role in restoration of soil fertility. Application of the proposed ameliorative measures contributed to an increase in wheat and maize yields by 15-20%. This confirms that an integrated approach including deep loosening, organic enrichment and water regime management is an effective method to restore degraded soils.

Thus, the conducted study has demonstrated that integrated reclamation measures allow not only to improve physical and chemical properties of soil, but also to activate its biological processes. These methods can be recommended for wide application in arid regions, where rehabilitation of degraded lands is critical for sustainable agricultural production. Prospects for further research include long-term monitoring of changes in soil characteristics under the influence of reclamation measures, as well as the study of optimal dosages and types of organic fertilizers. Additionally, it is necessary to assess the impact of land reclamation on soil microbiological community and its relationship with yield in long-term dynamics.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Обґрунтування впливу комплексної меліорації на родючість ущільнених сіроземних ґрунтів зрошуваних земель Жамбилської області

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Анотація. Метою дослідження була розробка ефективних методів поліпшення фізичних, хімічних і біологічних властивостей ґрунту для підвищення його продуктивності та стійкості до деградації в умовах інтенсивного сільськогосподарського використання. У статті представлено дослідження впливу комплексних меліоративних заходів на відновлення ущільнених сероземів в умовах зрошуваних земель Жамбилської області. Експериментальна частина включала застосування глибокого розпушування та внесення органічних добрив, а також управління водним режимом з використанням крапельного зрошення. Результати дослідження засвідчили, що меліоративні заходи дали змогу знизити щільність ґрунту на 15-20 %, що забезпечило поліпшення його структури та збільшення водопроникності на 300-400 %. Це створило умови для більш рівномірного розподілу вологи в кореневмісному шарі, що мінімізувало поверхневий стік на 60-70 % і запобігло втратам поживних речовин. Внесення органічних добрив сприяло збільшенню вмісту гумусу на 15-20 %, що поліпшило хімічний склад ґрунту та підвищило його здатність утримувати поживні елементи. Особливу увагу приділено біологічній активності ґрунту, яка зросла на 25-30 % за рахунок активізації мікробних спільнот. Ці зміни покращили процеси розкладання органічної речовини та підвищили доступність азоту, фосфору і калію для рослин. У результаті застосування комплексних заходів спостерігалося збільшення врожайності пшениці та кукурудзи на 15-20 %, що підтвердило ефективність запропонованих підходів. Зроблені висновки демонструють, що використання глибокого розпушування, органічного удобрення та краплинного зрошення в комплексі є ефективним методом відновлення деградованих сероземів. Результати дослідження мають значущу практичну цінність і можуть бути рекомендовані для впровадження в сільськогосподарське виробництво в посушливих регіонах

Ключові слова: меліорація; зрошення земель; родючість ґрунтів; урожайність культур; глибоке розпушування; екологічні технології; сільськогосподарська продуктивність; водопроникність

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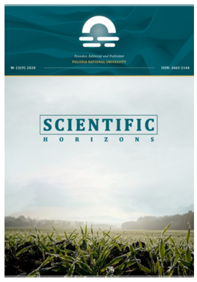

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Bioconversion of livestock by-products into biogas: Experimental study of optimal fermentation conditions

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Abstract. The bioconversion of organic waste into biogas is a substantial part of the company's strategy for sustainable development and reducing its environmental impact. The key factors affecting the efficiency of this process are fermentation temperature, carbon-to-nitrogen (C/N) ratio and substrate type. The study aimed to

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investigate the effect of temperature conditions, C/N ratio and different types of organic waste on biogas yield, particularly methane concentration, during anaerobic fermentation. Two temperature conditions were compared in the experiment: mesophilic (35°C) and thermophilic (55°C), using three types of organic waste: poultry manure, cattle manure and pig manure. The optimal C/N ratio was also studied to improve the energy efficiency of the process. Under thermophilic conditions, an increase in biogas yield by 20-28% and an increase in methane concentration by 5-10% were recorded compared to the mesophilic regime. The highest biogas yield (0.42 m^3/kg of organic dry matter (OSR)) and methane concentration (70%) were achieved with poultry manure. In the thermophilic regime, the time to achieve stable gas production was also reduced to 7-8 days, which confirmed the effectiveness of this approach for industrial use. The thermophilic fermentation mode is more efficient for biogas production and increases the energy efficiency of the process. Optimisation of the C/N ratio and co-fermentation of different substrates further improved the efficiency. Poultry manure proved to be the most efficient substrate for bioconversion, which opens prospects for its use on an industrial scale. The results of the study can be used to optimise biogas fermentation technologies to improve the performance of biogas plants and reduce energy costs

Keywords: renewable energy sources; organic waste; methane; anaerobic fermentation; thermophilic mode; mesophilic mode

INTRODUCTION

The growing demand for renewable energy sources is driving the development of innovative technologies aimed at the efficient use of organic waste. One of the most promising areas is the bioconversion of livestock by-products into biogas through anaerobic fermentation. This process produces methane, a valuable energy resource while reducing the amount of organic waste and related environmental problems. An important factor affecting the efficiency of the biogas fermentation process is the temperature regime, which significantly changes the speed and quality of biogas fermentation (Danylyshyn & Koval, 2023). Mesophilic and thermophilic fermentation regimes have their advantages and disadvantages depending on the type of substrate (Kovtun & Merzlov, 2023). In this regard, research on the effect of temperature on the bioconversion of organic waste is relevant. For instance, C. Morales-Polo *et al.* (2021) noted that temperature changes can significantly alter the energy and environmental potential of bioconversion using the example of barley residues processing into biogas in Spain. Such studies determined the mechanisms that affect the efficiency of these processes in greater detail.

Despite numerous scientific developments, there is a lack of research on specific substrates and conditions that ensure maximum biogas yields at different temperature conditions. The problem of biogas fermentation efficiency depending on the type of substrate, is understudied. N. Yahmed *et al.* (2021) consider the processing of date palm waste into biogas, biohydrogen, and date syrup, noting the high potential of such waste, but without specific conclusions on the optimal fermentation conditions. The study by M. Djaafri *et al.* (2019) adds important information on the biogas fermentation of date palm leaves under anaerobic digestion conditions but does not consider the effect of temperature. Expanded use of agro-industrial waste, in particular poultry manure and cattle manure, which are promising substrates for biogas plants, is emphasised. G. Leni *et al.* (2021) underline the importance of new opportunities for the utilisation of agricultural waste, in particular through the use of insects that can process organic waste into biogas. However, there is no generalised data yet on how temperature affects these types of substrates. Other studies, such as the work of V. Kumar *et al.* (2022), focus on bioinoculants for organic waste biodegradation and agricultural waste bioconversion, which indicates the importance of optimising fermentation processes to achieve high efficiency.

One of the key issues requiring further study is the optimisation of the biogas fermentation process for different types of organic waste. A. Rashwan *et al.* (2023) demonstrated the importance of food and agricultural waste processing to combat climate change, highlighting the need to optimise technologies to maximise the efficiency of these processes. According to their study, the use of agricultural waste for biogas production can substantially reduce greenhouse gas emissions. F. Ranjbar *et al.* (2022) studied the use of wheat straw in anaerobic cofermentation with cattle manure, which increases biogas yields and reduces the need for additional energy. The study highlighted that such a combination of substrates can be more efficient than using each type of waste separately, especially in conditions of limited resources. The study by N. Mahato *et al.* (2021) focuses on the bioconversion of citrus waste into biofuels and valuable compounds through fermentation, which can be an important component in the introduction of alternative energy sources. The authors noted that waste such as orange peels can be a significant source for biogas production, rendering the process even more cost-effective. The use of agricultural waste is not limited to biogas production (Donchak & Shkvaruk, 2024). J. Tuly *et al.* (2022) demonstrated the possibility of processing agricultural waste into valuable peptides through solid-state fermentation of *Bacillus* sp.

mutant, which is also a promising area for extracting additional value from agricultural waste. However, this requires further research into the fermentation conditions and specific characteristics of different types of waste. The study of anaerobic digestion technologies used for agro-industrial waste remains an important stage of development. A. Neri *et al.* (2023) provide an overview of anaerobic fermentation for biomethane production from agricultural and food waste, highlighting the importance of optimising these processes to increase productivity and energy efficiency.

These studies indicated the significant potential of biogas technologies and the existence of gaps in knowledge regarding the interaction of temperature regimes and substrate types in biogas plants. The study aimed to determine the optimal fermentation conditions for maximising the yield of biogas with a high methane content using different types of livestock by-products.

MATERIALS AND METHODS

The study was conducted between February and July 2024. The sample consisted of three main types of livestock by-products that are widely used in the biogas industry: cattle manure – collected from the Elita farm in Poltava region. This farm specialises in the production of agricultural products and has a stable record of high-quality by-products. Pig manure was sourced from the commercial pig farm Podillya-Agroprodukt, located in the Vinnytsia region. The poultry manure was collected from the Yasensvit poultry farm located in the Kyiv region. This enterprise is one of the leaders in the production of chicken eggs and poultry by-products in Ukraine.

The criterion for inclusion in the sample was a high content of organic matter – at least 70% of dry weight. Measurements were made using an organic matter analyser (Shimadzu TOC-L, Japan); absence of foreign impurities – substrates should not contain bedding materials (straw, sawdust), sand, stones or other insoluble inclusions. This was checked by visual inspection and sieving through a 2 mm mesh. Exclusion criteria: Preservatives – samples should not be treated with chemicals (formaldehyde, urea, etc.) for long-term storage. Information about the methods of substrate treatment was verified by interviewing suppliers. Treatment of materials with chemicals – samples that were exposed to pesticides, herbicides or other pollutants were excluded from the study. Before being loaded into the bioreactors, all samples were pretreated by drying at 105°C for 24 hours, grinding to a fraction of less than 2 mm, and standardising the dry matter content (8%). This drying temperature and duration are commonly used as a baseline in laboratory practice to prepare samples for further experiments and to obtain stable and reproducible results.

Several methods were used in the study to determine the biogas yield and methane concentration. The biogas yield was determined by collecting the gas produced during fermentation and measuring its volume under normal pressure and temperature (Nm^3/t). The experiment was carried out in laboratory anaerobic bioreactors Biostat B (Sartorius, Germany) with a volume of 10 litres (working volume – 8 litres). The bioreactors were equipped with temperature, pH, and gas pressure control systems, as well as gas outlet systems for biogas collection. The substrates were loaded into the bioreactors, adding water to achieve an optimal consistency (8% dry solids). Each substrate was tested at two temperature conditions: mesophilic (35°C) and thermophilic (55°C), which are standard and common for many microbiological and biotechnological processes such as composting, anaerobic digestion and fermentation, as well as under normal conditions (temperature: 0°C (273.15 K), pressure: 101.325 kPa (1 atmosphere)). The thermophilic mode, at 55°C, provides a significantly higher biogas yield and reduces the time to reach stable gas production.

The fermentation process lasted 30 days for each type of substrate. The control parameters included biogas volume, methane concentration and time to reach a stable gas yield. To determine the effect of the carbon to nitrogen (C/N) ratio, each substrate was tested at three values: 20:1, 25:1, and 30:1. The ratio was adjusted by adding corn silage or ammonium nitrate. The volume of biogas was recorded using gas meters connected to the bioreactor systems. The methane concentration was determined by gas chromatography using an Agilent 7890A instrument with a thermocouple detector. The fermentation time was determined by the achievement of stable gas production (the daily gas volume changed by no more than 5%). The collected data were processed using SPSS v.27 software. Analysis of variance was used to compare the groups. In addition to the Biostat B-Plus bioreactors (Sartorius, Germany), the study used an Agilent 7890A gas chromatograph (Agilent Technologies, USA) to analyse the composition of biogas, an automatic pH meter Mettler Toledo SevenCompact (Mettler Toledo, Switzerland) to monitor acidity, and a laboratory balance Radwag AS 220.X2 (Radwag, Poland) for accurate dosing of components.

RESULTS

The study obtained comprehensive data on the effect of fermentation temperature, substrate type and C/N ratio on biogas yield and its quality composition. The influence of temperature on the bioconversion of organic waste. Temperature is a critical factor that determines the efficiency of fermentation processes in biogas plants. The study compared two temperature regimes – mesophilic (35°C) and thermophilic (55°C) – to determine how temperature affects biogas yield and quality composition depending on the type of substrate. The mesophilic regime (35°C) of fermentation ensures stable gas production 10-12 days after the start of the process. The following results were obtained for different types of substrates: for poultry manure, the biogas yield was 0.35 m^3/kg of organic dry matter (OSR), which is the highest among the substrates studied (Fig. 1). The methane concentration in the biogas was 60-65%. The biogas yield from cattle manure was 0.28 m^3/kg OSR, while the methane content in biogas reached 60%, which is slightly lower than in poultry manure. For pig manure, the biogas yield was 0.25 m^3/kg OSR, which is the lowest among all the substrates studied in the mesophilic regime. However, despite this, the methane concentration in the biogas reached 62%, which is a significant indicator for this type of organic matter. Along with the highest biogas yield, poultry manure showed a good methane concentration, which indicates its potential for use in biogas plants due to its high nitrogen content, which contributes to greater methane production with an appropriate C/N ratio adjustment.

In the thermophilic regime (55°C), the results are as follows: biogas yield from poultry manure increased to 0.42 m^3/kg OSR, which is 20% more than in the mesophilic regime. The methane concentration in the biogas increased to 70%. This indicates the high potential of such a substrate in the thermophilic regime, especially given its high amount of organic matter and optimal C/N ratio. In the study of cattle manure, the biogas yield was 0.36 m^3/kg OSR, which is 28% higher compared to the mesophilic regime. The methane concentration reached 68%, which is a significant improvement compared to the mesophilic regime. Pig manure at thermophilic temperature demonstrates an increase in biogas yield of 0.31 m^3/kg OSR. The methane concentration in biogas from cattle manure increased to 65%, which is the optimal value for energy-efficient biogas production. Reducing the time to achieve stable gas production to 7-8 days in the thermophilic mode is another significant result, as it reduces the overall cost of the fermentation process and increases the overall efficiency of the biogas plant.

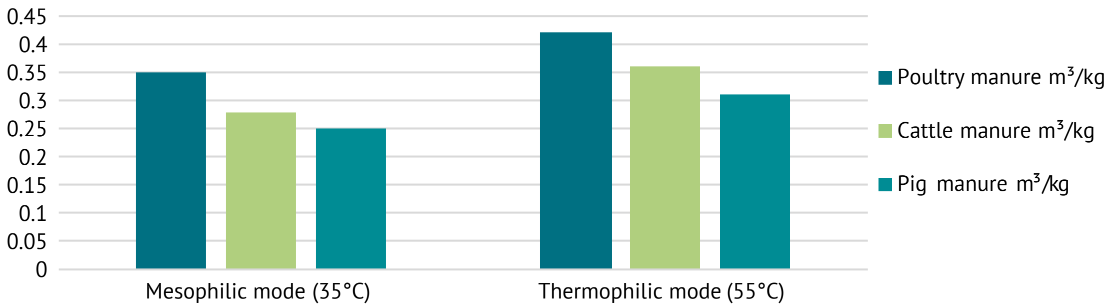

***Figure 1**. Indicators of biogas yield from the studied substrates*

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

The results of the analysis of variance showed that the thermophilic regime has a statistically significant effect on increasing biogas yield and methane concentration compared to the mesophilic regime ($p < 0.05$). Poultry manure showed the highest results, biogas yield increased by 20% and methane concentration by 10%, which confirms the advantages of using this substrate in the thermophilic mode. Cattle manure and pig manure also showed a significant improvement in indicators, but less pronounced than poultry manure. The type of substrate is one of the main factors determining the efficiency of the bioconversion of organic waste into biogas. Different types of manure have different characteristics that affect the biogas and methane yields, as well as the overall energy efficiency of the process (Kucher *et al.*, 2022). The study examines the efficiency of the main types of substrates, namely poultry manure, cattle manure and pig manure.

Poultry manure demonstrated the highest performance among all the substrates tested. The average biogas yield from poultry manure was 140 Nm^3/t of substrate, and the methane yield was 90 Nm^3/t of substrate. These indicators indicate the high efficiency of poultry manure in the biogas fermentation process, which is explained by the high nitrogen content, which contributes to the formation of methane in the process of anaerobic decomposition. In addition, poultry manure has an optimal C/N ratio, which achieves higher methane concentrations in biogas, especially under thermophilic fermentation conditions (55°C), where its potential is fully revealed. Cattle manure is the second most efficient substrate among the tested substrates. The average biogas yield from this substrate was 80 Nm^3/t of substrate, and the methane yield was 34 Nm^3/t of substrate. Due to its high organic matter content and more balanced C/N ratio (approximately 25:1), cattle manure demonstrates high biogas and methane yields and, therefore an effective substrate for fermentation processes in both mesophilic and thermophilic fermentation modes.

Pig manure demonstrated the lowest biogas, and methane yields of all the substrates studied. The average biogas yield from pig manure was 28 Nm^3/t of substrate, and the methane yield was 17 Nm^3/t of substrate. This is attributed to the lower level of organic matter in pig manure and the less-than-optimal C/N ratio. However, pig manure, if the C/N ratio is optimised (e.g., with corn silage or ammonium nitrate), can show a significant improvement in biogas yield by 15-20%, making it more efficient in fermentation processes than poultry manure with an incorrect ratio. The C/N ratio is a critical factor for efficient biogas fermentation, as it affects the activity of the microorganisms in the bioconversion process. The balance between C/N in the organic substrate determines the rate of decomposition and the amount of biogas produced, as well as its composition, particularly the methane content. Correction of the C/N ratio is an important factor in improving biogas yield and methane concentration when using different types of manure in biogas plants. The optimal C/N ratio varies depending on the type of substrate, and correcting this parameter by adding corn silage or ammonium nitrate to the substrate significantly increases the fermentation efficiency (Table 1).

***Table 1**. Biogas yield and methane concentration before and after C/N correction for different types of manure*

Type of substrate	C/N ratio	Biogas yield before correction (m^3/kg OSR)	Methane concentration before correction (%)	Biogas yield after correction (m^3/kg OSR)	Methane concentration after correction (%)
Cattle manure	25:1	0.36	68	0.46	72
Pig manure	25:1	0.31	65	0.37	68
Poultry manure	30:1	0.42	70	0.5	74

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

For cattle manure, the optimal C/N ratio was 25:1. By adding corn silage or ammonium nitrate to correct the C/N ratio, the biogas yield increased by 28%, yielding 0.46 m^3/kg OSR. The methane concentration also increased to 72%, which increases the energy efficiency of the process. The optimal C/N ratio for pig manure was 25:1. When the C/N ratio was adjusted with the addition of corn silage or ammonium nitrate, the biogas yield increased by 20%, resulting in a result of 0.37 m^3/kg OSR. The methane concentration increased to 68%, which improves the overall fermentation efficiency. For poultry manure, the optimal C/N ratio was 30:1. The experiment showed that the correction of C/N in poultry manure leads to a 20% increase in biogas yield, which gives 0.5 m^3/kg OSR. The methane concentration increases to 74%, which ensures the maximum yield of energy-efficient biogas. Thus, the study showed that adjusting the C/N ratio significantly improves the efficiency of biogas fermentation. This is especially important for substrates with an uneven C/N ratio, such as pig manure or poultry manure. The addition of organic materials such as corn silage or ammonium nitrate balances the C/N ratio, which can increase the biogas yield by 15-20% for all types of substrates. This improves both the quantity and quality of biogas, particularly the methane concentration.

C/N adjustment has also been shown to improve the stability of the fermentation process by avoiding problems associated with too high or low nitrogen levels. The increase in methane concentration and decrease in carbon dioxide emissions as a result of the C/N ratio adjustment contributes to the energy efficiency of biogas plants and reduces the cost of the fermentation process (Pryshliak *et al*., 2021). Biogas is an important source of renewable energy, and its composition depends on various factors, such as the type of substrate, fermentation conditions, and the technology used to produce it. According to the results of the Agilent 7890A gas chromatograph, biogas produced by the anaerobic decomposition of organic materials consisted mainly of methane (CH_4) and carbon dioxide (CO_2), with smaller amounts of hydrogen sulphide (H_2S) and traces of other gases. Methane (CH_4) is the main component of biogas responsible for its energy value. Depending on the type of substrate and fermentation conditions, the methane content ranges from 50% to 70% of the total biogas composition (Pryshliak *et al*., 2021). Methane has a high calorific value, which makes it an ideal energy source for further use in generators or boilers to produce electricity and heat. Importantly, the higher the methane content, the more efficient the energy production process.

Carbon dioxide is the second main component of biogas, with a content ranging from 25% to 30%. CO_2 is the result of the anaerobic decomposition of organic materials, but it has no energy value as it cannot be used for energy production. However, its presence in biogas is a natural and unavoidable part of the process. To increase the energy efficiency of biogas, it is important to reduce the CO_2 content, as this allows for an increase in the methane concentration (Golub *et al.*, 2020). Hydrogen sulphide is a harmful component of biogas that is produced during the fermentation of organic materials containing sulphur, such as manure, poultry manure or food waste. Biogas typically contains up to 2% hydrogen sulphide. This gas is highly corrosive and can damage equipment, so its concentration must be monitored. A high H_2S content can also reduce the efficiency of biogas use for energy needs, as sulphur can contaminate engines and generators (Golub *et al.*, 2017). Therefore, additional methods are often used to purify biogas from hydrogen sulphide to reduce its content to a safe level.

Biogas may also contain other gases in trace amounts, such as ammonia (NH_3), nitrogen (N_2), water vapour and other volatile organic compounds. Their amount is usually minimal, but they can affect the overall composition of the gas and its quality. Thermophilic conditions, maintained at 55°C, can significantly improve the composition of biogas, by reducing impurities such as CO_2 and H_2S. Under thermophilic conditions, anaerobic microorganisms are more active, which accelerates the decomposition of organic materials and improves methanogenesis. Compared to mesophilic conditions, thermophilic conditions contribute to a reduction in CO_2 content – due to the more active activity of methanogenic microorganisms, the CO_2 content can be reduced in thermophilic conditions, which contributes to an increase in the methane concentration in biogas. An increase in methane concentration – 55°C provides better conditions for methanogenic archaea, which increases methane yield. As a result, the methane content in biogas can increase by up to 70%, which is a significant improvement compared to mesophilic conditions. Reduced hydrogen sulphide (H_2S) content – higher temperatures can reduce the concentration of hydrogen sulphide in biogas due to faster decomposition of sulphur-containing compounds or their absorption in other phases of the fermentation process (Skliar *et al.*, 2019).

The thermophilic regime also reduces the time to reach stable gas production, which is an important factor in increasing the overall efficiency of biogas plants. The analysis of the biogas composition shows that thermophilic operation is an effective way to improve the quality of biogas to reduce the content of impurities and increase the concentration of methane. This improves energy efficiency and reduces operating costs for gas treatment. As a result, thermophilic operation makes biogas plants more cost-effective and provides greater stability in energy production. The fermentation process is much faster in the thermophilic regime. Experimental results show that the time to achieve stable gas production is usually 7-8 days compared to 10-12 days in the mesophilic regime. As such, under thermophilic conditions, gas production stabilises twice as fast, which is an important factor for industrial biogas plants, where increasing the process speed can significantly increase productivity. Reducing the time to stable gas production allows for an increase in the number of substrates treated per unit of time. This is relevant in industrial biogas plants where biogas production is a continuous process. Increasing productivity by reducing the fermentation time increases the overall energy production efficiency, as the plant moves to the next fermentation cycle faster.

Reduced energy and resource costs are also achieved by shortening the fermentation time, as the process is faster, and less time is required to maintain the optimum temperature at all times. This also reduces the cost of heating the fermentation tanks, making the technology more economical. Reduction in the fermentation time also impacts the composition of the biogas. Thermophilic microorganisms that operate at high temperatures are more active and can decompose organic materials faster, leading to an increase in methane content and a decrease in impurities such as carbon dioxide and hydrogen sulphide. As a result, biogas becomes more energy efficient. In addition, high temperatures reduce the risk of pathogenic microorganisms, which can be a problem in mesophilic conditions where the likelihood of contamination increases. This ensures more stable and predictable biogas production (Skliar *et al.*, 2019).

Recommendations on the use of livestock by-products to improve the energy efficiency of the bioconversion process. To improve the energy efficiency of the bioconversion process using livestock by-products, several key aspects need to be considered. The selection of appropriate substrate types is important for increasing the efficiency of biogas plants. However, it is necessary to choose the right type of substrate for different fermentation conditions. Correction of the C/N ratio is also important for increasing biogas yields, and it is necessary to maintain an optimal C/N ratio in the substrates. This can be achieved by adding organic additives, such as corn silage or ammonium nitrate, which improves the decomposition of organic matter and promotes active methanogenesis. The use of thermophilic conditions (55°C) promotes faster and more efficient decomposition of organic matter, which can significantly reduce the fermentation time and increase the efficiency of the process.

The use of by-products with high carbon content can be realised by adding silicate materials such as straw or chopped plant residues, which in turn can be useful for correcting the C/N ratio, especially for substrates with high nitrogen content such as pig manure. Residues from grain processing, such as wheat bran or corn stover, can also be added to increase the carbon content of the substrates, which increases the biogas yield. Improving the efficiency of the fermentation process through inoculation can be done by using special microbiological additives, such as methanogenic bacteria cultures or enzymes, which can accelerate the fermentation of organic matter. This can be particularly useful for substrates that are difficult to anaerobically degrade. The implementation of waste-free technologies is based on the creation of biogas plants, which makes it possible to reduce the amount of waste and generate energy at the same time. Given the large amount of waste generated on farms, using it in biogas plants can significantly reduce the negative environmental impact. The study demonstrated the importance of optimising parameters such as temperature, humidity, pH and stirring speed in the reactors to achieve maximum biogas fermentation efficiency. The use of automated control systems for these parameters can significantly improve the process.

DISCUSSION

The results of the study confirm the importance of temperature conditions for the efficiency of the biogas fermentation process. In particular, the thermophilic regime (55°C) demonstrated a significant increase in biogas yield (by 20-28%) and an increase in methane concentration (by 5-10%) compared to the mesophilic regime (35°C). These findings correlate with previous studies, particularly the work of N. Pryshliak *et al.* (2021), which also confirmed the importance of optimising temperature conditions to improve the efficiency of biogas plants. The authors noted that temperature has a significant impact on the fermentation rate and overall biogas yield, which is critical for the industrial use of such technologies. The study confirms the conclusions of O.G. Skliar *et al.* (2019), who presented a programme and methodology for experimental research at a laboratory biogas plant, which allows for a detailed analysis of the impact of various factors on biogas yield. The application of this methodology confirms the feasibility of the chosen approach for analysing temperature conditions and choosing substrates since the data obtained show similar trends in improving the efficiency of biogas plants.

V.S. Chubur (2023) also emphasised the importance of selecting a suitable substrate for biogas plants. In the present study, poultry manure showed the best results as a substrate, which confirms its high efficiency, in contrast to cattle manure and pig manure. The results also correlate with the research of other international scientists, such as O. Alghoul *et al.* (2019), who conducted experimental studies on biogas production from food waste. The study also emphasised that the right choice of substrate and optimisation of fermentation conditions are key to achieving the high performance of biogas plants. In particular, the use of a thermophilic process in this experiment demonstrates the advantage of this approach compared to a mesophilic one, which can significantly reduce the time to achieve stable gas production. Another important aspect is the impact of optimising the C/N ratio, which, according to A. Nsair *et al.* (2020), are also critical for improving the energy efficiency of the process. However, in this work, the authors did not conduct separate experiments to study this variable, which is a promising area for further research.

The results of this study demonstrated the importance of optimising key fermentation parameters, which is consistent with previous studies, in particular, with a study by M. Zhou *et al.* (2018), which determined that increasing the temperature to the thermophilic range significantly increases the efficiency of methanogenesis. Similar conclusions were made by E. Liu and S. Liu (2017), who demonstrated that the use of a mixture of duck manure and straw under optimised fermentation conditions allows for maximum biogas yields. The study confirms the effectiveness of combining different types of organic feedstock to increase methane yield. The optimisation of the C/N ratio in this study is consistent with the analysis of M. Safari *et al.* (2018). Using the response surface methodology in their study, the study determined that the optimal C/N ratio is a key factor for increasing biogas yield. Similarly, S. Djimtoingar *et al.* (2022) confirmed the effectiveness of this methodology for predicting and optimising fermentation parameters.

This study correlates with the research of W. Romaniuk *et al.* (2022), which determined that the fermentation of molasses bards at high temperatures significantly improves the performance of biogas plants due to the increased availability of organic matter for methanogenesis. The study also points out the importance of substrate preparation, which is in line with the findings of J. Sun *et al.* (2024), who emphasise the importance of pre-treating plant residues such as corn stalks with microbial agents to increase biogas yields. This proves that the combination of substrate preparation and the choice of the optimal temperature regime can significantly improve the overall performance of the plants. The quality and composition of the biogas produced were emphasised. The study by Y. Chen *et al.* (2021) demonstrated that biogas enrichment technologies, such as pressure adsorption, can significantly improve its quality characteristics, which can be used in the future to improve existing biogas plant systems. This correlates with the conclusion on the importance of not only increasing the production volume but also improving the composition of the biogas produced. The results confirm the potential of alternative substrates for co-fermentation. This coincides with the data of P. Gupta and A. Gupta (2014), who noted that even unconventional materials such as coal can be used in anaerobic fermentation processes, although the main focus should be on biologically active waste.

The results of this study correlate with the findings of P. Dobre *et al.* (2014), stating that the main factors affecting biogas production are temperature, pH, C/N ratio and substrate composition. Their analysis shows that the optimal fermentation conditions depend on the combination of these parameters. The data also confirms the importance of selecting the type of waste, especially those with a high nitrogen content, such as poultry manure. This correlates with the research of Z. Recebli *et al.* (2015), concluding that cattle manure and pig manure provide lower biogas yields compared to more concentrated organic waste. The study demonstrated the importance of an integrated approach to the selection of substrates, temperature conditions and biogas enrichment. One of the main limitations of the study is the narrow specialisation in certain types of organic waste, which may not fully reflect the diversity of the raw material base for biogas plants. In addition, the experimental conditions on a laboratory scale may not consider all possible technical and economic challenges when scaling up the process to an industrial level. Further research should focus on the development of efficient methods for pretreating substrates and the integration of the latest biogas treatment technologies to increase their energy value.

CONCLUSIONS

Comparison of the mesophilic (35°C) and thermophilic (55°C) modes showed significant advantages of the latter. In the thermophilic mode, biogas yield increased by 20-28%, and methane concentration increased by 5-10%. Poultry manure reached 0.42 m^3/kg OSR of biogas with a methane concentration of 70%, which is the best result among the substrates studied. Reducing the time to stable gas production to 7-8 days confirms the feasibility of using the thermophilic regime in industrial conditions. Correction of the C/N ratio for different substrates increased the biogas yield by 20-28% and increased the methane concentration by up to 74%. Cattle manure, pig manure and poultry manure demonstrated increased energy efficiency after optimising the C/N ratio.

The highest quantitative and qualitative indicators were recorded for poultry manure, which is determined by its high nitrogen content. This substrate proved to be the most promising to produce energy-efficient biogas. The results of the study confirm the significant potential of livestock by-products for bioconversion, especially if key fermentation parameters are optimised. Practical recommendations include the use of thermophilic conditions, correction of the C/N ratio, and the introduction of co-fermentation to increase biogas yields. Despite achieving the goal, the study has limitations, including the dependence of the results on precise control of parameters and substrate specificity. Further research should analyse the optimisation of fermentation technologies, studying mixed substrates and the impact of microbial additives to maximise biogas yield and process efficiency.

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CONFLICT OF INTEREST

None.

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Біоконверсія побічних продуктів тваринництва в біогаз: експериментальне дослідження оптимальних умов ферментації

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Анотація. Біоконверсія органічних відходів у біогаз є важливою складовою стратегії сталого розвитку та зменшення впливу на довкілля. Ключовими факторами, що впливають на ефективність цього процесу, є температура ферментації, співвідношення вуглецю до азоту (C/N) та тип субстрату. Метою цієї роботи було дослідження впливу температурних режимів, співвідношення C/N та різних типів органічних відходів на вихід біогазу, зокрема концентрацію метану, при анаеробній ферментації. У експерименті порівнювались два температурні режими: мезофільний (35°C) та термофільний (55°C), із застосуванням трьох типів органічних відходів: пташиного посліду, гною великої рогатої худоби та свинячого гною. Вивчалося також оптимальне співвідношення C/N для покращення енергоефективності процесу. В умовах термофільного режиму було зафіксовано збільшення виходу біогазу на 20-28 % та зростання концентрації метану на 5-10 % у порівнянні з мезофільним режимом. Найвищий вихід біогазу (0.42 $м^3$/кг органічної сухої речовини (OSR)) і концентрація метану (70 %) були досягнуті при використанні пташиного посліду. У термофільному режимі також було зафіксовано скорочення часу досягнення стабільного газовиділення до 7-8 днів, що підтвердило ефективність цього підходу для промислового використання. Термофільний режим ферментації є більш ефективним для виробництва біогазу та підвищує енергоефективність процесу. Оптимізація співвідношення C/N та ко-ферментація різних субстратів додатково покращили ефективність. Пташиний послід виявився найбільш ефективним субстратом для біоконверсії, що відкриває перспективи для його використання в промислових масштабах. Результати роботи можуть бути використані для оптимізації технологій біогазової ферментації, зокрема для поліпшення продуктивності біогазових установок та зменшення витрат на енергозабезпечення

Ключові слова: відновлювані джерела енергії; органічні відходи; метан; анаеробне бродіння; термофільний режим; мезофільний режим

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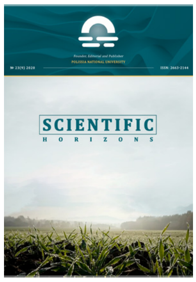

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Current trends in the application of alpha-amylase in feed production to enhance animal productivity

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Abstract. This study aimed to assess the efficiency of using alpha-amylase in the production of feed for farm animals. The study involved a systematic review of scientific literature, patent documents, regulatory acts, and experimental research, enabling the identification of key trends in the use of alpha-amylase, its mechanisms of action, and

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prospects for industrial feed production. It was established that using thermostable enzymes ensures effective starch breakdown during feed extrusion, while encapsulation technologies help preserve alpha-amylase activity during pelleting. The study analysed microbiological methods of enzyme production, including the use of bacteria from the genera *Bacillus* and *Streptomyces*, as well as fungi from the genera *Aspergillus* and *Penicillium*. It was found that solid-state fermentation on agricultural waste is a cost-effective approach to enzyme production, yielding high levels of active alpha-amylase. The results confirmed that the application of alpha-amylase in pig feed increases dry matter digestibility by 4.9% and average daily weight gain by 27.4%. The feed conversion ratio decreases by 12.4% for poultry, while body weight gain increases by 18.2%. In cattle, average daily weight gain increases by 16%, and milk yield rises by 1.7%. It was determined that enzyme use contributes to an 8-12% reduction in feed costs and improves livestock farming profitability. The findings demonstrate the effectiveness of enzyme supplements in the feed industry and support the feasibility of implementing enzymatic feed processing technologies to enhance animal productivity

Keywords: agriculture; exoenzymes; additives; carbohydrates; enzyme preparations

INTRODUCTION

One of the key aspects contributing to increased productivity in farm animals and reduced maintenance costs is the optimisation of animal diets through the use of additives, including enzyme preparations. Specifically, alpha-amylase breaks down starch and polysaccharides and is one of the most effective enzymatic feed additives, enabling a reduction in feed costs and improving nutrient absorption, which in turn enhances animal productivity. The problem of inadequate digestion of feed components and the resulting decrease in their biological value is observed across various livestock sectors, including poultry farming, pig farming, and dairy cattle farming. To address this issue, methods have been developed for adding exogenous enzymes, such as alpha-amylase, to animal diets. However, research into the application of these additives remains in active development and requires further scientific advancements.

The use of enzyme compositions containing alpha-amylase is a promising direction for improving feed digestibility in animal husbandry (Bohatko & Utechenko, 2024). In the dissertation study by V. Novakovska (2020), the impact of a multi-enzyme composition combining cellulolytic and amylolytic enzymes on carbohydrate absorption in pigs was analysed. The results confirm that such an enzyme supplement enhances nutrient absorption, reduces feed consumption, and improves pig productivity, making it an important tool in animal diets. Meanwhile, P. Sahu *et al.* (2024) investigated the potential for microbiological production of alpha-amylase using agricultural waste as a substrate. The authors emphasise that this approach supports the development of biorefineries and the bioeconomy by effectively utilising secondary resources to obtain high-quality enzymes.

The study by S. Yrgynbayeva *et al.* (2024) examines the effect of carbon sources on alpha-amylase synthesis in rice callus culture. The results indicate that different types of carbohydrates significantly influence enzyme productivity, particularly by increasing synthesis under favourable conditions. These findings are important for developing effective alpha-amylase production technologies based on plant systems, which could be applied in the feed industry. A recent study by T. Van den Bossche *et al.* (2024) demonstrates that alpha-amylase-based supplements not only improve nutrient digestibility but also enhance nitrogen balance in dairy cow diets. This reduces excess nitrogen compounds in livestock systems, which is crucial for the environmental sustainability of agricultural production. In the context of environmental sustainability, the use of agricultural waste as substrates for fermentation to obtain alpha-amylase is discussed in the study by T. Bellaouchi *et al.* (2021). The authors investigated the use of *Aspergillus niger* strains for amylase production from date by-products, aligning with trends in enzyme production optimisation and cost reduction through the ecological utilisation of waste.

The study by A. Kiribayeva *et al.* (2022) provides data on the application of alpha-amylase obtained through recombinant technology from *Bacillus licheniformis* in the hydrolysis of plant biomass, which is a critical stage in the development of new feed additives. The use of alpha-amylase in compound feeds enables the effective breakdown of complex carbohydrates, significantly improving nutrient absorption in animals (Montayeva *et al.*, 2023: Iakubchak *et al.*, 2024;). This approach could be key to increasing animal productivity, as it enhances the bioavailability of feed ingredients, which is particularly important for optimising diets in modern animal husbandry. The research by C. Bruch *et al.* (2024) highlights the impact of alpha-amylase supplementation on broiler performance under restricted energy intake conditions. It was found that alpha-amylase use not only improves overall poultry productivity but also enhances intestinal health, confirming the importance of enzyme additives in maintaining animal health under stressful feeding conditions with limited energy content. Meanwhile, M. Glaser *et al.* (2022) conducted research on the effects of maize containing the alpha-amylase gene on feed digestibility and animal performance in cattle fattening. It was demonstrated that genetically modified crops producing alpha-amylase could become a vital component in strategic feed management for farm animals, ensuring more efficient feed utilisation and overall productivity improvements. Research on alpha-amylase activity is a key aspect of optimising processes in the food and feed industries, allowing for improved starch digestion efficiency. Specifically, the study by K. Danilova *et al*. (2022) analyses the dynamics of alpha-amylase enzyme activity under substrate dilution conditions, enabling the identification of optimal parameters for maximum enzyme yield. Meanwhile, the study by W. Rusche *et al*. (2020) examines the effects of including alpha-amylase-treated silage on pig performance and carcass characteristics. It was shown that alpha-amylase use in silage positively affects animal growth and enhances feed efficiency, reaffirming the significance of enzyme additives in improving feed quality and increasing animal productivity.

The current state of research indicates that the application of alpha-amylase as a feed additive is a promising direction; however, gaps remain in understanding its mechanisms of action and optimal dosages for different animal species. Scientific studies require a more detailed examination of alpha-amylase's effects on the gut microbiome of animals and its long-term impact as a feed additive. The aim of this study was to systematise existing data on alpha-amylase application and evaluate its effectiveness in enhancing animal productivity, specifically analysing the impact of enzyme additives on feed digestibility and overall economic indicators in livestock farming.

MATERIALS AND METHODS

The study was based on a theoretical analysis of scientific sources dedicated to the application of alpha-amylase in the production of animal feed. A comprehensive approach was employed to examine trends in this field, which included the analysis of scientific literature, patent documents, regulatory acts, and a review of the results of experimental studies published in peer-reviewed journals. For the analysis, articles, patents, and regulatory acts were selected (a total of 55 sources, including 3 patents, 3 regulatory acts, and 49 scientific articles) that contained relevant research on the use of alpha-amylase in feed production. The articles were sourced from international scientific databases such as Scopus, Web of Science, Google Scholar, and Google Patents for the period from 2014 to 2024. The main criteria for selecting articles for analysis were the language of the source (predominantly English and Ukrainian), the year of publication (2014-2024), the research field (animal husbandry, feed industry, biotechnology), the type of experiments (experimental research and mathematical modelling of the impact of alpha-amylase on feed efficiency), as well as the availability of confirmed experimental or analytical data. Excluded from the analysis were non-scientific sources (popular articles, blogs, advertising materials).

Patents were selected based on criteria of innovation and practical significance for feed production. Regulatory acts were chosen for analysis based on their relevance to the regulation of enzyme additives in animal husbandry and feed production. All documents had to have official status and be published no earlier than the year 2000. A manual approach was applied for organising and classifying scientific articles and patents, allowing for precise identification of relevant materials and ensuring a high level of accuracy in selection. The information was structured into thematic categories such as the efficiency of alpha-amylase use, its mechanism of action, its impact on animal productivity, and economic feasibility. A combined approach was used for analysis, incorporating both qualitative synthesis of key findings from the literature and quantitative summarisation of data obtained from experimental studies. Verification of the reliability of the results was carried out through a comparative analysis of experiments described in peer-reviewed scientific journals, focusing on result reproducibility and comparison of research conditions. This approach enabled an assessment of the validity of conclusions and enhanced the reliability of the obtained data.

A review was conducted of registered patents related to innovative technologies for the application of alpha-amylase in feed production, including United States Patent No. US2695863A (2012), European Patent No. EP2999352B1 (2016), and Japanese Patent No. JP6560214B2 (2019). Documents regulating the use of enzyme preparations in animal husbandry were analysed, in particular, Regulation of the European Parliament and of the Council No. 1831/2003 (2003) and Regulation of the European Parliament and of the Council No. 767/2009 (2009), which establishes a feed safety system covering the entire food production chain.

RESULTS AND DISCUSSION

Application of alpha-amylase in feed production. Alpha-amylase is an enzyme that catalyses the hydrolysis of internal bonds in starch molecules, converting them into maltose, dextrins, and glucose. Due to its ability to break down complex carbohydrates, this enzyme plays a role in increasing the bioavailability of energy from feed. The use of exogenous alpha-amylase allows for the optimisation of nutrient absorption, which positively influences animal productivity and the economic efficiency of feeding. A. Torres-Pitarch *et al*. (2017) conducted a systematic review and meta-analysis examining the impact of feed enzymes, including alpha-amylase, on digestibility and growth in weaned piglets. The authors emphasise that enzyme supplements significantly improve nutrient absorption efficiency, resulting in enhanced growth rates and reduced feeding costs. The review by A. Torres-Pitarch *et al*. demonstrates that the use of alpha-amylase reduces the amount of undigested starch components in feed, thereby increasing the bioavailable energy for young animals. A key document in the application of exogenous enzymes is the European Food Safety Authority (2012), which provides a scientific opinion on the safety and efficacy of Ronozyme RumiStar (alpha-amylase) as a feed additive for dairy cows. This work analyses numerous experimental studies confirming that enzyme supplementation is not only safe for animals but also enhances starch digestibility and optimises energy utilisation. M. Farooq *et al*. (2021), in a review article, examine the biosynthesis and industrial applications of alpha-amylase, highlighting that the microbiological production of this enzyme is optimal in terms of quality and economic feasibility. The study summarises modern methods of genetic optimisation of microorganisms to increase enzyme yield and improve its thermostability.

A. Ferreira *et al*. (2020) analyse recent patent developments in the industrial application of alpha-amylase. The article describes the latest patented technologies aimed at improving enzyme stability during thermal feed processing. These patented solutions help preserve enzyme activity even at high temperatures, which is critical for extrusion and pelleting processes. M. Johnson (2019), in a dissertation, examines the impact of feeds containing the alpha-amylase gene (Enogen Feed Corn) on productivity and digestibility in young animals. The study found that integrating exogenous alpha-amylase into feed rations improves feed conversion, weight gain, and nutrient absorption efficiency. The research by M. Johnson suggests that using genetically modified maize with alpha-amylase activity may be a promising solution for enhancing the economic efficiency of feed production in large livestock farms. R. Singh *et al*. (2022) provide a detailed overview of the microbiological sources of alpha-amylase and focus on modern biotechnological approaches to its production. The authors summarise different microorganism cultivation methods and discuss genetic optimisation strategies that increase enzyme yield and thermostability. This study highlights that thanks to new enzyme production technologies, the integration of alpha-amylase into feed systems is becoming more economically viable and efficient.

The study by C. Vargas-Rodriguez *et al*. (2014) focuses on the impact of adding exogenous amylase and sucrose to the diet of cows fed low-starch diets. The authors analyse the interaction between the enzyme and sucrose, indicating the potential to optimise rumen fermentation and improve the efficiency of feed component utilisation. While the results are not always statistically significant, the study demonstrates that even minor changes can have economic implications when applied on a large scale in the dairy industry. In the chapter dedicated to enzymes in the food and feed industries, P. Fernandes (2019) examines both traditional and modern approaches to the use of alpha-amylase. The author focuses on the enzyme's role in improving starch digestion, which leads to enhanced feed quality. He notes that innovative enzyme production technologies allow for a significant reduction in feeding costs, which is a key factor in the economic efficiency of the industry. This review highlights that the synthesis of traditional methods with modern technological solutions creates new opportunities for integrating alpha-amylase into production processes.

Exogenous amylase stimulates the rate of starch breakdown, ensuring more efficient formation of substrates available for microorganisms. This mechanism helps optimise digestion conditions and positively impacts production performance, demonstrating that enzyme application can enhance the economic efficiency of the diet, even if the results are not always large-scale (Kropyvka *et al.*, 2024). In their review, S. Sujani and R. Seresinhe (2015) present a wide range of studies dedicated to the use of exogenous enzymes in ruminant feeding. The authors provide a detailed analysis of the mechanisms of alpha-amylase action, revealing its role in improving nutrient absorption and reducing production costs. Particular attention is given to the economic aspects of enzyme additives, emphasising the importance of optimising enzymatic processes to lower feed costs and increase farm profitability. This review concludes that the integration of exogenous alpha-amylase is a promising strategy for the modern livestock market.

In the study by S. Comtet-Marre *et al*. (2017), meta transcriptomics is used to examine active bacterial and eukaryotic fibro lytic communities in the rumen of dairy cows receiving a mixed diet. The authors analyse in detail which microorganisms are responsible for breaking down the cell walls of plant fibres, which is a crucial aspect of improving feed digestion efficiency. This research not only reveals the composition of the rumen microbiota but also emphasises that the activity of fibro lytic enzymes, including alpha-amylase, directly influences energy assimilation from feed, which can positively affect animal productivity. Another study by M. Imran *et al*. (2016) focuses on the role of enzymes in animal feeding, examining both the biochemical and economic aspects of exogenous enzyme application, with a particular emphasis on alpha-amylase. The article highlights that the use of this enzyme enhances the digestibility of complex carbohydrates, which, in turn, optimises the energy balance of the diet. The study by M. Brinton (2019) presents a practical evaluation of the impact of feeds containing alpha-amylase on productivity and digestibility in cattle. This approach allows for the assessment of not only the biological effects but also the economic benefits of enzyme application, which can reduce feeding costs and improve productivity in meat production. D. Guerrand (2018) focuses on the economic aspects of enzyme use in the food and feed industries. The author analyses the current state of the enzyme market, comparing production costs and application efficiency, particularly of alpha-amylase, across different sectors. The study indicates that enzyme use significantly reduces feeding costs and enhances overall feed production efficiency, which has direct economic implications in terms of increasing farm profitability.

The research by C. Takiya *et al.* (2017) is dedicated to the effect of increasing doses of the enzyme obtained from *Aspergillus oryzae* extract with alpha-amylase activity on nutrient digestibility and ruminal fermentation in lactating cows. The authors demonstrate that increasing the enzyme dose contributes to the optimisation of starch breakdown, leading to improved energy absorption, stabilisation of ruminal flora, and increased feeding efficiency. The study provides a detailed description of how dosage adjustments influence feed digestibility parameters, which has direct economic significance for the dairy industry.

Thus, scientific literature on animal feeding extensively explores the application of exogenous alpha-amylase as an effective means for improving feed digestibility, optimising energy resource utilisation, and enhancing animal productivity. Several review articles and systematic studies indicate that the use of microbial enzymes facilitates the breakdown of starch into simpler carbohydrates, ensuring better energy bioavailability and optimising fermentation processes in the gastrointestinal tract. Other studies emphasise the importance of genetic optimisation of microorganisms to increase yield and thermal stability of alpha-amylase, making its production more efficient and economically viable. Moreover, practical experiments conducted in the dairy, meat, and poultry industries demonstrate the positive impact of enzyme use on weight gain, feed conversion, and milk yield, which collectively contribute to reduced feeding costs and increased production profitability. Overall, the integration of exogenous alpha-amylase into feeding systems is a promising strategy for modern livestock farming, combining fundamental biochemical mechanisms with practical economic benefits.

Review of patent documents on technologies for using alpha-amylase in animal feed. United States Patent No. US2695863A (2012) describes technologies that use thermostable alpha-amylase to improve the efficiency of the feed extrusion process, particularly at high temperatures encountered during this technological process. Feed extrusion is a method in which raw materials pass through an extruder, where they are subjected to high temperatures (up to 90°C) and high pressure (Montayev *et al.*, 2023). As a result of this process, starch gelatinisation occurs, which can make digestion in the gastrointestinal tract of animals more difficult. However, the thermostable alpha-amylase described in the patent can withstand these conditions and retain its activity during extrusion. Due to this enzyme's stability, the starch contained in the feed can be more effectively broken down even at high temperatures. Thermostable alpha-amylase breaks down starch into simple sugars (glucose and maltose), ensuring more complete nutrient absorption by animals. This is particularly important for animals requiring high energy intake, such as pigs and poultry. Extrusion becomes more efficient due to enzymatic hydrolysis, as the starch becomes more accessible for digestion by animals in greater quantities.

This technology has been applied in various livestock industries, particularly in the production of feed for poultry, pigs, and other agricultural animals. It is used to manufacture feeds containing large amounts of starch, which require additional enzymatic processing to ensure complete digestion. In this context, thermostable alpha-amylase is a key element that enhances the overall efficiency of feed formulations. European Patent No. EP2999352B1 (2016) describes methods for encapsulating alpha-amylase to prevent its deactivation during the feed pelleting process. Pelleting is a crucial stage in feed production, during which feed components are compressed and formed into pellets under high pressure and temperatures that can destroy enzyme activity, particularly alpha-amylase. Encapsulation prevents this effect by protecting the enzyme from thermal and mechanical impacts until it is consumed by animals.

The method described in the patent involves treating alpha-amylase with a material that not only protects the enzyme during pelleting but also ensures its gradual release in the animal's gastrointestinal tract. This allows for maximum enzymatic hydrolysis of starch in the feed. Encapsulation is performed using polymeric materials, such as natural or synthetic polymers, which form a coating around the enzyme. These coatings can withstand high temperatures and mechanical impacts occurring during pelleting, ensuring enzyme protection until it reaches the animal's stomach, where the coating dissolves and the enzyme becomes active. European Patent No. EP2999352B1 (2016) can be applied in industries related to the production of feed for poultry, cattle, and young cattle, as it introduces new possibilities for improving feed production technology through enzyme encapsulation, particularly alpha-amylase. The technology enhances enzyme stability, increases starch digestion efficiency, and helps reduce feed costs. It can be effectively used in various livestock industries, making it an essential tool for improving economic performance in agriculture.

Japanese Patent No. JP6560214B2 (2019) describes a technology that involves the use of genetically modified strains of microorganisms to produce alpha-amylase with increased activity across different pH levels. This innovation is crucial for the effective use of alpha-amylase in feed additive production, particularly for ruminant animals such as cows, sheep, and goats, whose gastrointestinal tracts have a wide and variable pH range depending on the digestion stage and feed fermentation conditions. The patent also details methods for developing genetically modified microorganisms (such as bacteria or fungi) capable of producing alpha-amylase that remains highly active across various pH levels. Typically, alpha-amylase exhibits optimal activity only at a specific acidity level, but in the gastrointestinal tract of ruminants, pH varies depending on the enzyme's location: in the oral cavity and rumen, pH can be acidic (around 5.5), whereas in other parts of the digestive system, such as the small intestine, pH may be neutral or alkaline (7-8). Genetic modification enables microorganisms to produce enzymes that remain active despite fluctuating or low pH levels, thereby ensuring effective starch and complex carbohydrate breakdown at different digestion stages.

Given the specifics of the ruminant gastrointestinal tract, the use of such enzymes, which function across a broad pH range, offers several key advantages. The primary benefit is improved digestion efficiency, as the high activity of alpha-amylase at different digestion stages ensures more complete starch hydrolysis, increasing energy availability for animals, especially in cases where traditional enzymes do not function optimally under low or high pH conditions. Another significant aspect is enhanced nutrient absorption: improved starch breakdown allows for more efficient nutrient utilisation from feed, potentially leading to increased weight gain and improved overall animal productivity. An expected outcome is the reduction in the need for additional supplements, as the use of such enzymes may lower the demand for other feed additives or more expensive enzyme formulations, thus reducing feed production costs. Japanese Patent No. JP6560214B2 (2019) presents significant opportunities for improving feed technologies by utilising genetically modified microorganisms to produce alpha-amylase with increased activity at different pH levels. Thanks to these innovations, it has become possible to use alpha-amylase effectively in various feed production processes, enhancing their nutritional value and digestibility. Specifically, the application of thermostable and encapsulated forms of alpha-amylase helps preserve its activity during production processes, while the use of genetically modified enzymes ensures efficient functionality under different digestive conditions in animals.

Analysis of international regulatory acts and standards on the use of enzymes in animal feed. The regulation of enzyme use, particularly alpha-amylase, in animal feed is a crucial aspect of ensuring its safety, efficacy, and product quality. Numerous regulatory acts have been adopted at both national and international levels to establish requirements for the application of enzyme additives, their registration processes, labelling, and safety. This study examines the main regulatory acts governing the use of alpha-amylase and other enzymes in the feed industry. Regulation of the European Parliament and of the Council No. 1831/2003 (2003) is a key document governing the use of feed additives in European Union countries. According to this regulation, all additives, including enzymes, must undergo registration and safety assessment before being used in animal feed production. The regulation defines the general procedure for submitting applications, testing requirements, and approval procedure stages, which include technical product characteristics (this involves studying the enzyme's composition, activity, and safety for animals and humans); environmental safety (it must be proven that the enzyme does not harm the environment); and efficacy (the product must demonstrate its effectiveness in feed mixtures, particularly in breaking down complex carbohydrates such as starch). Patents and scientific research must be included in the application to confirm the practical benefits of enzyme use in feed production. Following registration and approval, the use of enzymes such as alpha-amylase in feed is subject to ongoing monitoring by the competent EU authorities.

Regulation of the European Parliament and of the Council No. 767/2009 (2009) establishes requirements for the labelling and safety of animal feed, including enzyme additives used in animal husbandry. This regulation is important for ensuring transparency and accuracy in information regarding the composition of animal feed. It includes labelling requirements for feed products. All feed products containing enzymes must be properly labelled, specifying the type of enzyme (e.g, alpha-amylase), its concentration, usage instructions, and safe application. Feed safety stipulates that feed additives, including enzymes, must meet safety requirements for both animals and humans. This includes toxicity testing, potential accumulation of toxic substances, and long-term health effects on animals. The regulation also provides for monitoring compliance with safety and labelling requirements. Importantly, violations of labelling rules or enzyme application in feed are subject to sanctions and fines.

The Food and Agriculture Organization (2025) Code of Practice on Animal Feeding is an international document providing recommendations on the safe use of enzymes in animal husbandry. This code covers several key aspects, including general safety principles, quality monitoring and control, as well as transparency and ethics. General safety principles stipulate that the use of enzymes such as alpha-amylase must adhere to general safety principles for animal health, the environment, and humans. Each enzyme used in animal husbandry must undergo preliminary assessment based on parameters such as efficacy, safety, potential allergic reactions, and toxicity. Quality monitoring and control is also a crucial aspect, with the Code offering quality control methods for enzyme-containing feed, including regular testing of feed additives for efficacy and safety under various conditions. Transparency and ethics are highlighted by the Code, emphasising the importance of transparency in the use of feed additives by providing recommendations on informing consumers (both national regulatory bodies and end users of feed) about enzyme content and functionality. Thus, this document serves as an important guideline for national governments and companies engaged in feed additive production, ensuring scientifically sound and ethically appropriate enzyme use practices.

The regulation of alpha-amylase and other enzyme use in feed also involves the interaction between national and international standards. International organisations such as Food and Agriculture Organization play a key role in establishing recommendations worldwide. However, national authorities, particularly within the EU, the USA, and other countries, may have additional requirements that specify international standards in line with local conditions and needs. For example, in the USA, the use of enzymes in feed is regulated by the Food and Drug Administration, which reviews and approves all feed additives and conducts ongoing monitoring of their application. Overall, the analysis of regulatory acts and standards governing the use of enzymes, particularly alpha-amylase, in animal feed has shown that the application of such additives is a strictly regulated process involving rigorous assessment of safety, efficacy, and environmental security. Both international and national authorities oversee not only the products themselves but also their production, labelling, and application processes to ensure safety and benefits for animals, humans, and the environment.

The impact of alpha-amylase on the efficiency of feed digestion in animals and the economic efficiency of its application. The study confirmed that the use of alpha-amylase in animal feed positively affects the productivity of various types of livestock, as evidenced by numerous studies. Adding alpha-amylase to pig diets promotes increased starch digestibility and overall feed energy. This leads to improved average daily gain and feed efficiency. According to the dissertation research of V. Novakovska (2020), the addition of alpha-amylase to pig diets increased dry matter digestibility by 4.9% and raised the average daily gain by 27.4%. An improvement in the feed conversion ratio of 12.5% was also recorded, indicating more efficient use of feed resources. Nitrogen balance improved by 7.3%, suggesting an increase in overall animal productivity.

In poultry farming, the use of alpha-amylase has also shown positive results. In particular, a study conducted within the scientific work of M. Johnson (2019) found that adding this enzyme to broiler diets reduced feed conversion by 12.4%, meaning more efficient use of feed resources. Additionally, body weight gain in poultry increased by 18.2%, which is a significant indicator for industrial poultry farming. Thus, the inclusion of alpha-amylase in broiler diets can contribute to improving the economic efficiency of poultry production. In cattle diets, the addition of alpha-amylase promotes improved starch digestibility and increased milk yields. According to the study by C. Vargas-Rodriguez *et al.* (2014), cows fed a diet supplemented with alpha-amylase had 1.7% higher milk yields compared to the control group. An increase in average daily gain by 16% and an improvement in feed conversion efficiency by 11.5% were also recorded, indicating more effective utilisation of the feed's energy resources. The findings from these studies confirm that the use of alpha-amylase is an effective practice for enhancing livestock productivity (Table 1).

Table 1*. The impact of alpha-amylase on the efficiency of feed digestion in different animal species*

Animal species	Efficiency parameter	Control group	Alpha-amylase group	Percentage change (%)
Pigs	Dry matter digestibility coefficient (%)	80.1%	85.0%	+4.9%
	Average daily gain (g/day)	647 g	824 g	+27.4%
	Feed conversion ratio (kg feed/kg gain)	3.2	2.8	Improvement by 12.5%
	Nitrogen balance (absorption, %)	52.3%	59.6%	+7.3%
Poultry (broilers)	Feed conversion ratio (kg feed/kg gain)	1.69	1.48	Improvement by 12.4%
	Body weight gain (g/day)	55 g	65 g	+18.2%
Cattle	Average daily gain (kg/day)	1.25 kg	1.45 kg	+16%
	Feed conversion efficiency (%)	6.1	6.8	+11.5%
	Milk yield (kg/day)	34.3 kg	34.9 kg	+1.7%

Source: *compiled by the authors based on data from M. Johnson (2019), Y. Novakovska (2020), C. Vargas-Rodriguez et al. (2014)*

Alpha-amylase is a key enzyme in the starch hydrolysis process, which facilitates the breakdown of long-chain polysaccharides into maltose, dextrins, and ultimately glucose. This process significantly improves the absorption of energy from feed by animals, which in turn leads to increased productivity. The primary mechanism of action of alpha-amylase is based on the cleavage of α-1,4-glycosidic bonds in starch molecules, occurring at the initial stages of digestion. This facilitates the subsequent work of other enzymes and accelerates the absorption of nutrients. In the gastrointestinal tract of pigs, starch is broken down by amylase produced by the pancreas. However, a significant portion of starch remains inaccessible for digestion due to the dense cell walls of cereal grains. This limits the efficiency of energy absorption from feed and can lead to reduced animal productivity. The introduction of exogenous alpha-amylase into pig diets helps overcome this problem, as the enzyme actively disrupts the structure of starch granules, improving their availability for enzymatic hydrolysis. This promotes an increase in the amount of glucose absorbed in the small intestine, ensuring higher feed energy value and improving animal growth.

For broilers, maximising the use of the feed's energy resources is extremely important, as their rapid growth requires high nutrient absorption. The introduction of alpha-amylase into poultry diets improves starch breakdown efficiency from the early stages of digestion, ensuring the rapid release of available monosaccharides. This optimises the digestion process and enhances the efficient use of feed energy. As a result, poultry gains weight more quickly, and the feed conversion ratio decreases, making production more economically viable. In cattle, a significant portion of starch undergoes fermentation in the rumen due to microbial activity. However, some polysaccharides that are not broken down in the rumen pass into the small intestine, where they may be less efficiently absorbed. The addition of alpha-amylase to cattle diets promotes better starch breakdown and increased availability of energy resources in both the rumen and intestines (Buchkovska & Ievstafiieva, 2023). This positively affects the growth rates of young stock, improves the feed conversion ratio, and enhances milk production in dairy cows. Studies confirm that the use of alpha-amylase significantly improves starch absorption in animals. The reduction in residual starch levels in faeces indicates that more energy from feed has been utilised by the body rather than excreted without absorption. This is particularly important for livestock farms aiming to enhance feeding efficiency and reduce feed costs.

Economic efficiency of the application of alpha-amylase. The study confirmed that alpha-amylase optimises feed utilisation and reduces its costs. According to a series of studies (for example, in the dairy and meat sectors of livestock farming), the use of exogenous alpha-amylase results in the following economic effects. The reduction in feed costs is achieved through the improved digestibility of feed components by enzymatic breakdown of starch, with a decrease in feed costs of 8-12%. This is explained by the fact that increased bioavailability of energy allows for a reduction in the overall feed intake while maintaining or increasing productivity.

Increased live weight gain in pigs and poultry (broilers) occurs through the use of alpha-amylase, as it improves feed conversion, leading to an increase in live weight gain by 10-15%. This is due to accelerated starch breakdown and faster access to glucose, which provides the energy needed for growth. In cattle diets, the addition of alpha-amylase optimises starch fermentation in the rumen and improves the absorption of nutrients in the small intestine, leading to a 5-7% increase in milk yield. This effect is particularly important for improving the economic indicators of dairy farming (Table 2).

Table 2. *Economic efficiency of using alpha-amylase in feed production*

Indicator	Pigs	Poultry (broilers)	Cattle
Reduction in feed costs (%)	8-12%	8-12% (by analogy)	8-12%
Increase in live weight gain (%)	10-15%	10-15%	–
Increase in milk yield (%)	–	–	5-7%
Improvement in feed conversion (%)	10-15%	4-6%	5-7%

Source: *created based on data from M. Johnson (2019), Y. Novakovska (2020), C. Vargas-Rodriguez et al. (2014)*

Through improving feed efficiency, reducing feed costs, and enhancing animal productivity, the introduction of alpha-amylase into feed production contributes to increased profitability. Therefore, the economic efficiency of using this enzyme is confirmed by the reduction in feed costs, increased live weight gain, and improved productivity indicators (e.g., milk yield). Thus, the integration of data from various studies indicates that the use of alpha-amylase in diets for different animal groups is a promising tool for increasing the economic efficiency of feed production.

The study showed that the introduction of exogenous alpha-amylase contributes to improving the digestibility of feed components and, consequently, animal productivity, which is consistent with the findings of other researchers. The results of the study presented by E. Aranda-Aguirre *et al.* (2021) confirm the positive impact of exogenous enzymes, including alpha-amylase, on pig productivity at different growth stages, which aligns with the conclusions obtained in the current research. The use of alpha-amylase improves the absorption of energy and nutrients, which, as shown in the work of E. Aranda-Aguirre *et al.*, directly leads to increased growth rates and reduced feed costs, particularly in pigs, demonstrating the economic efficiency of such approaches in livestock farming. S. de Faria Castro *et al.* (2019) also noted that different levels of alpha-amylase supplementation in broiler feed contribute to a significant improvement in final productivity and feed conversion, which is consistent with current observations of reduced feed conversion ratios and increased weight gain in poultry. Similarly, C. Stefanello *et al.* (2019) found that combining energy supplements with enzymes, including alpha-amylase, optimises the use of feed resources and enhances growth, supporting the results obtained regarding improved productivity through more efficient starch breakdown. Moreover, in the work of B. Ojha *et al*. (2019), a wide range of enzymes in animal feeding were discussed, highlighting their economic benefits, which align with the conducted analysis of feed cost reduction through optimised digestibility of nutrients. The research by M. Meschiatti *et al*. (2019) demonstrates that the combination of exogenous alpha-amylase with other additives (e.g., essential oils) can significantly improve productivity and meat quality in the meat industry, expanding the prospects of applying authors' approach in various sectors of animal husbandry.

In studies of enzyme use in the livestock industry, it is noted that the interpretation of data and a comprehensive approach to analysing their impact on nutrient absorption are critical for optimising feeding. For example, M. Bedford (2018) emphasises that modern data analysis methods allow for accurate assessment of the impact of enzymes on feeding, confirming the importance of using such technologies to improve poultry productivity. Similarly, a study published by S. Rebello *et al*. (2019) indicates that the use of industrial enzymes, including alpha-amylase, contributes to the optimisation of feed component digestion, leading to reduced feeding costs and improved energy balance in the diet. In the article by S. Tiwari *et al*. (2015), the mechanism of action of alpha-amylase is detailed, involving the hydrolysis of internal starch bonds to form maltose and dextrins, which contribute to more efficient energy utilisation from feeds. The findings of the study align with this concept, as the optimisation of starch breakdown improves digestibility, which is reflected in increased productivity in both pigs and poultry.

The review by B. Far *et al*. (2020) shows that modern methods of microbial production of alpha-amylase can significantly increase enzyme yield and thermotolerance, ensuring its economic feasibility for large-scale use in feed production. Comparison of the obtained data with the conclusions of B. Far *et al*. indicates that the integration of exogenous alpha-amylase is a promising strategy for optimising feeding, reducing feed costs, and increasing farm profitability. The results of the study confirm the positive impact of exogenous alpha-amylase on broiler productivity and nutrient absorption. H. Zhou *et al*. (2021) confirm that exogenous alpha-amylase significantly improves corn starch absorption and glucose metabolism in broilers, which aligns with the findings of the current study regarding the positive impact of alpha-amylase on animal productivity. The use of alpha-amylase in poultry feed improves energy and nutrient utilisation efficiency, leading to better growth and reduced feed costs. At the same time, the work of A. Movahedpour *et al*. (2022) emphasises the importance of recombinant technologies in alpha-amylase production, which correlates with the conclusions of the current study regarding the use of genetically modified microorganisms to enhance fermentation efficiency and enzyme stability. This highlights the importance of further development of biotechnological methods in alpha-amylase production for achieving even better results in feed production.

L. Bassi *et al*. (2023) investigated the effect of adding alpha-amylase on individual growth variations, productivity, and starch digestibility in chickens. The authors found a positive effect of the enzyme on growth and nutrient absorption indicators, which aligns with the conclusions obtained. S. Motahar *et al*. (2020) developed a new thermotolerant alpha-amylase for poultry feed, which improves the biodegradation properties of feed and contributes to more efficient energy utilisation. These conclusions align with the obtained results regarding the positive impact of the enzyme on feed conversion ratio and broiler productivity. Comparison of the results with international researchers' works indicates that the integration of alpha-amylase in broiler feed systems is a promising strategy for improving productivity and economic efficiency, opening up broad opportunities for further research and practical implementation in feed production.

Examining works that, although somewhat distant from livestock, also investigate the use of enzyme additives, similar trends are observed. In the study by Q. Liang *et al*. (2022), it was noted that the addition of enzymes to fish feed improves the digestibility of both plant and animal ingredients, contributing to improved growth rates in aquaculture animals. The conclusions of the study by B. Velázquez-De Lucio *et al*. (2021) confirm the importance of using exogenous enzymes, particularly alpha-amylase, as zootechnical feed additives, which directly aligns with the findings of the current study. The use of alpha-amylase improves feed digestibility and nutrient absorption, leading to increased animal productivity, particularly in pigs, poultry, and cattle, as noted in the authors' review. This highlights the broad potential for enzyme application in animal husbandry to optimise feed rations and enhance production efficiency.

V. Martens *et al*. (2020) emphasise the importance of amylase activity in the stomach of pigs for starch digestion kinetics, which influences overall nutrient absorption efficiency. This is consistent with the data obtained, demonstrating that the addition of amylase facilitates more efficient starch digestion in animal diets. The study by A. Pech-Cervantes *et al*. (2022) supports the conclusions of the current research regarding the significance of exogenous alpha-amylase in enhancing productivity and nutrient absorption in lactating cows. Their findings confirm that alpha-amylase improves feed digestibility, enhances ruminal fermentation, and increases energy efficiency, which, as in the current study, contributes to improved overall productivity indicators. The work of V. Pham *et al*. (2021) highlights the use of *Bacillus sp.* for alpha-amylase production, reflecting similar approaches described in the present research regarding the use of microorganisms for enzyme production. This underscores the significance of such methods for increasing enzyme production efficiency, which can subsequently be used to improve feed rations in animal husbandry. The study by N. Melnichuk *et al.* (2020) also confirms the feasibility of using agricultural waste for alpha-amylase production, aligning with the findings of the present study on the use of agro-waste as substrates for solid-state fermentation. This approach not only reduces enzyme production costs but also ensures environmentally sustainable utilisation of agricultural residues. According to T. Almanaa *et al.* (2020), solid-state fermentation for obtaining alpha-amylase from *Bacillus subtilis* is an economically viable method, supporting the current study's results on employing this approach for enzyme production from agro-waste. This confirms that such technologies can enhance enzyme production efficiency while being economically advantageous for feed manufacturing.

After analysing results and comparing them with data from other researchers, it can be concluded that the application of exogenous alpha-amylase holds significant potential for optimising animal feeding, which is a crucial step towards improving the profitability of livestock farms. This study not only confirms the positive effect of the enzyme on digestive biochemical processes but also highlights the prospects for further research aimed at developing new combined technologies to enhance the economic efficiency of feeding systems.

CONCLUSIONS

The application of exogenous alpha-amylase in animal feeding significantly improves feed digestibility, optimises energy resource utilisation, and enhances animal productivity. Systematic reviews and meta-analyses demonstrate that the use of this enzyme allows for more effective starch breakdown, increasing energy bioavailability and improving weight gain, feed conversion, and milk production. Studies also confirm the importance of genetic optimisation of microorganisms to ensure high yield and thermostability of alpha-amylase, enhancing its production efficiency. Given the positive economic impact, expressed in reduced feeding costs and increased profitability, integrating alpha-amylase into feed systems is a promising approach for modern animal husbandry, contributing to both productivity improvement and cost optimisation.

A review of patent documents shows that modern technologies for applying alpha-amylase in feeds focus on increasing its stability, efficiency, and adaptation to production and digestion conditions. The use of thermostable alpha-amylase (US8304212B2) ensures effective starch breakdown during feed extrusion, facilitating better nutrient absorption. Enzyme encapsulation (EP2999352B1) protects it from degradation during pelleting, ensuring controlled release in the animal gastrointestinal tract. The use of genetically modified microorganism strains (JP6560214B2) enables the production of alpha-amylase with an extended activity range across different pH values, making it particularly effective for ruminants. All these developments contribute to improving feed production efficiency, reducing feed costs, and enhancing animal productivity. The incorporation of alpha-amylase in feed formulations improves starch digestibility and efficient nutrient absorption in animals. Research results confirm that applying this enzyme in pigs increases dry matter digestibility by 4.9%, average daily gain by 27.4%, and feed conversion ratio by 12.5%. In poultry farming, the use of alpha-amylase reduces feed costs per unit of weight gain by 12.4%, resulting in a body weight increase of 18.2%. In cattle, enzymatic feed processing increases average daily gain by 16%, feed conversion efficiency by 11.5%, and milk yield by 1.7%.

The economic efficiency of alpha-amylase application is reflected in an 8-12% reduction in feed costs, associated with improved energy absorption and ration optimisation. The use of the enzyme also enhances animal productivity, particularly increasing weight gain in pigs and broilers by 10-15%, while in dairy farming, milk yields increase by 5-7%. Based on the obtained results, it can be concluded that the integration of alpha-amylase into livestock diets is an effective tool for increasing productivity and reducing feed costs. The prospects for using alpha-amylase in feed production include developing enzymes with enhanced thermostability and tailored activity for different digestive conditions in animals, which will further improve nutrient absorption. Future research may focus on integrating encapsulated forms of alpha-amylase and optimising enzymatic feed processing to reduce costs and enhance livestock productivity.

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CONFLICT OF INTEREST

The authors declare no conflict of interest in this paper.

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Сучасні тенденції застосування альфа-амілази у кормовиробництві для підвищення продуктивності тварин

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Анотація. Метою дослідження було оцінити ефективність використання альфа-амілази у виробництві комбікормів для сільськогосподарських тварин. Дослідження включало систематичний огляд наукової літератури, патентних документів, нормативно-правових актів та експериментальних досліджень, що дозволило визначити основні тенденції використання альфа-амілази, механізми її дії та перспективи промислового виробництва комбікормів. Встановлено, що використання термостабільних ферментів забезпечує ефективне розщеплення крохмалю під час екструзії кормів, а технології капсулювання сприяють збереженню активності альфа-амілази під час гранулювання. У дослідженні проаналізовано мікробіологічні методи виробництва ферментів, включаючи використання бактерій з родів *Bacillus* і *Streptomyces*, а також грибів з родів *Aspergillus* і *Penicillium*. Було виявлено, що твердофазна ферментація на сільськогосподарських відходах є економічно ефективним підходом до виробництва ферментів, що дозволяє отримувати високі рівні активної альфа-амілази. Результати підтвердили, що застосування альфа-амілази в кормах для свиней підвищує перетравність сухої речовини на 4,9 % та середньодобові прирости на 27,4 %. Коефіцієнт конверсії корму зменшується на 12,4 % для птиці, тоді як приріст маси тіла збільшується на 18,2%. У великої рогатої худоби середньодобові прирости збільшуються на 16 %, а надої зростають на 1,7 %. Встановлено, що використання ферментів сприяє зниженню витрат на корми на 8-12 % та підвищенню прибутковості тваринництва. Отримані результати свідчать про ефективність застосування ферментних добавок у комбікормовій промисловості та підтверджують доцільність впровадження технологій ферментативної переробки кормів для підвищення продуктивності тварин

Ключові слова: сільське господарство; екзоферменти; добавки; вуглеводи; ферментні препарати

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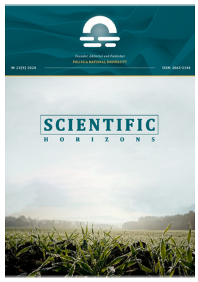

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Automation and intelligent water distribution control systems for optimising water use in agricultural irrigation systems

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Abstract. The purpose of this study was to analyse the methods of automation, intelligent distribution, and consumption of water in Central Asian irrigation systems using the example of the Kyrgyz Republic. The study considered the use of sensor networks for monitoring water data by Wzzard LRPv and John Deere Operations Centre. The study analysed the work of AquaCrop software for modelling water balance and irrigation optimisation and the use of drones for monitoring the state of water resources and land plots, including Da-Jiang Innovations Phantom 4 Real-Time Kinematic and P4 Multispectral drones. An analysis of the effectiveness of each method revealed considerable water conservation and improved water distribution performance. For the sensor networks, the level of water use in the irrigation system was 85% – with a supply of 1,000 m^3, losses amounted to 150 m^3. For the software,

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the water use efficiency was determined to be 70%, considering that the total volume of water supplied was 1,000 m^3 and the factual volume of water retained in the root zone of plants was 700 m^3. The efficiency of using drones reached 90%, which meant that out of 500 m^3 of water filled into the drones for spraying, 450 m^3 were evenly distributed, while losses due to evaporation and spraying inaccuracies amounted to 50 cubic metres. The study analysed the capabilities of the Demand Driven Distribution water distribution management system revealed a 25% reduction in pump energy consumption, a 15% reduction in water leaks and a 50% reduction in pipe damage. An analysis of the capabilities of the Siemens Water Leak Finder system revealed that artificial intelligence algorithms accurately detected even minor water leaks of 0.2 litres per second, reducing resource losses by up to 50%. The analysis of the performance characteristics of the Rain Bird controller and the CropX platform revealed an increase in water consumption efficiency and water conservation in Central Asia, which was a major step towards the sustainable development of the agricultural sector in the region

Keywords: data monitoring; sensor networks; software; use of drones; resource conservation; irrigation efficiency

INTRODUCTION

Agricultural irrigation systems play a key role in ensuring food security, especially in arid regions where natural moisture is insufficient for crop production. The efficiency of water use in such systems determines not only agricultural productivity but also the sustainability of ecosystems that depend on water resources. Irrigation systems involve a complex interaction of hydraulic structures, engineering networks, and management solutions that ensure the even and prompt distribution of water. With water scarcity exacerbated by climate change, population growth and agricultural intensification, special attention is being paid to the introduction of innovative approaches to water management. However, despite the significance of irrigation systems for agriculture, their efficiency often stays low due to outdated management practices, extensive water losses in networks, and uneven distribution of resources. This is especially true in Central Asia, where much of the infrastructure is outdated. The lack of modern monitoring systems, limited integration of automated solutions, and insufficient adaptation to changing climate conditions greatly complicate sustainable water use. The problem also lies in the lack of a comprehensive analysis of the effectiveness of available technologies and their adaptation to local conditions, which reduces the potential for introducing innovative approaches.

A. Batykova *et al.* (2023) investigated the issues of integrated management of land and water resources in Kyrgyzstan, which are key to sustainable agricultural development and environmental safety. The researchers noted the need to modernise the management of these resources, strengthen local land management institutions and rational use of water, considering the specifics of the mountainous and foothill regions of the country. K. Maatov (2024) analysed the use of economic and mathematical models and computer technologies to optimise resource management in agriculture. The researcher presented a model that allows determining the optimum sown areas and volumes of mineral fertilisers, considering financial capabilities, which contributes to the rational use of resources and increase the efficiency of agricultural production. N. Temirbaeva *et al.* (2024) investigated the prospects for the use of autonomous sources of renewable energy, particularly microelectric power plants, for the energy supply of agricultural enterprises. The researchers noted the significance of optimising the use of water resources in the Kyrgyz Republic for the development of such systems, which will help to improve the efficiency of irrigation and energy supply in the agricultural sector.

S. Ray and S. Majumder (2024) highlighted the significance of using innovative irrigation technologies, such as drip irrigation and automated water management systems, to improve water supply efficiency and conserve resources in agriculture. The study revealed that the use of such methods helps to reduce water and energy consumption and improve crop productivity. F. Behzadipour *et al.* (2024) demonstrated the effectiveness of an intelligent irrigation system for greenhouses, which reduced water consumption by 15.6% compared to conventional irrigation without reducing yields and product quality. The findings confirmed the feasibility of using smart technologies to optimise water distribution in conditions of limited water resources.

M. u Nisa *et al.* (2024) considered an ontological intelligent irrigation system that allows increasing water use efficiency and yields through accurate monitoring and control. The findings revealed that the use of sensors, actuators, and data processing algorithms contributes to the sustainable management of water resources in the agricultural sector, reducing water loss and adverse environmental impact. Moreover, L. Aiswarya *et al.* (2024) analysed the prospects for automating irrigation canals as a tool for improving the efficiency of water distribution and reliability of water supply. The study revealed that automatic flow control can minimise water losses, especially in arid regions, providing flexibility and accuracy in water management.

On the other hand, M. Pourgholam-Amiji *et al.* (2024) found that the introduction of drip irrigation for wheat cultivation in Iran reduced water consumption by 134.1 million m^3 and increased water productivity. The key advantages of the method are increased yields and reduced labour costs, although the high cost of implementation is still a considerable limitation. S. Zhao *et al.* (2024) developed an optimisation method for managing end canals and field irrigation, which reduced water losses and improved water use in irrigation areas of China. Improving water supply schedules reduced filtration losses by up to 4.6% and irrigation time by up to 14 hours, which demonstrated the prospects of the approach for improving water management efficiency. R. Pierre *et al.* (2024) proposed a methodology for estimating water consumption for irrigation at the catchment level, which allows identifying farms with high irrigation levels. The application of artificial intelligence (AI), machine learning (ML) and regression approaches helped to estimate the volume of irrigation water with a minimum error (14%), create water consumption maps, and identify areas with high water demand (Mamchur & Studinska, 2024).

These studies lack data on a comprehensive analysis of automation methods and an overview of intelligent water distribution control systems in irrigation systems in Central Asia, particularly in the Kyrgyz Republic, which determined the purpose of the present study. The objectives of the study were to analyse sensor networks, drones, and software, as well as automated and intelligent water distribution management tools.

MATERIALS AND METHODS

The study performed a comprehensive analysis of methods for automating water distribution control in agricultural irrigation systems, namely sensor networks for monitoring the irrigation process, software for planning and forecasting, drones for monitoring the state of water resources, irrigation and land plots. Schemes and architectures of these methods were presented. The study examined the sensors that monitor humidity, water levels in canals and water flow in the Wzzard LRPv and John Deere Operations Center™ sensor network systems (New Level of..., 2021; Smart Irrigation System, 2023).

The efficiency of each automation method was calculated, which helped to determine the best approaches to irrigation for the conditions of the Kyrgyz Republic. The level of water use in the irrigation system was defined as the ratio between the volume of water that was effectively used for irrigation and the total volume of water supplied (1):

$$\eta_u = \frac{W_u}{W_a} \times 100\%, W_u = W_a - W_l, \tag{1}$$

where η_u is the level of water use in the irrigation system, %; W_u is the volume of water used directly for irrigation, m^3 (cubic metres); W_a is the total volume of water supplied to the system, m^3; W_l is the water losses, m^3 (Ware, 2023).

Water balance modelling and optimisation of irrigation schedules were performed using AquaCrop software from the Food and Agriculture Organisation of the United Nations (Standard AquaCrop proogramme..., n.d.). The model of efficient water use in irrigation systems is based on an estimate of the amount of water that reached the root zone of plants compared to the amount of water supplied to the field. This approach was based on the calculation of irrigation efficiency (2):

$$\eta_a = \frac{W_z}{W_a} \times 100\%, \tag{2}$$

where η_a is the irrigation efficiency, %; W_z is the volume of water stored in the root zone of plants, m^3; W_a is the total volume of water supplied for irrigation, m^3 (Ware, 2023).

The study considered the technologies for the use of drones: Da-Jiang Innovations Phantom 4 Real-Time Kinematic (DJI Phantom 4 RTK mobile mapping station), Global Positioning System (GPS), and DJI P4 Multispectral, which contributed to more efficient water distribution management (Jingao Technology Co., n.d.). The efficiency was assessed by calculating the fluid application efficiency coefficient (3):

$$\eta_c = \frac{W_l}{W_r} \times 100\%, \tag{3}$$

where η_c is the efficiency of liquid application by drones, %; W_l is the volume of liquid that reached the crops, m^3; W_r is the total volume of liquid filled in drones, m^3 (Ware, 2023).

The study analysed intelligent and automated water distribution management systems, including examples of their use in the Central Asian region. Particular attention was paid to the study of the Kyrgyz Research Institute of Irrigation (KRII), namely, the creation of an automated system for irrigation control, water accounting, and water distribution. In this context, the possibilities of using the geospatial platform Geographic Information System (GIS) and ArcGIS (n.d.) software were explored (Bairamukova, 2024; What is GIS?, n.d.). The features of the Demand Driven Distribution (DDD) (n.d.) intelligent water distribution management system was analysed using the example of the Grundfos CU 354 pumping system: the operation scheme, methods of assessing efficiency in reducing water losses and increasing distribution accuracy. The study described the operation scheme, capabilities, and advantages of the Siemens Water (SIWA) Leak Finder application designed to intelligently reduce water losses associated with leaking pipes, the Rain Bird Electronic Smart Programming (ESP) controller, and the CropX platform (Siemens makes it..., 2024; Patil, 2024; ESP-Me Series Controllers, n.d.; Cropx platform overview, n.d.).

RESULTS

Methods of automation of water distribution control in irrigation systems. Automation of water distribution management in irrigation systems is a key area of hydromelioration aimed at ensuring the rational use of water resources. The approach allows optimising water consumption, increasing crop productivity, and minimising environmental impact, factoring in the regional climatic, hydrogeological, and agronomic conditions. The irrigation system is increasingly being integrated with a sensor network to improve the efficiency of water distribution management (Fig. 1). Such a network allows for continuous monitoring of soil, climatic conditions, and canal water levels, providing accurate data for real-time decision-making. This is particularly relevant for Central Asia, where uneven distribution of water resources and high evaporation make irrigation management challenging.

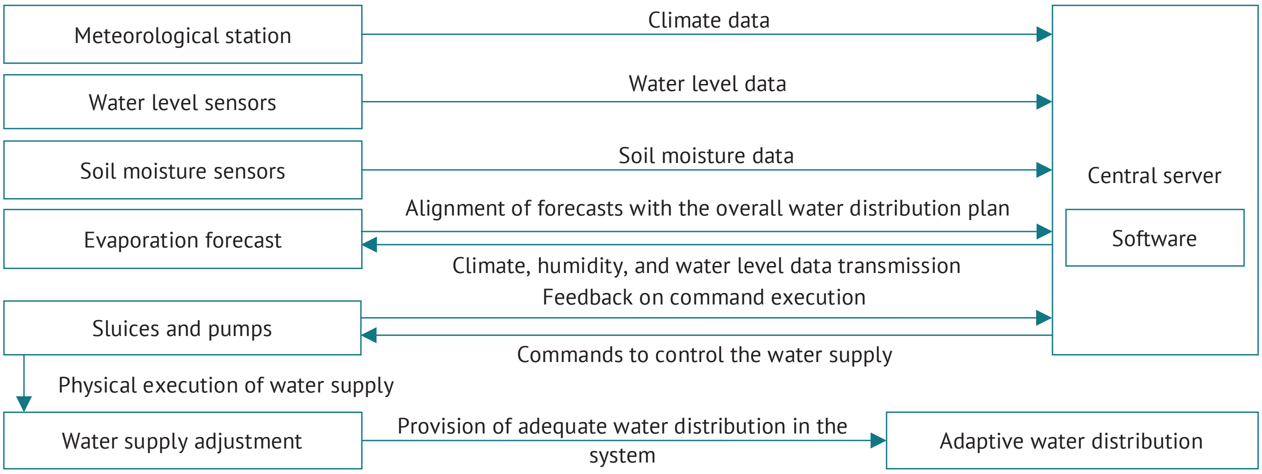

Figure 1*. Sensor network architecture for monitoring irrigation systems*
Source: *compiled by the authors*

The weather station of the sensor network collects temperature, humidity, and precipitation data and sends it to the central server, where it is processed by the software. Canal water level and soil moisture sensors record the relevant parameters and transmit them to the central server. Based on the results of the data analysis, the server predicts evaporation and generates an optimum water distribution plan. Based on the plan, the server sends commands to the gateways and pumps to regulate the water supply. Feedback on the execution of commands ensures constant monitoring and adaptation of the system to current conditions, which enables efficient and adaptive distribution of water resources in real time. Sensor networks automatically analyse the collected data using built-in processing algorithms (ML, neural networks, forecasting methods) and optimise water supply by adapting irrigation modes to current conditions. The Wzzard LRPv wireless sensor network for real-time soil and irrigation monitoring, with the ability to integrate data with weather forecasts, and the John Deere Operations Centre monitoring and control system for monitoring tillage equipment have been adapted to agricultural production conditions (New Level of..., 2021; Smart Irrigation System, 2023).

To evaluate the efficiency of the sensor network, the irrigation monitoring system uses a water use rate that reflects the ratio of water used to the total amount of water supplied (Formula 1). For instance, if the system shows = 85% on the central server monitor or the operator's mobile application, it means that 85% of the water is effectively used for irrigation, and losses are only 15%. This is calculated based on the fact that, for instance, the total volume of water supplied to the system is 1,000 m^3, and the volume of water lost through evaporation, filtration, and other processes is 150 m^3. Thus, the volume of water used for irrigation is 850 m^3, and the percentage of efficient water use is defined as the proportion of water saved to the total volume of water supplied, expressed as a percentage. This approach allows optimising water supply through prompt detection of losses.

For planning and forecasting, the study considered software with integrated algorithms that factor in the climatic, hydrogeological, and agrotechnical conditions of the region, as well as data obtained from sensor networks (Fig. 2). An example of such software was the AquaCrop crop growth model, which allowed assessing the effects of the environment and management practices on yields. It is particularly useful in environments where water is a limiting factor in crop production (Standard AquaCrop proogramme..., n.d.). The software integrated a variety of inputs that were employed to calculate the water balance. This includes modelling water reserves and demands, and forecasting changes in parameters associated with droughts and floods. The analysis results were used to formulate an optimum water distribution plan, considering irrigation schedules and priority zones, to ensure efficient and rational use of water resources.

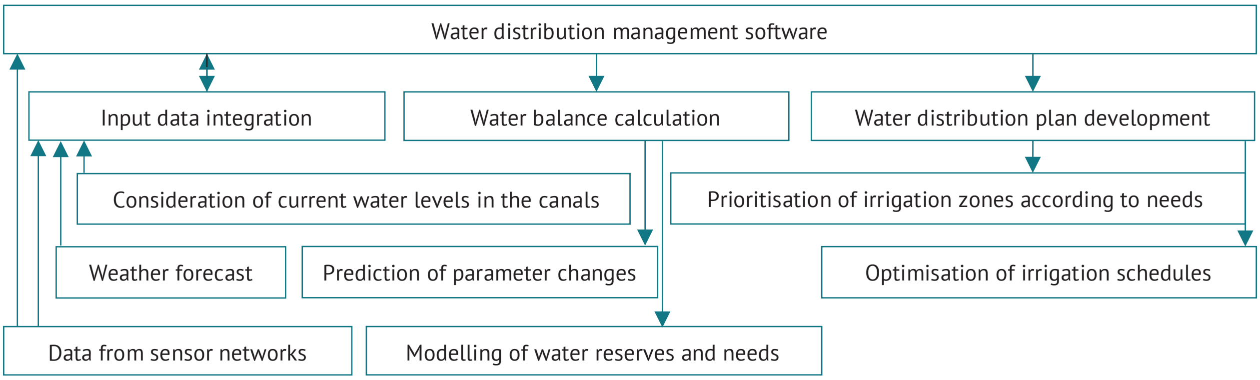

***Figure 2**. Scheme of software use in the automation of water distribution management*
***Source:** compiled by the authors*

This diagram illustrates the automation of water distribution management using software that worked in three stages: integration of input data, calculation of water balance, and generation of a water distribution plan. At the first stage, the system received data from sensor networks, factored in the weather forecast and current water levels in the canals. The system predicted the impact of weather conditions and evaporation and adjust the irrigation plan accordingly by integrating with data from meteorological stations. At the second stage, the data was used to model water reserves and needs, and to predict changes in parameters, which allowed estimating future water consumption. For this, the algorithms analysed data on the amount of water supplied and consumed, considering evaporation and filtration losses. The final stage involved prioritising irrigation zones according to needs and optimising irrigation schedules, which ensured efficient use of water resources, reduced water losses, and increased agricultural productivity. The software calculated the optimum time and volume of water supply according to crop needs and soil conditions.

The software also had to account for the irrigation efficiency, which is the ratio of the volume of water retained in the root zone of plants after irrigation to the total volume of water applied (2). For instance, the total volume of water applied is 1,000 m^3, and according to the analysis results of soil moisture sensors, the volume of water stored in the root zone of plants is 700 m^3. The water use efficiency is 70%, which means that 70% of the applied water was stored in the root zone of the plants for their use. The remaining 30% of the water is lost through evaporation, infiltration into deeper soil layers, or runoff. Additionally, the software should ensure accuracy in water distribution, reduce excessive losses, and increase crop yields (Yeraliyeva *et al.*, 2017). For instance, by adapting irrigation schedules to weather forecasts, waterlogging or water shortages can be avoided (Shuka *et al.*, 2011). Thus, this approach helps reduce water losses and ensures the stability of irrigation processes.

Another promising method of automating water distribution management in irrigation systems is the use of drones to monitor the state of water resources, land, and irrigation conditions (Fig. 3). In Central Asia, where fields and orchards are often located in remote or inaccessible areas, the use of such technologies can reduce the time and resources required to collect the necessary information. In Kyrgyzstan's agricultural sector, drones such as the DJI Phantom 4 RTK are commonly used to provide accurate mapping (Jingao Technology Co., n.d.). These devices are equipped with cameras and GPS technology, which contributes to the efficiency of irrigation management.

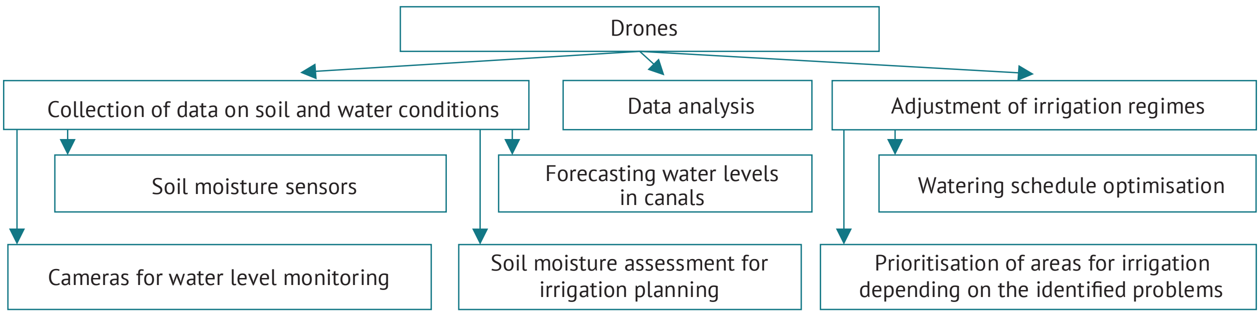

***Figure 3**. Scheme of using drones in water distribution management*
***Source:** compiled by the authors*

Figure 3 shows the key stages of data collection, analysis, and management of irrigation regimes. Overall, drones with high-sensitivity sensors can be used to assess soil conditions, monitor soil moisture and water levels in canals with high accuracy. A drone with built-in DJI P4 Multispectral sensors can be used to assess the condition of vegetation (Jingao Technology Co., n.d.). An essential criterion was to assess the effectiveness of using drones to distribute water during fine-dispersed (local) irrigation or the application of working solutions of fertilisers or biological products (Formula 3). For instance, if the volume of water evenly distributed by drones over crops was 450 m^3, and the total volume of water filled into the drones was 500 m^3, the process efficiency was 90%. This means that 90% of the water was effectively used for irrigation, while losses due to evaporation, spraying outside the plots or other factors amounted to 10%.

The key processes that were automated included monitoring soil moisture levels, real-time control of water supply volumes, and management of water distribution between individual plots. Sensor networks allowed reading data on soil moisture, temperature, and evaporation levels, which were transmitted to a central server for processing. The software analysed this data and generated recommendations or automatically adjusted the operation of pumps and valves to ensure optimum irrigation. Drones were used to collect additional data on the condition of vegetation, water levels in canals, and potential leaks. The collected information was integrated into an automated control system, which enabled prompt decision-making on redirecting flows or regulating water flow. In 2023, the Kyiv Scientific Research Institute of Water Resources, Agriculture and Processing Industry implemented six research projects on hydromelioration topics at the request of the Ministry of Water Resources, Agriculture and Processing Industry. Among them is the development of an automated system for water metering, water distribution, and irrigation control to improve the efficiency of water use in irrigated agriculture in the Chui Valley (Bairamukova, 2024). This system includes the installation of 72 electronic water level sensors at gauging stations equipped with antennas for long-distance wireless data transmission. By 2023, the sensors had been installed on the Kegeti and Shamsi river systems (32 sensors), covering an area of about 15 thsd ha. A computer and telecommunication equipment were purchased for the Water Use Department of the District Water Management Department to organise communication with the gauging stations. It was planned to install the remaining 40 gauges to complete the system.

In another study on the creation of a reference and analytical database of indicators of the reclamation status of irrigated lands in the Chui Oblast, GIS technologies were employed to ensure accurate monitoring and adaptive management of water distribution, contributing to the rational use of water resources and increasing the productivity of irrigation systems (What is GIS?, n.d.). GIS provided monitoring of water supply and distribution through the integration of geographic data, software and hardware, and analysis methods. In other words, geographic data included spatial coordinates of objects and attribute information, which enabled accurate tracking of the condition of irrigated land. ArcGIS (n.d.) software provided the tools for processing this data, and hardware, such as GPS devices and drones, facilitated its collection. Furthermore, ArcGIS software enabled a comprehensive assessment of the water balance over large agricultural areas. Spatial and thematic analysis methods helped to optimise water distribution, increasing irrigation efficiency and rational use of water resources.

Intelligent water distribution management systems. The Demand Driven Distribution (n.d.) system for the Grundfos pumping system used self-learning algorithms to optimise the pressure in the water supply network (the algorithm is integrated in the Grundfos CU 354 pump controller), which reduced water losses, energy consumption and maintenance costs. It provided adaptive pressure control, adjusting to the real needs of consumers, which increased the efficiency of municipal water pumping stations and extended the service life of the pipeline network. According to the manufacturer, the reduction in overpressure in the DDD intelligent pumping system network could lead to a 25% reduction in pump energy consumption, while a 10% reduction in average pressure could reduce the cost of active water leakage management by 10%. Optimum pressure management could reduce water leakage by 15%, which reduced losses and increased water supply efficiency. Therewith, pressure stabilisation over 24 hours proved to be effective in reducing the number of pipe bursts, and a 16% reduction in night-time pressure could reduce the number of pipe bursts by 50% (Demand Driven Distribution, n.d.).

One of the leaders in the use of AI in water distribution management was Siemens with its SIWA Leak Finder, which analysed data from smart flow meters and enabled the detection of water leaks in pipelines with high accuracy, reducing water losses by up to 50% (Siemens makes it..., 2024). The system can detect leaks as small as 0.2 litres per second, which facilitates rapid response and reduces water losses. Integration of SIWA Leak Finder with Siemens Sitrans FM Mag8000 flow meters simplified the installation process and did not require specialised knowledge or additional services. The system could process and analyse operational data from smart sensors via a cloud connection, providing access to information within two hours of installation. The AI algorithms were automatically trained and adapted to the data from the moment of installation, which increased the efficiency of monitoring and management of the water distribution network. The implementation of SIWA Leak Finder contributed to the sustainability of water resources by reducing water losses and improving the efficiency of water supply systems. Thanks to the use of AI, the system ensured reliable monitoring and management, which was a major step towards the sustainable development of water infrastructure.

Siemens offered intelligent solutions for cybersecurity of water infrastructure, specifically through its Mendix platform (Siemens makes it..., 2024). Using Mendix, companies could create interfaces to integrate data from SIWA applications into Enterprise Resource Planning (ERP) systems, ensuring secure information exchange between distinct infrastructure components. This enabled efficient data management and increased cybersecurity of water systems. Siemens provided guidance and templates for creating secure network and system architectures, and offered certified cybersecurity solutions to help water infrastructure operators protect against cyber threats. These initiatives have contributed to improving the resilience and security of water resources.

Overall, the use of various tools and technologies for accurate measurement and control was an integral element in water distribution management systems. For instance, the amount of useful water that actually reached the root zone of plants was determined using soil moisture sensors. These were tensiometers or capacitive sensors that measured soil moisture in real time. Furthermore, usable water was estimated by direct soil sampling before and after irrigation and observing changes in moisture levels in the root zone. Evaporators or weather stations were used to measure evapotranspiration losses, which helped to calculate the evapotranspiration rate, the sum of evaporation from the soil and transpiration from plants. Water loss through infiltration into deep soil layers was estimated using soil permeability models or observations of water movement in the soil. Monitoring systems that measure the volume of water flowing over the field can be used to estimate losses due to runoff (Haleeva *et al.*, 2024).

The processes were automated by intelligent irrigation systems that integrated data from various sensor networks (e.g., soil moisture sensors, weather stations, water levels in canals) and analysed them to make decisions. Such intelligent systems comprised hardware and software, including controllers, data processing algorithms, applications, and online platforms. The controllers used were Rain Bird ESP series, which supported integration with various sensors (including those measuring soil moisture, atmospheric parameters, and water levels) and could adapt to changing conditions to ensure optimum irrigation. Rain Bird ESP-Me is a high-tech controller of the ESP series, designed for automation and integration of intelligent solutions into irrigation systems, supporting a variety of irrigation settings through flexible programming (ESP-Me Series Controllers, n.d.). It supported from 4 to 22 stations and could be equipped with the LNK™ module for Wi-Fi connection, which enabled monitoring and control via mobile applications on iPhone Operating System (iOS) and Android platforms. Thanks to this functionality, the ESP-Me controller could reduce water consumption by 30% by using data from online weather services to adjust irrigation schedules in real time. This enabled efficient application of adjustment seasons, as well as customisation of restrictions for each station to adapt irrigation to weather conditions.

One of the key advantages of the ESP-Me controller was the ability to control irrigation both automatically and manually and monitor water flow. The user could set a schedule for each station separately or start watering on demand. Furthermore, the ESP-Me supported the seasonal adjustment function, which allowed changing the watering intensity according to weather conditions. The controller was also equipped with a rain sensor that automatically stopped watering during precipitation, preventing unnecessary water consumption. A delayed watering function allowed pausing the system for a certain time, e.g., after heavy rain. For even more control, the number of stations could be expanded, making ESP-Me the best option for large areas. The ESP-Me controller could support a Wi-Fi connection (by connecting the LNK2 module). This allowed controlling irrigation remotely via a mobile application, which is especially convenient for people who are often on the move or manage several facilities at the same time.

The ESP-Me controller is designed for both irrigation of private gardens and programming of commercial irrigation systems, enabling efficient management of water supply to different areas (Zavertaliuk & Naumovska, 2024). Thanks to its flexible settings, it allows you to control the time, duration, and frequency of irrigation, which helps to save water and ensure optimum plant care. ML and forecasting algorithms were also employed to analyse the collected data, which helped to determine the best irrigation regimes depending on current conditions. These could be algorithms for predicting soil moisture based on weather data and historical indicators. There were also software solutions that enabled users to monitor and control irrigation systems in real time. For example, the CropX platform offered a mobile application that displayed sensor data, provided irrigation recommendations, and allowed remote control of equipment (Cropx platform overview, n.d.).

Overall, the efficiency of water distribution in an irrigation system depended on various factors: the type of irrigation system, soil characteristics, climatic conditions, and the technical condition of the equipment. Drip irrigation usually provided the least water loss compared to other methods, while conventional canal systems could have major losses due to evaporation and infiltration. Thus, the findings of the present study substantiated the significance of automation and implementation of intelligent water distribution management systems to optimise the use of water resources in the Kyrgyz Republic.

DISCUSSION

The findings of the study confirmed a considerable improvement in water consumption efficiency and water conservation through automation and intelligent water distribution management systems. The use of sensor networks helped to achieve a level of water use in the irrigation system of up to 85%, while reducing losses to 150 m^3 out of 1,000 m^3 of supplied water. The study by H. Ojaghlou *et al.* (2024) on alfalfa crops also reported water savings due to the adjustment of irrigation time, but three times higher, as the crop is not demanding on humidity. The introduction of intelligent water distribution management systems, such as DDD, reduced water leakage by an average of 15% and pipe damage by 50%. These findings are substantially better than the conventional irrigation methods mentioned by K.R. Choudhary (2024), including sprinkling, surface or drainage irrigation, and flooding, which also had limitations: they contributed to soil erosion and significant water losses.

The precision irrigation methods (drip, sub-surface drip, micro-irrigation) investigated by K.R. Choudhary (2024) provided high precision and resource savings by minimising water loss and precisely distributing water directly to the root zone of plants. Compared to these conventional methods, the DDD system demonstrated efficiency mainly in water conservation and reduction of energy consumption and infrastructure repair costs. The findings confirmed the need for the development and application of innovative technologies in irrigation, primarily for intelligent water distribution management. This is consistent with the findings of Y. Li (2023), who noted the significance of integrating IoT and sensor systems for water resources monitoring. However, the researchers did not pay attention to methods of reducing water losses and infrastructure damage.

J. Singh *et al.* (2024) investigated the use of ML algorithms to optimise irrigation and confirmed the significance of automation technologies. Sensor networks in the study by J. Singh *et al.* were integrated with intelligent systems to achieve high accuracy in predicting plant water needs. In contrast, the present study found that the integration of sensor networks with intelligent water distribution control systems reduced water losses to 150 m^3 when supplying 1,000 m^3 of water, which resulted in substantial resource savings and contributed to water management efficiency. The studies complemented each other as they demonstrated the potential of combining sensor technologies and intelligent systems to optimise irrigation and increase water use efficiency.

H. Liu and Q. Li (2021) developed an intelligent system for automated greenhouse irrigation based on a microcontroller that helped to control soil moisture and reduce water consumption. The researchers' study confirmed the findings of the present study, but it did not cover the possibility of integrating water monitoring and optimisation technologies, which enabled a reduction in infrastructure damage and a 15% reduction in water losses. The findings of the current study on the significance of using energy-efficient systems were also consistent with the findings of M. Tripathi (2022), who studied automatic micro-irrigation based on solar energy in remote areas. The findings obtained in both studies demonstrated the possibility of large-scale implementation of integrated solutions that combined automation, intelligent systems, and innovative monitoring technologies, which ensures integrated resource management and minimises energy supply costs.

Analogously to the study by B. Mason *et al.* (2019) on agriculture and its adaptation to different climatic conditions, the present study substantiated the effectiveness of smart irrigation systems and confirmed that smart irrigation systems could operate effectively in different conditions without loss of yield. The findings demonstrated the efficiency of using drones for spraying, which was estimated at 90%, enabling the uniform distribution of 450 m^3 of spray solution from an initial volume of 500 m^3, minimising losses of up to 50 m^3. On the other hand, A.R. Alex *et al.* (2025) confirmed the significance of automation for optimising irrigation and water conservation. This approach, which focused on continuous monitoring of soil moisture using soil moisture sensors and an Arduino Uno microcontroller, enabled localised irrigation automation. The present study, on the other hand, included a review of an automated system for water metering, water distribution, and irrigation control in Kyrgyzstan, which enabled the integration of automation into larger irrigation networks, improving water use efficiency at the macro level.

The study found that the integration of sensor networks, drones, and water distribution management software saved resources and increased irrigation efficiency. Y.K. Kushwaha *et al.* (2024) applied the Smart Irrigation Monitoring System (SIMS) system for real-time irrigation management, which uses IoT components to monitor soil moisture and forecast precipitation, which also helps to optimise water consumption. Both approaches included intelligent monitoring and control systems, although Y.K. Kushwaha's *et al.* study focused on the use of IoT for real-time monitoring and forecasting. At the same time, the present study focused on methods of automating water distribution, including not only monitoring but also active management using drones and integrated software for irrigation networks.

D.M.C.D. Le Veut *et al.* (2024) explored an autonomous solar pumping system with a controller for local irrigation. In the present study, on the contrary, solar panels were not included in the automation system, which may reduce its efficiency. Still, both studies were aimed at saving water and, accordingly, sustainable agricultural development, and therefore contributed to optimising water consumption in various climatic zones. The study also confirmed the effectiveness of integrating intelligent water distribution management systems, which is consistent with the findings of

M.C. Lallawmkimi *et al.* (2024), who noted the significant potential of nanotechnology to improve water and irrigation management through the use of nanomaterials for water purification and real-time nanosensors for water quality and soil moisture. The integration of such technologies helped to save water, increase yields, and ensure sustainable agricultural development.

B. Askaraliev *et al.* (2024) confirmed the effectiveness of drip irrigation and automatic IoT-based systems in reducing water consumption by 50% while increasing yields by 30%. As in the present study, the introduction of agrodrones for monitoring and precise irrigation control in this study confirmed the significance of innovative technologies in reducing water costs and increasing productivity. Therewith, the findings of the present study revealed that the data collected by drones can be integrated into the automation system by automatically reading and transmitting them to the central server or the operator's mobile application.

The findings of the present study demonstrated a considerable improvement in the efficiency of water consumption and water conservation through the introduction of automated systems. K.V. Joshi *et al.* (2024) confirmed the significance of such irrigation systems for optimising water use. N. Patel *et al.* (2024) investigated the improvement of irrigation efficiency in horticulture, specifically through the strategy of deficit irrigation and the use of hydrogels. The findings of the present study, which included technologies for precise monitoring and management of water resources, complemented this approach, confirming the effectiveness of integrated solutions for water conservation and irrigation optimisation. The study also found that SIWA's intelligent Leak Finder system detects water leaks with an accuracy of 0.2 litres per second, reducing water losses by up to 50%, while the DDD system reduces pump energy consumption by 25%, water leaks by 15% and pipe damage by 50%. At the same time, a study by M.C.A. Diallo *et al.* (2024) highlighted that smart irrigation technologies can reduce water consumption by 30% and increase productivity by up to 125%, with maximum savings of up to 78% in arid regions. Notably, the present study focused on an integrated approach to reducing water loss, energy consumption, and infrastructure damage, while M.C.A. Diallo *et al.* focused more on optimising water consumption and increasing productivity in drought conditions.

D. Mukhamedieva *et al.* (2024) explored the creation of an intelligent irrigation system based on fuzzy Sugeno logic that optimises water use and increases yields. The software proposed by the researchers can make decisions on the need for irrigation and the optimised amount of water supply based on the collected data on soil moisture. In terms of the findings of the present study, the software (AquaCrop and ArcGIS) considered in this study was more focused on water balance and irrigation optimisation based on geospatial data and agronomy models, but did not provide the flexibility to make decisions in the presence of uncertainty as the Sugeno model does. However, it had the advantage of providing a comprehensive assessment of water balance over large agricultural areas, considering various agronomic and geographic factors (Fedoniuk & Skydan, 2023).

This study analysed the effectiveness of using automated water distribution management systems to conserve water and improve irrigation efficiency. In the study by W. Patel *et al.* (2024), an IoT system for irrigation optimisation collected data on soil and plant health and used neural networks to provide recommendations to farmers, resulting in improved water conservation efficiency and productivity. This study confirmed the findings of the present study, as both approaches used intelligent systems to monitor and manage irrigation. However, the present study focused on the integration of sensor networks, drones, and software to automate water distribution in agricultural areas, allowing for integrated water management at the macro level.

I. Abd-Elaty *et al.* (2024) showed that the use of modern irrigation systems in the Nile Delta can save significant amounts of water (2.15×10^9 m^3), but there are problems with increased salinity and lower groundwater levels. The conclusions of the present study also pointed to the significance of an integrated approach to water management, where the introduction of innovative technologies can greatly increase efficiency without harming the environment. Additionally, the findings obtained were consistent with the study by P. Kumar *et al.* (2023), who focused on the automation of drip irrigation using wireless sensor networks and IoT, which ensured an increase in water use efficiency. However, the current study concentrated not only on improving water use efficiency, but also on predicting water balance and using various technologies.

Z. Yang *et al.* (2024) proposed a method for optimising irrigation profits, considering climate risks, which complements current approaches to water balance modelling and irrigation optimisation. Overall, the findings obtained in this study confirmed the efficiency of automated systems for improving water supply and optimising agricultural production. Thus, compared to other studies, the present study demonstrated a more comprehensive approach to water management, including monitoring, optimisation of water balance, and the use of intelligent systems that significantly reduce water leakage and pipe damage.

CONCLUSIONS

The use of sensor networks to monitor soil moisture, canal water levels, and water flow in the Wzzard LRPv and John Deere Operations Centre systems was found to be highly effective. Their implementation enabled the irrigation system to achieve a water use efficiency of up to 85%, which corresponded to losses of 150 m^3

when supplying 1,000 m^3. AquaCrop and ArcGIS water balance modelling and irrigation optimisation software helped to reduce water losses and improve water management efficiency, ensuring water use efficiency of 70%. This was achieved when the total volume of water applied was 1,000 m^3, and the volume of water retained in the root zone of plants was 700 m^3. The use of drones for water and land monitoring, such as the DJI Phantom 4 RTK and P4 Multispectral, demonstrated the advantage of collecting data with high precision and speed. The efficiency of liquid distribution using drones was estimated at 90%, which allowed for an even spraying of 450 m^3 out of a total volume of 500 m^3, accounting for losses due to evaporation and other factors (e.g., dosing inaccuracy, battery wear, wind, and uneven surface coverage). Overall, the findings revealed improved water distribution performance and reduced water consumption, which is essential for the sustainable use of water resources in the agricultural sector.

The introduction of intelligent systems and their improvement with GIS allowed increasing the accuracy and efficiency of water management. The DDD intelligent system reduced pump energy consumption by 25%, water leakage by 15%, and pipe damage by 50%. The SIWA Leak Finder system could detect minor water leaks, reducing resource losses by up to 50%. Thus, the findings of the present study confirmed the significance of integrating intelligent and automated systems into agriculture in Central Asia, where water resources are limited. The use of such technologies has helped to conserve water and reduce energy consumption, which is significant for the development of sustainable agriculture in the region. Additionally, the Rain Bird ESP controller enabled efficient irrigation automation, while the CropX platform provided monitoring and remote control of the process. Limitations of the study included the integration of the latest technologies into existing irrigation systems, which would require extensive investment and time, as well as dependence on specific climatic conditions that could vary from region to region. Areas for future research could include the development of common standards for integrating various technologies, ML-based water balance forecasting algorithms, and improving infrastructure to support the latest solutions in remote areas.

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CONFLICT OF INTEREST

None.

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Автоматизація та інтелектуальні системи управління водорозподілом для оптимізації використання води в сільськогосподарських зрошувальних системах

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Анотація. Метою цього дослідження був аналіз методів автоматизації, інтелектуального розподілу та споживання води в іригаційних системах Центральної Азії на прикладі Киргизької Республіки. У дослідженні розглянуто використання сенсорних мереж для моніторингу водних даних компанією Wzzard LRPv та John Deere Operations Centre. Проаналізовано роботу програмного забезпечення AquaCrop для моделювання водного балансу та оптимізації зрошення, а також використання дронів для моніторингу стану водних ресурсів та земельних ділянок, зокрема дронів Da-Jiang Innovations Phantom 4 Real-Time Kinematic та P4 Multispectral. Аналіз ефективності кожного методу показав значну економію води та покращення показників водорозподілу. Для сенсорних мереж рівень використання води в зрошувальній системі склав 85 % – при подачі 1,000 м^3 втрати склали 150 м^3. Для програмного забезпечення ефективність використання води була визначена на рівні 70 %, враховуючи, що загальний обсяг поданої води становив 1,000 м^3, а фактичний обсяг води, що утримується в кореневій зоні рослин, – 700 м^3. Ефективність використання дронів досягла 90 %, що означає, що з 500 м^3 води, заправленої в дрони для обприскування, 450 м^3 було рівномірно розподілено, а втрати через випаровування і неточності обприскування склали 50 кубічних метрів. Аналіз можливостей системи управління розподілом води Demand Driven Distribution показав зниження енергоспоживання насосів на 25 %, витоків води – на 15 % і пошкоджень труб – на 50 %. Аналіз можливостей системи Siemens Water Leak Finder показав, що алгоритми штучного інтелекту точно виявляють навіть незначні витоки води в 0,2 літра на секунду, скорочуючи втрати ресурсів до 50 %. Аналіз робочих характеристик контролера Rain Bird і платформи CropX показав підвищення ефективності водоспоживання та водозбереження в Центральній Азії, що стало важливим кроком на шляху до сталого розвитку сільськогосподарського сектору регіону

Ключові слова: моніторинг даних; сенсорні мережі; програмне забезпечення; використання дронів; ресурсозбереження; ефективність зрошення

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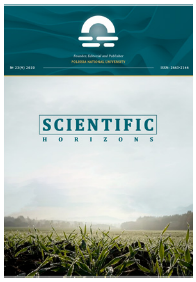

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Economic potential of the wine industry in the context of EU integration

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Abstract. The study aimed to assess the economic potential of the wine industry in the Odesa region in the context of Ukraine's integration into the European Union and to identify strategic directions for its sustainable development. The study analysed the natural, economic and social factors that contribute to the development of the industry, as well as the challenges faced by winemakers in the context of globalisation and adaptation to European Union standards. The study examined the functioning of leading wineries such as Shabo, Kolonist, French Boulevard and Vinhol Oksamytne, emphasising export success, innovations and marketing strategies. The main results of the study demonstrated that the Odesa region is the leader in wine production in Ukraine, accounting for more than 60% of the national output. Despite the high quality of its products and compliance with international standards, Ukrainian wine exports to European countries have been declining in recent years due to war and economic difficulties. At the same time, the main challenges were identified, including competition with European producers, the need to adapt to regulatory requirements, and the need for innovation in production and marketing. The proposed development strategies include improving technological processes, producing biological and premium wines, developing clusters of wineries and strengthening government support through subsidies, grant programmes and measures to promote Ukrainian wine internationally. The conclusions confirmed that the implementation of these strategies will help to strengthen the competitiveness of the wine industry in Odesa region, expand its export potential, develop wine tourism and establish Ukraine as a promising wine region in the global market. The results obtained can be used for the development of regional wine policy and the implementation of support programmes for the industry

Keywords: viticulture; wine tourism; innovative technologies; international trade; organic production; product competitiveness; European integration processes

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INTRODUCTION

Winemaking is one of the oldest branches of the agricultural sector, which not only has significant economic importance but also plays an important role in the cultural and social development of the regions. In Ukraine, the industry is a key sector of the economy, especially in southern regions such as the Odesa region, which is a leader in wine production due to favourable natural conditions, historical traditions and economic potential. In the context of EU integration, the relevance of studying the economic potential of the Odesa region's wine industry is growing, as new opportunities are opening for access to European markets, access to modern technologies and financial resources. At the same time, the industry is facing the challenges of globalisation, changing consumer trends, climate change and the need to adapt to EU standards. This requires a study of the current state, problems and prospects of the wine industry, as well as the identification of strategies to improve its competitiveness and sustainability in the context of European integration.

The topic of developing sustainable practices in winemaking is gaining increasing attention in scientific research. O. Shebanina *et al.* (2023) examined the role of environmental insurance as a tool for the recovery of Ukrainian regions after the war, focusing on green reconstruction. The authors emphasised the importance of insurance mechanisms for financing environmental projects and mitigating risks in an unstable economic environment. The study offered specific recommendations for integrating environmental insurance into the regional recovery system and assessed its impact on the economy and the environment. The potential of local economic development in the context of globalisation was studied by V. Shebanin *et al.* (2022). This analysis demonstrated that local industries, such as winemaking, can contribute to economic growth if innovative approaches to management, marketing, and export activities are applied. The authors emphasised the importance of international support, through grant programmes that help develop infrastructure and technology. Energy efficiency in the wine industry was studied by M. de Castro *et al.* (2024) in an analysis of current challenges and opportunities for improving the energy efficiency of production processes. The study presents an analysis of technologies that help reduce energy consumption and costs in winemaking, including the use of renewable energy sources. These approaches are of particular importance for wineries in the Odesa region that seek to reduce costs and meet European environmental standards.

J.W. Jiménez and R. Zurdo (2024) explored the potential of using blockchain technologies to ensure transparency and increase trust in winemakers' products. The study emphasised that digital technologies can significantly optimise production and marketing processes, in particular in product traceability. J.M. Alston and D. Gaeta (2021) analysed the economic and political aspects of European wine appeals, including their impact on market regulation, competition and product quality. The study analysed the historical background and current challenges, including consumer preferences, in detail. The main achievement of the study was the generalisation of data, but it did not propose innovative approaches to solving the identified problems. A. Soceanu *et al.* (2021) proposed an interdisciplinary approach to wine industry waste recycling, addressing economic, environmental and technological aspects. The study demonstrated how waste management can create added value for businesses and reduce environmental impact. However, the study addressed theoretical aspects, omitting practical implementations. R. Silvestri *et al.* (2023) investigated how blockchain technologies have contributed to building trust and creating competitive advantages in the wine industry. The paper considered a resource-based approach to innovation and demonstrated how blockchain ensures transparency and reliability of data. The main drawback was the limited coverage of technology adoption in small and medium-sized enterprises.

M. Wagner *et al.* (2023) examined the vision for sustainable development of the global wine industry, proposing strategies to reduce environmental impact. The authors analysed current challenges, including climate change, and proposed specific environmental initiatives. The study was in-depth, but limited to a broad conceptual vision, without specific actionable tools for local producers. The role of cooperatives in winemaking, in particular their impact on sustainable development and digitalisation, was analysed by B. Richter and J.H. Hanf (2021). The study demonstrated how innovation can support the sustainability and efficiency of cooperatives.

Despite the significant economic potential of the Odesa region's wine industry in the context of European integration, the issues of adaptation of producers to European regulations, the impact of climate change on viticulture, and economic challenges, including competition and financial barriers, remain insufficiently studied. Therefore, the study aimed to determine the economic potential of the wine industry in the Odesa region in the context of EU integration, as well as to outline ways to increase its competitiveness and sustainability. The study examined the current state of the industry, identifying the main problems and challenges related to adaptation to European standards, changing consumer trends and the impact of climate change, and developing recommendations for the integration of local producers into European markets.

MATERIALS AND METHODS

To conduct the study of the wine industry in the Odesa region, a comprehensive approach was applied, including quantitative, qualitative, comparative and historical methods of analysis. The main sources of data were official statistical reports of the State Statistics Service of Ukraine (n.d.). The analysis covered data from 2018 to 2024, which was used to study the dynamics of the industry development, export volumes, economic indicators and changes caused by geopolitical and economic factors. The historical method was used to analyse the evolution of the wine industry in the Odesa region, in particular, the development of viticulture and winemaking traditions from ancient times to the present. This identified the key factors that shaped the unique character of the region's products, such as local grape varieties, in particular Odesa Black and Sukholimansky White, which are an important element of the modern identity of the products.

To analyse the natural factors of the industry's development, data on the region's climatic conditions and soil characteristics were used. These indicators assessed the impact of the environment on winemaking and identified the key conditions that contributed to the development of the industry in the region under study. The benchmarking method was used to compare the practices of winemakers in the Odesa region with leading European wine regions such as France, Italy and Spain by key criteria, including soil quality, vineyard yields, production regulation and certification, marketing strategies, and the level of integration of producers into international trade networks. This was used to assess the competitiveness of the region's products and identify the prospects for implementing best practices to adapt to European standards and consumer requirements.

The case study was used to analyse in detail the activities of the region's leading wineries, such as Shabo, Kolonist, Frantsuzsky Bulvar and Vinhol Oksamytne, with a focus on their production strategy, grape growing practices, level of technological modernisation, export activity, marketing approaches and compliance with international quality standards. This explored unique business models, identifying best practices, comparing the strengths and weaknesses of the companies and defining the impact of the local and international contexts. This contributed to the development of recommendations for the development of the industry in the areas of marketing, production, export and wine tourism.

A content analysis of publications in industry and academic journals assessed current trends in the wine market, including the demand for biowine, the development of organic viticulture and the popularity of wine tourism. This method also identified key challenges, such as competition with European producers and the high cost of implementing environmental standards. The combination of these methods created a comprehensive overview of the current state of the industry, its prospects and challenges. This approach ensured both analytical depth and practical orientation of the study, which became the basis for formulating recommendations for the development of winemaking in the Odesa region.

RESULTS AND DISCUSSION

The importance of the wine industry for the Odesa region. The wine industry is one of the key sectors of the Odesa region's economy, providing production and employment, especially in rural areas. The region occupies more than 60% of Ukraine's vineyards, which is approximately 24-26 thousand hectares. However, over the past 10 years, there has been a downward trend in vineyards: while in 2013 the area under plantation in the region was approximately 30 thousand hectares, by 2023 this figure had decreased by about 15-20%, due to economic difficulties, climate change, and the effects of military operations (State Statistics Service of Ukraine, n.d.; Nahurna & Kurylenko, 2024). Wineries in the Odesa region, such as French Boulevard and Vynkhol Oksamytne, are examples of successful businesses that combine tradition with innovation.

The economic impact of the industry is manifested in the production of wine, which covers the entire value chain from growing grapes to selling finished products. Winemaking also stimulates the development of related sectors, such as agriculture, logistics, tourism, packaging, marketing and export operations. Viticulture and winemaking provide between 5,000 and 7,000 permanent jobs for residents of the Odesa region, with this figure doubling during the seasonal period, contributing to the development of local infrastructure and creating favourable conditions for attracting investment (Odesa Regional State Administration, 2023). Wine exports from the Odesa region, especially to the European Union, are an important source of foreign exchange earnings. During the prewar period (until 2022), the Odesa region demonstrated a steady increase in wine exports, which indicates a high level of confidence in its quality. In January-July 2022, the volume of exports of goods amounted to USD 1,082.2 million, which is 59.3% more than in the same period of 2021. Most goods were exported to Romania, Turkey, Bulgaria, Egypt, Moldova, Italy, and Spain (Steblovska, 2022).

The cultural impact of winemaking goes far beyond the economic sphere. Winemaking traditions are part of the cultural heritage of the region, reflected in folklore, artistic practices and local customs, attesting to their historical connection with viticulture. Wine festivals, such as the Days of Wine and Vines in Shabo, attract both Ukrainian and international tourists. Oenotourism (wine tourism) is becoming an important tool for promoting the region and stimulating the development of the hotel and restaurant business. In addition, winemaking actively promotes a positive image of the Odesa region as a region with a rich history, high-quality products and hospitable traditions. These factors contribute to the development of tourism in the Odesa region, combining the natural features of the area with the opportunity to learn about the traditions of winemaking and taste the products.

Ukraine's European integration creates both new opportunities and serious challenges for the Odesa region's wine industry. One of the key achievements was the opening of access to the European Union market, which is one of the largest consumer markets in the world. In January-September 2023, Ukraine exported 9.66 thousand tonnes of grape wine worth USD 6.59 million. The main importers of Ukrainian wine among the EU countries are Romania and Moldova (9.7 thousand tonnes..., 2023). In total, Ukrainian wines are exported to 49 countries, which indicates a growing interest in the products of Ukrainian winemakers on the international market (Ukrainian wines are..., 2024). In 2024, total exports of Ukrainian goods to the EU increased by more than USD 1 billion compared to 2023, reaching USD 24.5 billion, which is more than 59% of the country's total exports (Ministry of Economy of Ukraine, 2024).

For wine producers, this is an opportunity to expand their presence outside of Ukraine, increase exports and strengthen their position internationally. At the same time, integration requires winemakers to adapt to EU regulatory standards in terms of product quality, packaging, certification and environmental friendliness. This requires significant financial investments in the modernisation of enterprises, the introduction of new technologies and staff training. The need to create innovative products, such as biowine and premium wines, that meet current trends in the European market is particularly relevant. The Odesa wine industry faces competition from leading European producers such as France, Italy and Spain. As of September 2024, the average price of a 0.75-litre bottle of Ukrainian table wine in Ukraine was UAH 110.41, which is significantly lower than its imported counterparts (Minfin, 2024). This creates a competitive advantage in the price segment. Ukrainian winemakers actively participate in international events to promote their products. In particular, the Wine & Spirits Ukraine 2024 exhibition, which took place on 29-31 October 2024 in Kyiv, became a platform for meetings between producers and distributors and retailers.

Strategies for promoting Ukrainian wines include participation in international exhibitions, development of unique offers, marketing and branding, and government support. A comprehensive approach that combines affordability, product uniqueness and effective marketing will consolidate Ukrainian wines on the international market.However, there are significant opportunities alongside the challenges. Attracting European investment and grant programmes can help modernise production and improve product quality. Integration into global wine associations will facilitate the exchange of experience and strengthen international relations. In addition, European markets provide opportunities for the development of new niches, such as organic winemaking, which is becoming increasingly popular among consumers. Thus, the Odesa region's wine industry has significant potential in the context of European integration, which can be realised with active state support, investment and a strategic approach to the development of the industry.

Development of winemaking in the Odesa region. Odesa region is the largest viticulture region in Ukraine, with more than 60% of the country's wine production. The area of vineyards is about 24-39 thousand hectares, depending on the source, with production concentrated in Bolhrad, Tarutino and Saratsky districts (Steblovska, 2023). The region has a temperate continental climate with warm summers (+21-23°C) and mild winters (-2-5°C). Annual rainfall is 340-470 mm, which creates optimal conditions for viticulture. The growing season lasts 168-210 days. The soils are predominantly black: ordinary soils cover 66.4% of the vineyards, and southern soils cover 33.6% (Babych *et al.,* 2021). The high natural fertility is conducive to growing grapes and producing quality wines. The region's infrastructure includes modern wineries, laboratories, and wine tourism centres, which ensures the development of the industry and increases export potential.

Wine production in the Odesa region remains a key agricultural sector and an important element of the region's economy. The combination of long-standing traditions, favourable natural conditions and modern technologies allows local winemakers to create products that meet high-quality standards and are popular both in Ukraine and abroad. Overall, Ukraine produces more than 7 million decalitres of grape wines annually, with the Odesa region accounting for 60% of this volume (Odesa Regional State Administration, 2021). Among the most common are Aligote, which occupies 16.2% of the total vineyard area, Cabernet Sauvignon 13.1%, Rkatsiteli 7.4%, Odesa Black 6%, Merlot 5.7% and Chardonnay 5.3%. These varieties provide a wide range of wines that meet different consumer preferences and international quality standards (Verkhovna Rada of Ukraine, 2024). The main wineries in the Odesa region include industry leaders (Table 1).

***Table 1**. Main wine producers of the Odesa region*

Producer	Main specialisation	Peculiarities
Shabo	Wines, brandy, champagne, grappa	Exports to more than 20 countries, innovations, wine tourism
Colonist	Premium wines for export	Handmade, distinctive taste characteristics, participation in international exhibitions
French Boulevard	Champagne wines, sparkling wines, dry wines	Traditional production, modern technologies, and popularity in the domestic market
Vinhol Velvet	Table and semi-sweet wines, fruit drinks	Local varieties, affordable prices, focus on the mass consumer

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

Wine producers in the Odesa region vary significantly in terms of scale, market orientation and production approaches, creating a diverse ecosystem in the region. Shabo is the largest winery in the region, with 1,250 hectares of vineyards and a capacity to produce 15 million litres of wine per year. The company is focused on the mass production of high-quality products, including wines, brandy and sparkling wine. As of 2024, the company's exports exceeded 17% of total Ukrainian wine exports, which indicates its leading position in the international market. The company exports its products to more than 20 European countries, including Germany, Poland, Latvia, Lithuania, France and Sweden. The main export items are red wines, which account for about 60% of the company's total exports. The key to success was the introduction of certification following ISO 22000 and Hazard Analysis and Critical Control Points (HACCP) standards, which ensures the trust of European consumers. Moreover, in 2022, the company presented its products at 8 international exhibitions, winning 12 awards, including gold medals for sparkling wines.

Kolonist, unlike Shabo, is a medium-sized producer specialising in premium wines. Their vineyards cover 66 hectares, and production volumes are inferior to those of large farms. However, Kolonist focuses on high-quality products, which allows it to be successful in niche market segments. In 2024, the company exported about 28% of its production, mainly to the UK, Poland and Germany. The total volume of Kolonist exports was about 20 thousand bottles per year, with an emphasis on wines made from international grape varieties (Cabernet Sauvignon, Merlot, Chardonnay, Riesling). Medals won at international competitions, including the Decanter World Wine Awards in London, where Kolonist won a silver award for Chardonnay in 2020, played a special role in the development of exports. This has significantly increased brand awareness among European consumers.

French Boulevard is one of the oldest wineries in the Odesa region, known for its many years of experience and classical production traditions. The company has 1,500 hectares of vineyards and three wineries that process over 10,000 tonnes of grapes annually. The winery specialises in the production of sparkling wines, sparkling drinks and dry wines. By combining traditional methods and modern technologies, the company creates products that have gained popularity both in the domestic market and abroad. The French Boulevard winery combines traditional production methods with modern technologies to ensure the high quality of its products. In particular, the company uses the Charmat method to produce sparkling wines, in which secondary fermentation takes place in large steel tanks under pressure. This method preserves the freshness and brightness of the wine's flavour.

Established in 1998 in the village of Oksamytne, Bolhrad district, Odesa region, Vinhol Oksamytne specialises in the production of table and semi-sweet wines and fruit drinks. The company owns 550 hectares of domestic vineyards and cooperates with local growers to process grapes from an additional 600 hectares. Thus, the total area of vineyards operated by the company is about 1,150 hectares. In 2022, Vinhol Oksamytne produced 200,000 bottles of wine, but the company has ambitious plans to increase this volume to 1 million bottles in the coming years. The company is equipped with modern European-made equipment for all stages of production, including Italian crushers and French Vaslin Bucher pneumatic presses for delicate grape pressing, as well as an Italian bottling line for still and sparkling wines. The presence of a certified laboratory ensures full control of the production process and guarantees consistently high product quality.

Features of natural conditions: climate, soils and their impact on grape quality. Odesa region is characterised by a temperate continental climate with long warm summers and mild winters, which contributes to the uniform ripening of grapes. The growing season lasts from 168 to 210 days, and the sum of active temperatures ranges from 28-34°C. In the summer months, the average relative humidity at 13:00 does not exceed 55%, which is an important factor for the ripening process. However, the region's vineyards are exposed to several climate risks, including droughts, dust storms and windstorms, which can affect the quality and quantity of the harvest. The Black Sea acts as a natural thermoregulator, providing optimal temperature differences between day and night, which is important for preserving the aroma and acidity of grapes. According to the Ukrainian Hydrometeorological Centre, the average air temperature in Odesa in July is +23°C (daytime +27, nighttime +24). This indicates insignificant daily temperature fluctuations, which contribute to the formation of grape quality characteristics. Soil conditions in the Odesa region are central to the region's viticulture. The predominant soil types are chernozems, loams and sandy soils. Black soils, formed on loess rocks, are characterised by high humus and calcium content, which favours the cultivation of both international and local grape varieties. Loams, which consist of a mixture of sand, clay and silt, provide good fertility and moisture retention, which is important for the stable development of the vine. Due to their ability to drain quickly, sandy soils are conducive to growing grapes with a high sugar concentration, which is particularly suitable to produce light white wines with low acidity and low tannin concentration. In general, the mineral composition of the soils in the Odesa region, in particular the presence of calcium and other minerals, gives wines a rich flavour profile (Babych *et al.*, 2021). In the Danube region, where sandy soils predominate, growers obtain grapes with high acidity, which makes wines from this region particularly expressive (Table 2).

***Table 2**. Agroclimatic indicators of Odesa region*

Region	The sum of active temperatures, °C	The average temperature of the warmest month, °C	Precipitation per year, mm	Soil type
Odesa region	3200-3600	22-24	330-450	Chestnut, southern black soil

***Source:** compiled by the author based on I.M. Babych et al. (2021)*

Odesa region is characterised by favourable agricultural-climatic conditions for viticulture, combining a high sum of active temperatures, moderately warm summer temperatures, optimal rainfall and fertile soils. These conditions ensure stable ripening of grapes and the formation of high-quality raw materials for winemaking. These factors, together with the geographical location, create an ideal environment for the development of viticulture and winemaking in the region. Odesa region is a region where, along with international varieties, unique local grape varieties (Odesa Black, Sukholimansky White) are grown, which form the identity of local wines. One such variety is Odesa Black – a hybrid created by Ukrainian breeders. This variety is famous for its deep colour, pronounced tannins and rich aromatic profile. Odesa Black wines are well suited for ageing and are highly competitive on the international market. Another important variety is Sukholimansky White, which is used to produce light white wines with a delicate aroma and refreshing acidity. This variety is particularly appreciated by connoisseurs of dry wines with a delicate flavour profile. Unique grape varieties grown in the Odesa region add a local flavour to the products and help to promote them among consumers looking for authentic taste experiences.

The current state of the wine industry. The decline in vineyard areas in the Odesa region, which began to occur from 2022 to 2024, is determined by several factors. The economic reasons include higher production costs and low purchase prices for technical grapes, which reduce the profitability of viticulture. In addition, the decline in exports of Ukrainian wine products and the prevalence of imported wines on the Ukrainian market make it difficult for local producers to sell their products. Climatic factors, such as moisture deficit and soil degradation, also harm vineyard yields. Additionally, low motivation to establish new vineyards and a decline in the production of planting material exacerbate the problem. The lack of systematic control over the quality and safety of wine products and the high tax burden on the industry creates additional obstacles to the development of viticulture in the region. Figure 1 shows the dynamics of the reduction of vineyard areas in the Odesa region over the past 5 years.

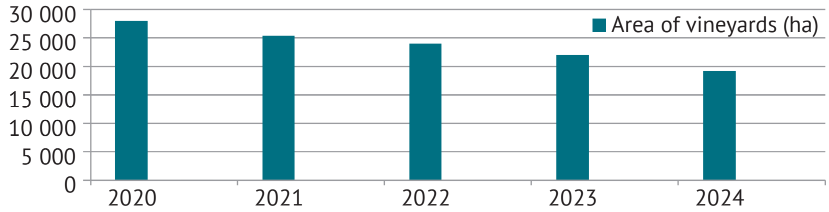

***Figure 1**. Dynamics of reduction of vineyard areas in the Odesa region over the past 5 years (2020-2024)*
***Source:** compiled by the author based on Odesa Regional State Administration (2021), Verkhovna Rada of Ukraine (2024)*

The graph shows a steady downward trend in vineyard areas in the Odesa region over the past five years. The main reasons for this decline are economic difficulties, reduced government support, climate change and the effects of military operations. According to the Odesa Regional State Administration (2021), the area of new vineyards decreased significantly in 2020, and yields decreased due to unfavourable weather conditions. The Verkhovna Rada of Ukraine (2024) also confirms the overall reduction in vineyard areas in the country, which directly affects wine production. This trend is causing concern among winemakers in the region and requires the introduction of programmes to support viticulture, modernise production processes and develop wine tourism to stimulate the industry.

In 2019-2023, grape yields in Ukraine, particularly in the Odesa region, were growing, reaching 93 cwt/ha in 2023. However, in 2024, due to drought and heat, the figure decreased by 30%. The increase in yields was driven by the introduction of drip irrigation, the use of biological products and genetically resistant varieties that increase the resilience of vineyards to stressful conditions (Fig. 2). At the same time, vineyard areas are shrinking due to economic factors, including rising production costs, difficulties with the sales market and reduced government support. The increase in yields partially compensates for the reduction in planted areas, ensuring a stable level of production. Climate risks, including rising temperatures and droughts, pose a significant challenge to the industry. Adapting to the changes requires the introduction of modern agricultural technologies, breeding of resistant varieties and the development of effective irrigation strategies.

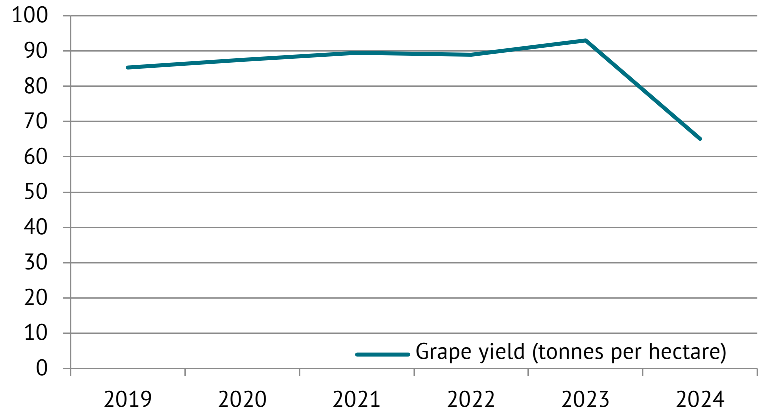

***Figure 2**. Dynamics of grape yield in Ukraine, 2019-2024 (t/ha)*
***Source:** compiled by the authors based on the State Statistics Service of Ukraine (n.d.)*

The economic performance of the wine industry is showing steady growth. In 2022, the Odesa region produced more than 140 thousand tonnes of grapes, from which more than 10 million litres of wine were produced. Exports of wine products from the region totalled approximately USD 7 million. Ukrainian wine producers exported products worth USD 16.5 million. Of this amount, the Odesa region exported wines worth USD 7 million, which is approximately 42% of Ukraine's total wine exports. The main markets were the EU and Asian countries, namely Germany, Poland and Lithuania, China, Japan and South Korea. Medium and premium wines are in high demand, which encourages producers to improve the quality of their products and adapt them to international standards. In addition, there is growing interest in organic and natural wines. Consumers are increasingly paying attention to the origin and production methods of wine, preferring environmentally friendly products (Nabiyev *et al.*, 2024). This requires producers to comply with international quality and safety standards. Adaptation of Ukrainian winemakers to international markets involves certification of products following EU standards, introduction of eco-friendly production, and improvement of labelling to ensure transparency of the origin and composition of wines. Such measures help to increase the competitiveness of Ukrainian wines on the global market and strengthen their position in the segment of high-quality wine products. The industry provides jobs for more than 20,000 people, including seasonal workers, and creates additional employment opportunities in related sectors, such as tourism, packaging and logistics.

The development of wine tourism in the region is an important area for economic growth. Every year, Odesa region's wineries welcome more than 200,000 tourists. For instance, the Shabo and Kolonist wineries have become popular tourist attractions, offering tasting tours and cultural events. The government recognises the potential of wine tourism and provides support for its development. In particular, the Odesa region is implementing the Tourism and Resorts Development Programme for 2021-2023, which provides measures to promote the development of wine tourism, including marketing support and infrastructure development. In addition, the state supports the development of wine tourism through programmes aimed at developing rural, green, wine, event and gastronomic tourism. This includes international marketing support and infrastructure development to improve the tourist experience (Report on the..., 2021). This approach helps not only to promote products but also to attract investment to the region. Thus, the Odesa region's wine industry demonstrates a high level of development and significant potential. Unique natural conditions, support for international standards and demand for Ukrainian wines abroad create prospects for further growth, modernisation of production and strengthening of the region's position in the global market.

The impact of war on the wine industry in the Odesa region. At the beginning of 2022, there were about 180 wineries in Ukraine. Of these, 49 were in the Odesa region. In 2021, wine production in Ukraine was about 100 million litres, with the Odesa region accounting for about 60% of this volume, which corresponds to approximately 60 million litres. The viticulture and wine industry in the Odesa region is an important source of employment. According to the Odesa Regional State Administration (2023), the industry employs between 5,000 and 7,000 permanent workers, and this number doubles during the seasonal period. In addition, almost 4,500 people work in the wine industry. The martial law that began in 2022 had a significant impact on the region's wine industry. In 2023, the area of vineyards decreased by 2,800 hectares, which indicates a significant reduction in production potential. The main reasons were the loss of access to certain areas, the destruction of infrastructure and general economic difficulties. As a result, wine production volumes decreased. In 2022, Ukraine produced 55 million litres of wine, which is half of the pre-war figures (State Statistics Service of Ukraine, n.d.).

The destruction of the Gostomel Glassworks, one of the largest producers of glass packaging in Ukraine, has created significant challenges for the wine industry. As a result, companies faced a shortage of glass packaging, which complicated production processes and increased costs. To overcome this problem, some producers have turned to alternative suppliers in Ukraine, such as Kostopil Glassworks, which is investing around UAH 500 million in the construction of a new furnace to increase production capacity. However, due to limited domestic resources, some wineries were forced to switch to imported glass packaging, which increased costs and dependence on external suppliers. The logistical difficulties caused by the hostilities also had a significant impact on Ukrainian wine exports. The blockade of the Black Sea ports, through which about 95% of Ukrainian exports passed before the war, led to an almost complete halt in sea deliveries from March to mid-August 2022. This forced producers to look for alternative routes, through the western land borders, which increased transport costs and delivery times. As a result, wine exports declined significantly, although the exact figures need to be further clarified. The blockade of ports has forced Ukrainian exporters to refocus on alternative markets and supply routes. Exports began to be made via Ukraine's western borders, using rail and road transport. This partially compensated for the losses caused by the blockade of ports but led to an increase in logistics costs and delivery times. Thus, the destruction of critical infrastructure and logistical constraints have had a significant impact on the Ukrainian wine industry, forcing producers to adapt to new conditions and look for alternative solutions to support production and exports (Russia's war against…, 2022).

As of 2023, there were 144 wineries in Ukraine, of which 29 were small producers. The decrease in the number of small wineries compared to the pre-war period indicates a decline in activity in the industry. The main reasons for this are financial difficulties caused by economic instability and rising production costs. Some small producers were forced to cease operations due to the inability to ensure profitability. Others tried to adapt by changing the format of their operations by switching to the production of craft wines or expanding their product range. However, such changes required additional investment and did not always bring the expected results. Thus, small wineries faced serious challenges, which affected their market presence.

The decline in vineyard areas and the decline in wine production negatively affected the region's economy. The wine industry, which provided thousands of jobs, has suffered significant losses. In villages and small towns, where viticulture is the main source of income, the impact was particularly severe. However, even in the face of war, wineries continue to adapt to new challenges (Rexhepi *et al.*, 2023). Leading producers, such as Shabo and Kolonist, have focused their efforts on maintaining production capacity and supporting exports. They are focusing on expanding their product range to include the production of craft wines and other grape-based beverages such as grappa and chacha. This improves the efficiency of raw materials and meets the diverse needs of consumers. In addition, winemakers actively participate in international wine fairs, promotional tours and tastings, which helps to promote Ukrainian wine on the global market and support exports even during the war. The martial law significantly affected the wine industry in the Odesa region, reducing production volumes, vineyard areas and the number of companies. At the same time, winemakers are demonstrating resilience and striving to maintain key positions in the domestic and foreign markets. The industry's further development will depend on government support, infrastructure upgrades and international investment.

European integration: challenges and opportunities. Despite the potential for Ukraine's integration into the European market, the volume of wine exports from the country has been declining over the past five years (2020-2024). In 2023, exports totalled 9.66 thousand tonnes, which is the lowest figure for the period (Fig. 3). The main reasons for the decline were challenges related to logistical constraints, war and economic instability. At the same time, demand for Ukrainian wine in Romania, Moldova and other countries remains stable, which creates the basis for restoring export potential in the future.

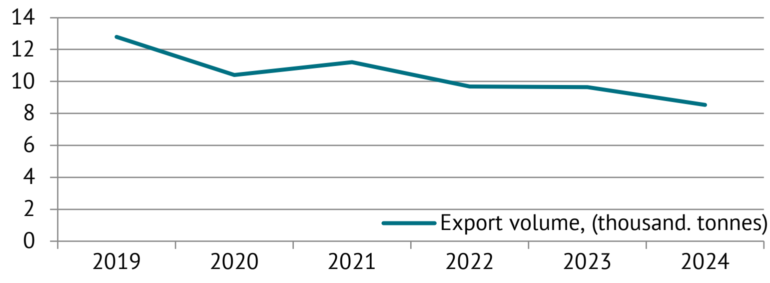

Figure 3. *Dynamics of wine exports from Ukraine, 2019-2024 (thousand tonnes)*
Source: *compiled by the authors based on the State Statistics Service of Ukraine (n.d.)*

European integration opens both significant opportunities and challenges for the Odesa region's wine industry. Joining the free trade area with the European Union creates favourable conditions for expanding sales markets. Ukrainian winemakers are gaining access to one of the largest and most developed markets in the world. European consumers are interested in new winemaking regions, and Ukrainian wines can attract their attention due to their uniqueness and value for money. Of particular interest are wines made from indigenous grape varieties, such as Odesa Black, which have no alternatives in the world. The introduction of European quality standards is a key area of development for Ukrainian winemaking, which helps to increase consumer confidence, and access to international markets and improve the competitiveness of products (Palamarchuk & Tysyachnyi, 2023). The main standards being introduced in the industry include HACCP, which ensures safety control at all stages of production, the International Food Standard, which guarantees that products meet international quality requirements, and EU organic standards, which regulate the production of organic wine. Ukrainian producers, such as Shabo and Kolonist, are actively working to certify their products following these requirements. However, certification requires significant financial resources, which makes it difficult for small businesses to access. To support producers, the government and international organisations provide financial assistance and advisory support, including through organic certification programmes. The introduction of these standards not only facilitates the integration of Ukrainian winemakers into the global market but also improves the quality of products in line with modern requirements.

Integration also opens access to European investment programmes and grants. EU funds, such as Horizon Europe (2019), offer financial support for modernising production, introducing innovative technologies and developing infrastructure. Thanks to these resources, wineries in the Odesa region can increase their competitiveness, expand their export potential and improve their production processes. However, along with opportunities, European integration also brings several challenges for winemakers. One of the most significant is competition with European producers such as France, Italy and Spain, which have many years of experience, developed infrastructure and strong brands. To gain a foothold in the market, Ukrainian winemakers need to offer a unique product and find their niche, such as through organic production or a focus on local grape varieties (Haleeva *et al.*, 2024). Another challenge is the need to adapt to new standards and regulatory requirements. The process of product certification, bringing production in line with EU norms and integrating environmental principles into viticulture requires significant financial and time investments. For many small producers, this can be a substantial; challenge that requires government support and educational programmes. Innovations in production and marketing are another important component of competitiveness. The introduction of modern fermentation, filtration and storage technologies, as well as the active use of digital platforms to promote products and attract consumers, help to compete effectively on an international level (Rama *et al.*, 2023). Thus, European integration creates broad prospects for the development of the Odesa region's wine industry, but the realisation of these opportunities requires adaptation, an innovative approach and active state and international support.

As of 2024, the main export markets for Ukrainian wine remain in European countries. Romania and Moldova account for the largest share of supplies, together accounting for 50% of total exports (Fig. 4). Other important markets are Poland, Germany and the Czech Republic. There is still scope for expanding exports to other EU countries, which can be achieved through marketing strategies and the adaptation of products to local consumers' requirements.

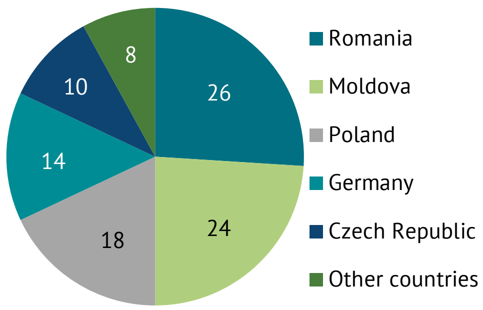

***Figure 4**. Main markets for wine exports from Ukraine, 2024 (share in %)*
***Source:** compiled by the authors based on the State Statistics Service of Ukraine (n.d.)*

Expansion of exports to the European Union is one of the most promising areas for Odesa region winemakers. Modern consumers in the EU prefer high-quality wines, especially those of premium and organic production. The Odesa region has the potential to develop both segments thanks to its unique grape varieties, such as Odesa Black and Sukholimansky White, and natural conditions that favour organic viticulture. Demand for biowine in the EU is growing at 10% annually, and the Odesa region can take advantage of this trend by expanding organic production. Focusing on the premium segment will also increase the added value of products, increasing the profitability of farms. For instance, Kolonist Winery is already implementing a strategy to enter the premium market in the EU, receiving high praise from international experts.

Development of wine tourism in the Odesa region. Odesa region already demonstrates successful examples of wine tourism development. For instance, the Shabo Wine Culture Centre is one of the most popular tourist destinations in the region, receiving more than 50,000 visitors annually. Tourists can witness vineyards, visit wine cellars and have wine tastings. This approach not only promotes the Shabo brand but also contributes to a positive image of the region. Kolonist Winery actively develops wine tourism by organising various events for wine connoisseurs. These include vineyard and winery tours, professional tastings, and participation in international festivals. For instance, in 2024, Kolonist presented its wines for the first time at the Dijon Vine Festival in France, where it received high praise from renowned French experts and sommeliers. The winery hosts festivals of young wine, which include vineyard tours, introduction to production technology, professional tastings and lunches with traditional dishes of Danube Bessarabia. Such events attract tourists from both Ukraine and abroad, promoting the region as a wine tourism destination. Thanks to successful examples of wine tourism, new opportunities for infrastructure development are emerging in the region, including the construction of themed hotels, restaurants and festivals. For instance, the annual Wine Days festival in Shabo has already become an international event that attracts tourists and winemakers from different countries.

The creation of clusters of wineries is a prominent way to strengthen the economic potential of the industry. One such example is the initiative to create the Odesa Region Wines cluster, which brings together several dozen small and medium-sized producers (Bolhrad District State Administration, 2023). As part of this initiative, winemakers work together to improve product quality, share experiences, and promote the region's brand on the international market. For instance, the Ukrainian brand Big Wines, which is part of the international group of companies Vinos de La Luz, has started operations in the Borodynska community of Bolhrad district, Odesa region. The company has leased 84 hectares of vineyards and purchased 20 hectares for new plantings (International Company to…, 2024). This initiative promotes the development of the region's wine industry and demonstrates the potential for attracting foreign investment through cooperation with international partners.

Development strategies for the wine industry in the Odesa region. To ensure the sustainable development of the wine industry in the Odesa region, it is necessary to implement a set of strategic measures aimed at increasing the competitiveness of products, adapting to modern market requirements and receiving support from the state. These strategies include improving production processes, expanding the product range and active government support for the industry. One of the key areas of development is the improvement of production technologies. Wineries in the Odesa region need to invest in modern equipment that allows them to control quality at every stage of production. For instance, the introduction of automated temperature and humidity control systems during fermentation significantly improves the quality of wine. It is also worth using modern methods of purification and filtration to ensure product stability during storage and transportation.

Expanding our product range is another promising area. Demand for bio and organic products is showing steady growth globally. According to a study by IWSR (2024), the global organic wine market reached 1 billion bottles in 2020, accounting for approximately 3.6% of total wine consumption. This figure is forecast to rise to 4% by 2026, with an average annual growth rate of 6.2%. The European Union, which is the largest market for organic wine, is experiencing particularly strong demand. In France and Germany, sales of biowine increased by 10% and 8% respectively in 2020. These trends indicate the prospects for the development of biowine production, and Odesa region producers, given the favourable natural conditions of the region, have the opportunity to successfully occupy this niche in the international market. In addition, a focus on premium wines made from indigenous grape varieties, such as Odesa Black and Sukholimansky White, will create a unique product that can become a hallmark of the region on the international market. Winemakers should also consider the trend towards lower alcohol content and the production of non-alcoholic wines, which are popular among young consumers in the EU.

Ukrainian integration into the European Union creates significant opportunities for the development of the wine industry, through access to numerous EU support programmes (Bezhenar, 2024). One of these initiatives is the EU4Business: Recovery, Competitiveness and Internationalisation of Small and Medium-sized Enterprises programme, which is co-funded by the European Union and the German government. The programme aims to support Ukraine's economic resilience, recovery and growth, create better conditions for the development of Ukrainian small and medium-sized enterprises, and support innovation and exports. It has developed a practical guide that provides detailed recommendations for Ukrainian winemakers on how to enter EU markets (Hellier & Nerpiy, 2024). These initiatives aim to finance innovation, modernise production, implement environmental standards, and promote products on international markets. Winemakers in the Odesa region, a key wine-growing region of the country, can actively use these tools to strengthen their competitiveness.

One of the leading programmes available to winemakers is Horizon Europe (2019), which funds innovative projects in the agriculture and food industry. This programme supports the development of the latest technologies in winemaking, such as the use of digital solutions for vineyard management or reducing the impact of climate change on crop quality. By participating in Horizon Europe, wineries can not only modernise production but also improve the quality of their products in line with current trends. The

EU4Business programme focuses on supporting small and medium-sized businesses in the Eastern Partnership countries, including Ukraine. For winemakers, the programme offers access to cost-effective financing to modernise production facilities, provide training and access international markets. For instance, through co-operation with the European Bank for Reconstruction and Development, wineries can receive loans to purchase modern equipment or implement environmental technologies. The COSME programme aims to improve the competitiveness of small and medium-sized enterprises (European Commission, 2014). Under this initiative, wineries can receive funding to participate in international exhibitions, develop marketing strategies and brand their products. This allows local producers, such as Shabo and Kolonist, to increase the visibility of their products and expand exports. Another tool is the Technical Assistance and Information Exchange Instrument, which provides technical support and advice to countries integrating into the EU (European Commission, n.d.a). This programme provides training for Ukrainian winemakers with the participation of European experts who help them implement modern quality standards, such as ISO 22000 and HACCP. Thanks to this initiative, wineries in the Odesa region can adapt their processes to the requirements of European markets.

The European Green Deal programmes aimed at supporting sustainable development should be noted separately (European Commission, n.d.b). Winemakers are offered grants to implement energy-efficient technologies, minimise production waste and develop organic wines, which are becoming increasingly popular in the European market. Additional opportunities are created by the European Agricultural Fund for Rural Development, which finances projects to modernise wineries, develop oenotourism, and support young farmers (European Commission, 2021). For instance, participation in this programme allows winemakers to invest in the creation of tourist routes and tasting rooms, which increases the popularity of local brands. For winemakers in the Odesa region, access to EU support programmes is not only an opportunity to modernise production but also a tool to enter new markets and strengthen their positions in a competitive environment. The use of financial instruments, training and technical assistance allows the region to remain a leader in winemaking in Ukraine and develop its reputation internationally.

The study determined that the wine industry in Odesa region has significant potential in the context of Ukraine's integration into the European Union. In particular, the study deterined that the region has unique natural conditions, historical traditions of winemaking and active implementation of innovations, which contributes to the competitiveness of products. These results are important as they confirm that the industry can become a key driver of regional economic development and exports. The results are consistent with the research of other scholars. For instance, G.O. Gratsiotova (2019) emphasised the importance of strategic changes in the wine industry, noting that technology modernisation and innovation can significantly increase the efficiency of enterprises. The study confirmed that such changes are crucial for adaptation to EU standards. Similarly, N.O. Gladun (2022) noted the importance of foreign economic strategies for wineries, emphasising that access to international markets requires product certification and compliance with European standards. In this context, the results of the study indicate that certification according to ISO 22000 and HACCP standards significantly contributed to increasing the credibility of Ukrainian wine at the international level.

The relevance of the results to international studies was also analysed. For example, M. Dressler and I. Paunovic (2021) examined innovative business models in winemaking, focusing on the importance of digitalisation and the integration of new technologies. The examples of the introduction of modern technologies at enterprises in the Odesa region, such as automated quality control systems, identified in the study, are consistent with the conclusions of these authors. E. Pomarici and R. Sardone (2020) analysed EU policy in the field of winemaking, noting that support through the Common Agricultural Policy contributes to the modernisation of production and the implementation of environmental standards. The study determined that access to European grant programmes, such as Horizon Europe and EU4Business, opens new opportunities for winemakers in the Odesa region. Particularly noteworthy are the results of research by R. Leonavičius (2024), which analysed the impact of the European Green Deal on winemaking. According to these studies, the integration of environmental standards and the introduction of energy-efficient technologies are key aspects for maintaining competitiveness. The study confirmed that such measures are already being actively implemented by leading producers in the Odesa region, such as Shabo and Kolonist. The identified challenges are also consistent with the findings of other researchers. For example, K. Deconinck and J. Swinnen (2015) focused on the economic barriers for small and medium-sized wineries in adapting to new market conditions. The study determined that high costs of certification and innovation are a significant challenge for producers in the Odesa region.

Additional analysis has confirmed that the results of the study are consistent with the findings of M. Dressler (2018), who analysed the German wine market and emphasised the importance of strategic management and economic planning to improve the competitiveness of the industry. Similarly, A. Figurek *et al.* (2023) emphasised the importance of a multi-level analysis of economic efficiency in the EU wine industry, which confirms the need to use several indicators to assess the efficiency of wineries in the Odesa region. In addition, E. Pomarici *et al.* (2021) studied the evolution and competitiveness of the Italian wine sector, pointing out the need to integrate innovation and preserve traditions. In this context, the study of the Odesa region's wine industry determined that the combination of innovative approaches and local authenticity contributes to the formation of a positive image of products in the international market.

P. Lombardi *et al.* (2016) emphasised the importance of competitiveness in intra-European trade. This is consistent with the results of the analysis of the export activities of wineries in the Odesa region, which are actively expanding their presence in the EU markets. The analysis of the profitability of viticulture in the EU presented in the study by G. Pappalardo *et al.* (2013) confirmed the importance of regional natural conditions and technological efficiency as key success factors. The economic potential of the Odesa region's wine industry, its export activity and profitability identified in this paper are consistent with these findings. In addition, the study by F. Cafaggi and P. Iamiceli (2010) emphasised the importance of inter-firm networks in the European wine industry, which correlates with the proposal to introduce a cluster model of cooperation between wineries in the Odesa region. This approach will facilitate the exchange of experience and joint promotion of the regional brand on the international market. The analysis of multi-level regulation of winemaking presented by V. Valle (2022) also corresponds to the findings of this study, in highlighting the challenges associated with adaptation to European standards and strategies to overcome them.

Additionally, F. Schulz *et al.* (2022) analysed the impact of the EU alcohol policy on the German wine industry, noting that increased regulation can create barriers to exports. This confirms the importance of the adaptation of Ukrainian producers to changes in the regulatory sphere. A. Galati *et al.* (2017) analysed internal resources as a key factor in increasing competitiveness, which was also confirmed by the results of the study of the activities of enterprises in Odesa region. A. Ugaglia *et al.* (2019) noted that the integration of third-party certification systems contributes to product quality assurance, which is consistent with the data on product certification of Odesa region enterprises. Prospects for further research include a deeper analysis of the impact of climate change on winemaking, which is especially important for the Odesa region. R. Skiba (2025) pointed out that climate change can significantly affect the quality of grapes and yields. C. Brito *et al.* (2024) proposed strategies for achieving sustainable development in winemaking that can be integrated into the development of the Odesa region. The results correlate with the ideas presented by J. Ibáñez-Jiménez and R. Palomo-Zurdo (2024), which discuss the potential of distributed ledger technologies in addressing the economic and social challenges of the wine industry. Based on the results of the study and their consistency with other works, it was concluded that the wine industry of the Odesa region has all the prerequisites for sustainable development in the context of European integration. However, the realisation of this potential requires active state support, attraction of investments and integration of innovations into production processes. A summary of the findings forms the basis for the next section, which is devoted to conclusions and practical recommendations.

CONCLUSIONS

The study determined that the Odesa region's wine industry is a key component of the region's economy and one of the most promising sectors in the context of Ukraine's integration into the European Union. The region's unique natural conditions, including a favourable climate, diverse soils and geographical location, create ideal conditions for growing grapes and producing high-quality wine. At the same time, the historical traditions of winemaking and modern innovative approaches ensure that the products are competitive both in the domestic and foreign markets. In 2024, the Odesa region exported a total of 8.54 thousand tonnes of wine, with the main markets being Poland, Germany and Latvia. These figures confirm the region's status as the country's leading wine-producing centre.

The study determined that the region's leading producers, such as Shabo, Kolonist, Frantsuzsky Bulvar and Vinhol Oksamytne, have successfully adapted to EU standards by implementing ISO 22000 and HACCP certification. This is not only to meet the requirements of the European market but also to create a positive image of Ukrainian wines. An important discovery was the growing demand for bio and organic products in the European Union, where the annual growth of this segment is about 10%. Odesa region producers have all the prerequisites to meet this demand thanks to unique local grape varieties such as Odesa Black and Sukholimansky White. Wine tourism has become another important driver of the industry. In 2022, more than 50,000 tourists visited the region's wineries, including Shabo and Kolonist, which demonstrates a high interest in tasting tours, wine festivals and cultural events. The development of enotourism not only promotes the popularisation of products but also shapes the image of the Odesa region as a unique tourist destination.

At the same time, the study revealed several challenges facing the industry. Among the main barriers are high competition with leading European manufacturers, with France, Italy and Spain, high costs of implementing environmental technologies and modernising production, and the need to comply with strict EU standards. Despite these challenges, the support of international programmes such as Horizon Europe, EU4Business and the Technical Assistance and Information Exchange Instrument creates the conditions for obtaining funding, technical assistance and advice to help winemakers improve their production and marketing processes. Based on the results of the study, the author proposes strategic directions for the development of the industry: expanding exports through a focus on the premium segment and organic products, intensifying oenotourism through the creation of wine and gastronomic routes and the organisation of festivals, the introduction of modern technologies and a cluster model of cooperation between wineries. The importance of state support was also highlighted, through subsidies for production modernisation, participation in international exhibitions and promotion of Ukrainian wines on foreign markets.

Limitations of the study include the lack of access to detailed economic and statistical data, which makes it difficult to predict long-term trends. Future research should focus on studying the impact of climate change on the wine industry in the Odesa region, analysing consumer preferences in different EU countries, and developing marketing strategies to promote Ukrainian wine. In general, the findings emphasise that the wine industry in the Odesa region has all the opportunities for sustainable development if the proposed strategic measures are implemented.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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Економічний потенціал виноробної промисловості в умовах інтеграції до ЄС

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Анотація. Метою дослідження було оцінити економічний потенціал виноробної галузі Одеської області в умовах інтеграції України до Європейського Союзу та визначити стратегічні напрями її сталого розвитку. У дослідженні було проаналізовано природні, економічні та соціальні фактори, що сприяють розвитку галузі, а також виклики, які постали перед виноробами в умовах глобалізації та адаптації до стандартів Європейського Союзу. Розглядалося функціонування провідних виноробних підприємств, таких як «Шабо», «Колоніст», «Французький бульвар» та «Винхол Оксамитне», з акцентом на їхній експортний успіх, інновації та маркетингові стратегії. Основні результати дослідження показали, що Одеська область є лідером у виробництві вина в Україні, забезпечуючи понад 60 відсотків національного виробництва. Попри високу якість продукції та відповідність міжнародним стандартам, експорт українського вина до європейських країн останніми роками знижується через воєнні дії та економічні труднощі. Водночас визначено основні виклики, зокрема конкуренцію з європейськими виробниками, необхідність адаптації до регуляторних вимог і потребу в інноваціях у виробництві та маркетингу. Запропоновані стратегії розвитку включають вдосконалення технологічних процесів, виробництво біологічних та преміальних вин, розвиток кластерів виноробних господарств і посилення державної підтримки через субсидії, грантові програми та заходи з популяризації українського вина на міжнародному рівні. Висновки підтвердили, що впровадження цих стратегій сприятиме зміцненню конкурентоспроможності виноробної галузі Одеської області, розширенню її експортного потенціалу, розвитку винного туризму та утвердженню України як перспективного виноробного регіону на світовому ринку. Отримані результати є корисними для розробки регіональної політики у сфері виноробства та впровадження програм підтримки галузі

Ключові слова: виноградарство; винний туризм; інноваційні технології; міжнародна торгівля; органічне виробництво; конкурентоспроможність продукції; євроінтегаційні процеси

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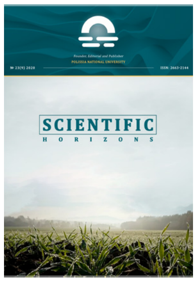

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Corporate governance in agricultural holdings: Ensuring transparency and efficiency in management decisions

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Abstract. The purpose of the study was to develop recommendations for improving the transparency and efficiency of corporate governance in agricultural holdings, consideirng the specifics of their activities and existing business challenges. To achieve this goal, a comprehensive analysis of corporate governance in the agricultural sector of Kazakhstan for 2018-2024 was carried out, which included an assessment of the effectiveness of management practices, the introduction of the latest technologies and environmental initiatives, and a comparison of the financial results of large agricultural holdings such as Olzha Agro, Atameken-Agro, Agrofirma TNK. It was established that corporate governance in the agricultural sector of Kazakhstan is critical for ensuring the efficiency, transparency and sustainable development of companies. It was determined that the introduction of the latest technologies, environmentally friendly practices and social responsibility contributed to improving financial performance

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and increasing investor confidence. In particular, companies that actively invested in precision farming and automation technologies showed significant productivity growth and cost reduction, which positively affects their financial results. However, current challenges, such as lack of skills, lack of a clear management structure in small businesses, and the influence of large shareholders, required attention to optimise management practices. The results confirmed the need for training and professional development of employees, and the creation of more transparent management mechanisms that would reduce the risk of conflicts of interest. In general, improving corporate governance was the key to increasing the competitiveness of agricultural holdings and ensuring their sustainability in the face of changes in the market. The study highlighted the need to strengthen oversight through external audits and involve independent directors who can ensure objectivity and transparency in management decision-making. The adoption of international financial reporting standards is recognised as an important step towards transparency of management decisions and attracting investment

Keywords: Olzha Agro; Atameken-Agro; Agrofirma TNK; sustainable development; Kazakhstan; agricultural sector

INTRODUCTIO

Corporate governance in agricultural holdings is an important aspect against the background of globalisation, economic instability, and growing social and environmental challenges. Agricultural holdings, as large integrated structures covering various stages of production, processing, and marketing of agricultural products, face problems of ensuring transparency, efficiency of management decision-making and sustainable development. Solving these problems is important for maintaining competitiveness, attracting investment, and making optimal use of resources. M.G. Teixeira *et al.* (2020) and F.F. da Silva *et al.* (2022), analysing the role of consideration of the interests of stakeholders and the impact of corporate governance on the financial performance of organisations, emphasised the need to introduce digital technologies to improve management processes and reduce operational risks. They stressed that the integration of information systems into decision-making processes can improve resource accounting, increase transparency of financial activities and reduce the risks of fraud and corruption.

A significant contribution to understanding the current challenges of corporate governance in agricultural holdings was made by M. Arévalo-Alegría *et al.* (2020), who analysed the risks of information asymmetry between management and shareholders, which can lead to inefficient management decisions. The researcher proposed mechanisms to reduce this asymmetry through the introduction of transparent reporting procedures, expanding the rights of shareholders to make key decisions, and ensuring an independent audit of the financial activities of agricultural holdings. In addition, the importance of adapting international corporate governance standards, such as the principles of the Organisation for Economic Cooperation and Development (OECD), was stressed, which contributes to the growth of investor confidence. The study by I. Makarenko *et al.* (2022) confirmed that the inclusion of environmental standards in the corporate governance of agricultural holdings has a positive impact on long-term competitiveness, especially in light of the growing demands of investors and consumers for the environmental responsibility of companies. Th.O. Maring *et al.* (2024) noted that the development of ethical principles and the creation of transparent communications within the corporate structure can significantly reduce the level of conflict in the organisation, which is especially important for agricultural holdings operating in a multifunctional environment.

H.G. Idagiju *et al.* (2024) and C. Iliopoulos *et al.* (2022) also emphasised the need for flexible management approaches in the agricultural sector. They noted that agricultural enterprises should consider seasonal and regional specifics, because these aspects significantly affect the organisation of production processes and market dynamics. In addition, the implementation of sustainable development strategies, which include environmental initiatives, social responsibility and efficient use of resources, is an important component of successful corporate governance (Boiko *et al.*, 2024). In particular, increased attention to environmental standards and integration of monitoring technologies allowed agricultural holdings to reduce the negative impact on the environment and increase business efficiency. The study by H.H.B. Ahmad *et al.* (2024) noted that the use of adaptive management models has contributed to improving the efficiency of agricultural companies even in unstable economic conditions. In particular, such models allowed quickly responding to changes in market demand, adjusting production or marketing strategies depending on external circumstances, which helped to ensure financial stability and maintain a high level of productivity. K.P. Pokharel *et al.* (2020) emphasised the importance of using digital technologies. The paper noted that the introduction of artificial intelligence and automated monitoring systems in the field of management can reduce administrative costs by 20-30% and significantly improve the quality and speed of strategic decision-making.

Kazakhstan has a significant agricultural potential, and the introduction of effective corporate governance in agricultural holdings is an important factor in its implementation. However, the country's agricultural sector faces a number of problems, including insufficient transparency in decision-making, uneven access to financial resources, and poor integration of modern technologies into production and management processes. According to M. Uspambayeva *et al.* (2020), improving corporate governance mechanisms in the agricultural sector of Kazakhstan allows optimising management processes, increasing the profitability of enterprises and promoting more efficient use of resources, and transparency in the activities of large agricultural companies increases the trust of shareholders and helps to attract foreign investment.

The environmental component of corporate governance in Kazakhstan is aimed at rational use of natural resources, minimising the negative impact on the environment and preserving biodiversity. However, its effectiveness depends on the level of implementation of environmental standards and compliance of corporate governance practices with international requirements for sustainable development. As stated by S.M. Tokenova *et al.* (2020), the introduction of environmentally responsible practices, such as the application of sustainable farming methods, reduction of greenhouse gas emissions and rational use of water and soil resources, is an important part of the strategy for the sustainable development of the country's agricultural economy. This allows not only minimising environmental risks, but also to increasing the efficiency of agricultural production, ensuring long-term economic stability (Zhanaltay, 2023). Most of the research focuses on general corporate governance issues or only partially concerns agricultural holdings. Issues related to the implementation of integrated systems for monitoring the effectiveness of management decisions or adapting corporate governance models to regional characteristics remain insufficiently studied.

The purpose of the study was to develop recommendations for improving the transparency and efficiency of corporate governance in agricultural holdings, considering the specifics of their activities and the existing challenges of the business environment.

MATERIALS AND METHODS

The theoretical segment of the study covered the analysis of research papers on corporate governance, transparency and efficiency in the agricultural sector, in particular, in agricultural holdings in Kazakhstan. The investigation of previous studies helped to determine the main approaches to assessing the effectiveness of corporate governance and its impact on the development of large agricultural companies. The statistical data of the United Nations (UN) (2024), materials of the Food and Agriculture Organisation of the United Nations (FAO) (Food Outlook, n.d.), data from the Bureau of National Statistics (2025a, 2025b) of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, and ARK-News publications (Analysts advise investing…, 2023) and information about shares and shareholders of Atameken-Agro (n.d.) Joint-stock company (JSC), Agribusiness (Komissarova, 2023). Field care (Atameken-Agro, n.d.), Agrofirma TNK (n.d.). Profit begins with strategy, which provided a well-founded analysis of the transparency and effectiveness of management decisions in agricultural holdings (Yakovleva, 2024).

Three large agricultural holdings in Kazakhstan were selected for the analysis: Olzha Agro (n.d.), Atameken-Agro (n.d.) and Agrofirma TNK (n.d.). The analysis of the dynamics of agricultural production, features, and key corporate governance strategies was carried out. In addition, it was important to investigate the mechanisms of control over management decisions, in particular, the role of internal and external audits, and the level of transparency of financial statements. The content of laws and regulations of Kazakhstan was analysed: the Law of the Republic of Kazakhstan No. 415 (2003), the Resolution of the Government of the Republic of Kazakhstan No. 732 (2021). International corporate governance standards were considered, in particular, the OECD (2015) Guidelines on Corporate Governance of State-Owned Enterprises and International Financial Reporting Standard (IFRS) for Small and Medium Enterprises (n.d.).

During the study, a comprehensive analysis of the main factors of sustainable development of the agricultural sector was carried out, considering the specifics of corporate governance. A thorough study of management decisions revealed how they affect not only the financial stability of enterprises, but also the level of innovation activity and the implementation of the principles of social responsibility. The study examined the impact of management decisions on the financial performance of agricultural holdings, in particular, it revealed which practices contribute to improving financial results, and which can have negative consequences. The analysis of transparency of companies' activities included the study of communication processes between the management of agricultural holdings and their shareholders, which made determined the level of satisfaction of the latter with the current situation. This approach helped to unlock the potential of management decisions in building investor confidence and creating conditions for sustainable development. Comparison of corporate governance practices in agricultural holdings of Kazakhstan helped to identify significant differences in the implementation of management approaches, which led to the identification of gaps in the management system and identification of barriers that hinder the achievement of high standards.

RESULTS

Corporate governance in large agricultural companies of Kazakhstan is a system of regulation of relations between shareholders, management and other stakeholders, which is aimed at ensuring efficient use of resources, transparency of business processes and achievement of strategic goals of the enterprise. Sound corporate governance includes a clear distribution of authority, management accountability, risk management, and compliance with ethical standards, which helps to increase investor confidence, improve financial results and ensure sustainable development of the company, considering the environmental, social and economic aspects of its activities.

However, the agricultural sector in Kazakhstan, as in other countries, faces a number of challenges, including the need to introduce the latest technologies, adapt to climate change, and manage large areas of land and resources. Consideration of these factors requires a high level of corporate governance, which includes strategic planning, financial control, risk management, and effective interaction with government agencies and other industry enterprises (Uspambayeva *et al.*, 2020). The introduction of effective corporate governance practices in agricultural companies in Kazakhstan allows achieving significant results in the development of the industry. The most notable is the improvement in financial results, production growth, and sustainable development through investment in environmentally friendly and resource-saving technologies.

It is worth noting that the sustainable development of the agricultural sector through corporate governance is based on several key aspects. Firstly, an important element is investing in innovation, which involves the use of modern technologies, such as precision farming, biotechnology, and automation of production processes, which contributes to improving production efficiency, reducing costs and improving product quality (Stepanenko *et al.*, 2023). Secondly, resource optimisation plays a significant role in sustainability. The introduction of energy-efficient and water-saving technologies allows for more efficient use of land, water, and energy resources, which is important for ensuring long-term productivity (Malik *et al.*, 2024). Another important aspect is environmental responsibility, which includes the introduction of practices that reduce the harmful impact on the environment. In particular, this refers to the development of circular agriculture, support for the sustainable development of ecosystems, and the conservation of biodiversity (Fig. 1). In addition, corporate governance should consider social responsibility, which includes creating decent working conditions for employees, ensuring fair pay, improving living standards and developing local communities. The combination of these aspects forms the basis for sustainable development of the agricultural sector, which benefits both agricultural holdings and society as a whole. In the context of globalisation and constant changes in the market, proper management is the basis for improving the competitiveness of enterprises and achieving economic stability.

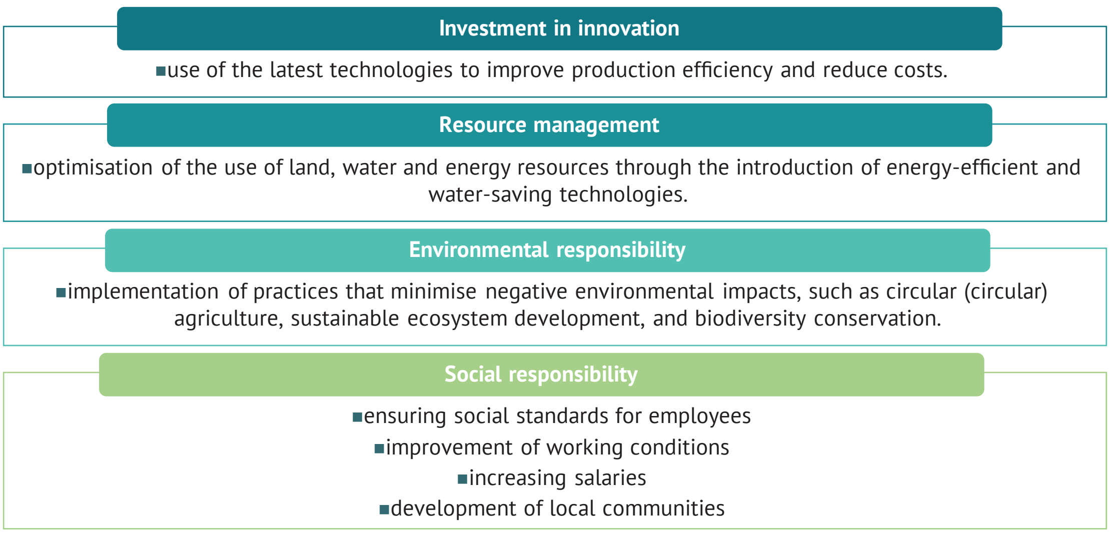

Figure 1*. Main factors of sustainable development of the agricultural sector through corporate governance*
Source: *compiled by the authors based on Law of the Republic of Kazakhstan No. 415 (2003), Materials of the Food and Agriculture Organization of the United Nations (n.d.), Ministry of Agriculture (n.d.), Resolution of the Government of the Republic of Kazakhstan No. 732 (2021)*

Kazakhstan's agricultural sector is a strategically important part of the national economy, and ensuring its sustainable development through effective corporate governance is crucial for the stability of the country's economy and ensuring food security (Tleubayev *et al.*, 2024). To achieve success in these areas, it is necessary to introduce modern technologies, improve management approaches, and actively involve all stakeholders in decision-making processes to ensure a harmonious balance between economic, social, and environmental interests. Corporate governance in agricultural enterprises of Kazakhstan has a significant impact on the efficiency of their activities due to a number of management mechanisms that allow companies to adapt to dynamic market conditions (Nurmanbekova *et al.,* 2018).

One of the most important aspects is the transparency of financial statements and the participation of shareholders in strategic decision-making. This allows not only ensuring the proper level of control, but also allows shareholders to influence the development of the company, monitor the achievement of strategic goals, and adjust the course of development in time if necessary. A well-developed corporate governance system, which includes transparent financial statements, stability, and efficiency in management, helps to build investor confidence. Due to clear management practices and cost control, agricultural enterprises can attract investment for development, technology improvement, and production efficiency, which reduces financial risks and allows implementing large-scale projects. The analysis of approaches to corporate governance in Kazakhstan shows that transparent governance mechanisms are actively developing in the country, in particular, in large corporations, including agricultural holdings. For example, the presence of independent members on the board of directors contributes to the creation of a balanced management system, but often this is only formal due to the influence of large shareholders or family ties. In addition, although corporate social responsibility is becoming an important element of enterprise strategy, its implementation is mainly limited to social projects, while environmental initiatives require more active implementation.

Since 2018, the agricultural sector has grown steadily, which was the result of effective management and innovation. In particular, one of the largest agricultural holdings in the country, Olzha Agro (n.d.), which owns a significant amount of land – about 960 thousand hectares, of which the main part is intended for arable farming, increased production volumes. The company actively implements modern management methods that contribute to the continuous improvement of business processes. Regular meetings of employees, during which they discuss modern management literature and practical approaches to implementing the acquired knowledge, create the basis for developing a culture of continuous learning and improvement. Chief Executive Officer (CEO) Alisher Khojanazarov emphasises the need for strategic vision and long-term planning, in particular, in the development of the dairy industry, emphasising the importance of state support to ensure stable growth. In addition, the company actively invests in environmental projects aimed at restoring soil fertility and developing renewable energy sources, which demonstrates its commitment to the principles of sustainable development. Compliance with IFRS ensures transparency and compliance with international requirements, which helps to increase the confidence of investors and partners.

Atameken-Agro, which manages land resources with an area of 440 thousand hectares, demonstrates stable financial growth due to effective approaches to corporate governance. The company has implemented a risk management system that allows timely identification, assessment, and control of potential threats associated with the company's activities. Regular quarterly meetings with shareholders ensure transparent communication between management and investors, helping to build mutual trust and quickly resolve management issues. An important aspect of the activity is the introduction of modern precision farming technologies, satellite monitoring, and automated control systems, which allows optimising acreage, increasing the efficiency of plant protection products and reducing the negative impact on the environment. The company also carries out measures to restore degraded land, which contributes to the preservation of soil fertility and ecological balance. All internal financial reporting processes comply with the requirements of IFRS standards, which are the key to high standards of corporate governance.

Agrofirma TNK, which manages 430 thousand hectares of land, demonstrates positive trends in production and financial performance due to the introduction of an effective corporate governance system. The company focuses on objective decision-making, involving independent directors in the development and implementation of strategic initiatives. One of the key tasks is to reduce the use of pesticides and switch to organic farming, which contributes to maintaining ecological balance and improving product quality. Investments in innovative technologies allow optimising production processes, increasing resource efficiency, and ensuring market competitiveness. Financial statements maintained in accordance with international IFRS standards guarantee transparency of the company's activities and increase confidence on the part of owners and investors. This strategic approach allows Agrofirma TNK to strengthen its position in the agricultural market and contribute to the sustainable development of the industry.

Thus, each of the companies demonstrates a unique approach to the organisation of corporate governance and the implementation of a sustainable development strategy. Olzha Agro focuses on innovation in internal governance and environmental initiatives to ensure long-term stability and growth. Atameken-Agro maintains financial stability and a high level of transparency based on its risk management system and modern technologies, which creates conditions for reliable interaction with shareholders. Agrofirma TNK, focusing on the objectivity of decision-making and the introduction of environmentally friendly technologies, demonstrates its desire to preserve the environment and increase competitiveness. The overall development of corporate governance in the agricultural sector of Kazakhstan is based on a comprehensive combination of economic, environmental, and social factors, which ensures the sustainable development of the industry in the face of modern challenges.

Notably, corporate governance in the agricultural sector of Kazakhstan is formed not only on the basis of transparency and accountability standards, but also under the influence of the social orientation of business, technological innovations and strategic partnership. Large agricultural holdings such as Olzha Agro, Atameken-Agro, and Agrofirma TNK have social responsibility, which is manifested in supporting local communities, financing educational programs and creating favourable working conditions for employees. This approach contributes to the development of regions and builds trust in companies. An important element of corporate governance is the introduction of modern technologies. Agricultural enterprises actively use precision farming, satellite monitoring, and automated production management systems, which allows increasing the efficiency of resource use, increasing yields, and reducing costs, which, in turn, has a positive impact on the financial performance of companies. A separate role is played by strategic partnership, which includes both international cooperation to attract investment and introduce advanced agricultural technologies, and interaction between agricultural holdings within the country. Joint initiatives contribute to the development of the processing industry and environmentally sustainable technologies. Thus, corporate governance in the agricultural sector of Kazakhstan combines conventional financial and managerial standards with social responsibility, technological progress, and strategic cooperation, which ensures the sustainable development of the industry.

Table 1 shows corporate governance mechanisms and sustainable development measures, and assesses the level of shareholder satisfaction in agricultural holdings in Kazakhstan. Olzha Agro and Atameken-Agro demonstrate a high level of transparency in their interaction with shareholders, including regular meetings and access to financial reports. The Agrofirma TNK has a less clear strategy for sustainable development and complains about certain shortcomings in planning for the future. This may indicate potential management challenges at the level of long-term strategies. All three companies use different approaches to sustainable development: Olzha Agro and Atameken-Agro are actively implementing resource-saving and energy-saving technologies, while Agrofirma TNK does not yet have a clear strategy. This may indicate a different degree of readiness of these companies for environmental and resource challenges in the future.

As for shareholder satisfaction, Olzha Agro has a high level, which indicates stable financial growth, while Atameken-Agro has a moderate level due to insufficient transparency of share returns, and Agrofirma TNK has an average level of satisfaction, especially in terms of dividend policy. Independent auditors and directors play an important role in ensuring transparency and independence. Olzha Agro has independent directors, while Atameken-Agro plans to attract them, and Agrofirma TNK already has two independent directors who influence strategic decisions, which also increases the level of transparency.

***Table 1**. Corporate governance mechanisms, sustainable development measures, and reporting in agricultural holdings of Kazakhstan*

	Olzha Agro	**Atameken-Agro**	**Agrofirma TNK**
Management responsibility mechanisms	Transparent reports, regular meetings with shareholders	High level of interaction with shareholders, feedback	Shareholders have access to financial statements and participate in decision-making
Measures to promote sustainable development	Introduction of resource-saving technologies, energy saving	Environmental responsibility programmes, sustainable development	Lack of a clear strategy for sustainable development, planning for the future
Level of shareholder satisfaction	High (key indicators of return on investment (ROI) and earnings per share (EPS) are growing steadily)	Moderate (stock returns are rising, but not transparent enough)	Average (dissatisfaction with the dividend policy)
External audits	Conducted annually, conclusions – stable financial condition	Audit every two years, recommendations for improving efficiency	External audit every three years, significant management shortcomings identified
Independent directors	There are members of the board of directors who guarantee transparency and independence	No independent directors, plans to engage	Two independent directors influence strategic decisions

***Source:** compiled by the authors based on Olzha Agro (n.d.), Information on shares and shareholders of JSC "Atameken-Agro" as of January 01, 2025 (n.d.), Atameken-Agro (n.d.), Agrofirma TNK (n.d.), Analysts advise investing in agriculture (2003), E. Komissarova (2023), Taking care of the fields (n.d.), N. Yakovleva (2024)*

Thus, the analysis shows different levels of efficiency and readiness of these agricultural holdings for sustainable development and management, which can affect their financial stability and long-term success. Among the main advantages of Kazakhstan's holdings is a high level of corporate responsibility, which is manifested in annual financial reporting and trust on the part of investors, which ensures stability in making strategic decisions. For example, the agro-industrial holding Atameken-Agro is experiencing stable investment growth due to the high level of corporate responsibility and transparency in management. Investor's trust this holding because of its clear financial reporting and fulfilment of its obligations, which allows it to attract new capital.

In addition, agricultural holdings actively introduced the latest technologies, which increased production efficiency. Olzha Agro has advantages in the form of high transparency and accountability, which allows effectively managing a large holding company. However, the complexity of managing a group of companies may be a certain limitation. This company has opportunities to increase the transparency of operations and reporting, which can help attract new investors. However, it faces threats such as high competition in the market, which may call into question its leadership and influence. Atameken-Agro is characterised by a high level of interaction with shareholders and active development of corporate practices, which contributes to effective management. However, excessive shareholder influence on operational management can negatively affect the speed and flexibility of decisions. The main opportunities are the development of environmental policies, which can improve the company's image, and open up new opportunities for cooperation. However, changes in regulatory policy may affect the company's internal processes, which may pose a risk to its development. Agrofirma TNK has strengths in the form of sustainable growth and partnership support, and high standards of corporate governance. However, the lack of flexibility caused by high standards can limit the ability to adapt to new conditions. The opportunity is to expand social responsibility, which will help to attract new customers. However, the company faces the risk of changes in socio-economic conditions, which will require rapid adaptation to new realities (information about shares and shareholders of Atameken-Agro JSC).

Thus, corporate governance is important for the development of agricultural companies, as it defines the basis for making strategic decisions and optimising management processes. It ensures transparency of activities, in particular, in aspects of financial reporting, strategy development and implementation, and corporate practices. This allows shareholders and stakeholders to properly monitor management's actions and evaluate their effectiveness. Well-organised corporate governance opens up opportunities for partnership with international companies, which promotes access to the latest technologies, new markets and resources. Participation in international agricultural networks allows exchanging experience and applying best practices (Table 2).

***Table 2**. Aspects of the impact of corporate governance on the development of large agricultural companies*

Corporate governance aspect	Promotion of sustainable development
Increase of management responsibility	Improvement of resource management, reduction of abuse, and ensuring accountability for environmental and social impacts.
Sustainability and long-term development	Reduction of the negative impact on the environment, development of resource-saving technologies, and maintenance of environmental standards.
Attracting investment and innovation	Stimulation of innovation, development of energy-efficient technologies, investing in environmentally friendly production and sustainable development.
Flexibility and adaptation to changes	Reinforcement of the ability to respond to climate change, natural disasters, and global market changes.
Risk management	Creation of a risk management system that reduces the negative impact on the environment and promotes social stability.
Competitiveness	The company's sustainability in a competitive environment, improving product quality, reducing costs, and developing innovative and environmental approaches.
Corporate culture	Increase of social responsibility, development of employee skills, and support of local communities and rural areas.
Attracting international partnerships	Implementation of international standards for sustainable development, exchange of best practices, access to new markets and technologies.

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

Thus, corporate governance in the agricultural sector of Kazakhstan plays a significant role in ensuring the sustainable development of companies, adapting to external changes, improving production efficiency and attracting investment. However, it is important to note that the introduction of transparent management practices faces certain difficulties, including imperfect legislation, low legal culture, and insufficiently qualified personnel in the field of finance and management, especially at the level of small and medium – sized agricultural enterprises. An additional problem is the concentration of power in the hands of individuals or groups, which reduces the transparency of management decisions and can lead to conflicts of interest. The low level of trust in government institutions and supervisory authorities also limits the effectiveness of monitoring compliance with corporate governance standards.

To overcome these barriers, it is necessary to create independent monitoring mechanisms, in particular, to strengthen the role of independent directors and ensure external audits, which will ensure transparency and objectively evaluate the activities of companies. It is also important to expand the implementation of IFRS, which will help to improve transparency and build investor confidence. In addition, it is necessary to step up the role of the state and civil society in monitoring the implementation of corporate governance standards and create conditions for the development of personnel qualifications in the field of management. One of the important steps is the introduction of modern digital technologies, automation of management processes, and the creation of electronic platforms for data collection and analysis. These technologies allow minimising the impact of the human factor, ensuring accurate and timely processing of information, which, in turn, contributes to effective management and rational use of resources in the agricultural sector of Kazakhstan.

The creation of electronic platforms for data collection and analysis will allow Kazakhstan's agricultural holdings to respond quickly to market changes, effectively plan production and logistics, and ensure transparency of processes for shareholders and external investors. These platforms may include systems for monitoring financial and production indicators, which allow managers to quickly obtain information for making informed decisions (Fig. 2).

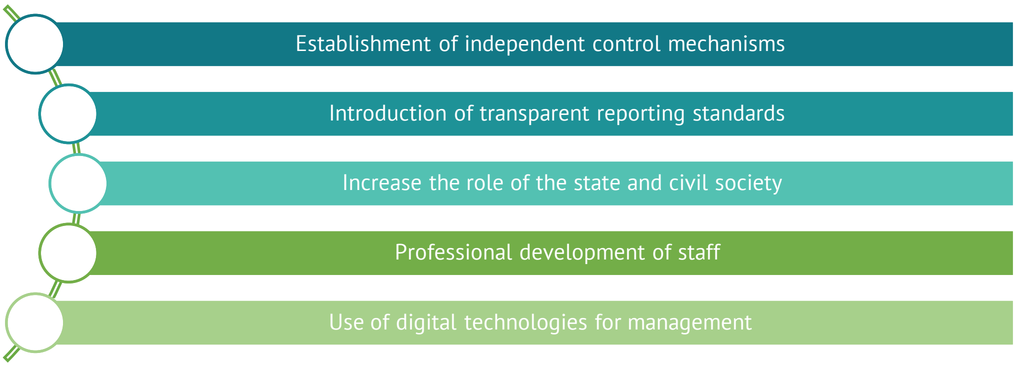

Figure 2. *Mechanisms for improving management processes*
Source: *compiled by the authors*

Integration of modern corporate governance tools will significantly increase the transparency of operations and help to build confidence on the part of investors and government agencies in agricultural holdings. Moreover, such measures will help to eliminate the current obstacles that limit the effectiveness of management decisions, in particular, insufficient qualification of personnel, lack of clear reporting, and the influence of subjective factors. As a result, these initiatives will contribute to the sustainable development of Kazakhstan's agricultural sector, combining economic efficiency with increased social responsibility and environmental sustainability.

Thus, corporate governance in agricultural holdings is a determining factor that ensures transparency and a high level of efficiency of management processes, which is important for the sustainable development of the agricultural sector of Kazakhstan. The introduction of appropriate management mechanisms increases the responsibility of management to shareholders, allows controlling financial flows and optimising the use of resources. Transparency of financial statements and active participation of shareholders in strategic decision-making create conditions for responsible management, which reduces the risks of corruption and unethical practices. Based on this approach, agricultural holdings can quickly respond to changes in the market, introduce innovations, and attract investment, which increases their competitiveness both in the domestic and international markets. Thus, effective corporate governance is the foundation for economic stability, productivity growth, and ensuring stable development of the agricultural sector.

DISCUSSION

Corporate governance in agricultural companies in Kazakhstan is a key factor contributing to the efficient use of resources, increasing transparency and achieving strategic goals. Good governance involves a clear distribution of authority, risk management, compliance with ethical standards, which ensures investor confidence, improves financial results, and promotes sustainable development through investment in environmentally friendly technologies. Important aspects are also the introduction of innovations, optimisation of resources and environmental responsibility, which contribute to the sustainable development of the agricultural sector, increasing its competitiveness in the market.

The study showed that the developed corporate governance system in Kazakhstan allows agricultural companies to attract investment, improve technologies, and increase production efficiency, which reduces financial risks. However, despite the positive trends, corporate social responsibility is often implemented through social projects, and environmental initiatives require more active implementation (Potryvaieva *et al.*, 2024). The significance of the results obtained also lies in the fact that they confirm the theory of the relationship between corporate governance and financial performance developed by O. Ryskeldi *et al.* (2024) and K.P. Pokharel *et al.* (2019). They point out that effective management helps to reduce agency costs and increase the profitability of companies. These results correspond to the conclusions of the study, because agricultural companies that implement transparent and accountable management mechanisms achieve better financial results. J. Hale *et al.* (2019) also found confirmation in the conclusions of this study, which show that agricultural enterprises that actively implement innovative technologies can significantly improve their competitiveness. The study found that investment in innovation increased from USD 450 million in 2018 to USD 700 million in 2023, which confirms the importance of investment in technological innovations for the development of the agricultural sector. The results are also consistent with the findings of M.G. Pirtea *et al.* (2021), who emphasised that investment in the latest technologies in the agricultural sector can significantly increase production efficiency and reduce costs, which will have a positive impact on the financial performance of companies.

The results of the study revealed some difficulties faced by agricultural companies in Kazakhstan because, despite the improvement of financial indicators, including production and investment volumes, problems arise when implementing international corporate governance standards, especially at the level of small and medium-sized enterprises. As noted by O.D.P.O. Júnior and A.E. Wander (2020), in developing countries, such difficulties are often associated with a lack of sufficient resources and qualified specialists. M.D.C.R. Neves *et al.* (2019) supports this opinion, pointing out that the main obstacles for small agricultural companies are low levels of training and limited access to financial resources.

According to C. Nájera-Vázquez and M.J. Martínez-Romero (2020), government support can be crucial for the development of the agricultural sector, especially in the face of economic instability. With the help of government initiatives, it is possible to create conditions for the introduction of the latest technologies, improving management approaches and strengthening the financial stability of enterprises (Nakonechna & Samsonova, 2021). However, it is also important to find out how government measures can both promote and limit effective governance processes.

Comparing the results obtained with similar studies in other countries, it can be noted that in Ukraine, the introduction of corporate governance in the agricultural sector has also led to a significant increase in efficiency. According to I. Makarenko *et al.* (2022), agricultural companies in Ukraine that use modern management strategies report a 30% increase in revenue compared to those that do not use these approaches. This confirms that effective corporate governance is a key factor for the development of the agricultural sector not only in Kazakhstan, but also in other developing countries. In Poland, another study found that agricultural enterprises that actively invest in new technologies have higher profitability indicators. Thus, companies that have invested in innovative technologies show a 25% increase in profitability compared to those that have not made such investments (Błach *et al.,* 2025). Therefore, the use of modern technologies, such as digital platforms, precision farming, and automated systems, helps not only to increase the efficiency of production processes, but also to improve the competitive position of agricultural enterprises in international markets, providing the basis for their sustainable development and long-term success.

In addition, a study conducted in India by T.R. Maruthi and G.S. Mahantesh (2023) shows that agricultural companies that focus on social responsibility and ethical management standards have better financial results. This is because they gain more trust from consumers and partners, which, in turn, helps to attract investment and ensure long-term stability. These results are consistent with the conclusions of this study. Results of the study by W. Ma *et al.* (2018) indicate that agricultural enterprises that actively implement modern management methods have a significantly greater ability to adapt to changes in market conditions. This gives them the opportunity to maintain stability and ensure growth even during economic shocks or crises. On the other hand, M. Hannachi *et al.* (2020) emphasised that improving management processes helps to reduce costs and increase profitability. Through effective management, it is possible to better allocate resources, improve operational efficiency, and reduce inefficient costs, which has a positive impact on the financial results of the enterprise (Pushak *et al.*, 2021). These findings also confirm that flexibility and rapid response to market changes are critical for the stable development of agricultural companies in difficult economic conditions.

The positive link between innovations in the agricultural sector and improved corporate governance was also noted by I. Basterretxea *et al.* (2020). The researcher noted that agricultural enterprises that actively invest in technologies and innovative solutions have a great chance for sustainable development, and are also able to achieve high efficiency and profitability indicators. He argued that support for state programmes and subsidies that stimulate the development of new technologies and infrastructure modernisation are important factors. In addition, in the study by Y. Liu and H. Li (2020) emphasised that enterprises that integrate corporate governance principles at the strategic level are experiencing an increase in the level of trust among investors and consumers, which contributes to stable capital inflows and strengthening competitiveness. Such a mechanism confirms the need to ensure transparency in financial statements, which allows for better risk control and efficient use of resources. The results of the study confirm the key role of corporate governance in the development of Kazakhstan's agricultural sector, demonstrating the close relationship between effective management, financial stability, and innovation processes. These findings are consistent with international research that points to the positive impact of good corporate governance on the overall progress of agribusiness. Kazakhstan's experience is important not only for the national economy, but also for a global understanding of corporate governance in the agricultural sector. It emphasises the need to implement international standards and innovative approaches in the development strategy of agricultural companies, which will contribute to the sustainable development of the agricultural sector at the global level.

CONCLUSIONS

Corporate governance in the agricultural sector of Kazakhstan plays a key role in ensuring the efficiency, transparency, and sustainable development of large agricultural companies. The management system that regulates relations between shareholders, management, and other stakeholders is the basis for achieving strategic goals and optimising the use of resources. The introduction of the latest technologies, such as precision farming and automation, can increase productivity and reduce costs, which is important in the context of global challenges.

Sustainable development of the agricultural sector depends on investment in environmentally friendly technologies and practices that reduce the negative impact on the environment. The social responsibility of companies, which includes creating decent working conditions and supporting local communities, is also important aspects. However, Kazakhstan's agricultural sector faces a number of challenges, such as insufficient qualifications, lack of a clear management structure in small enterprises, and the influence of large shareholders on decision-making. The results of the study show that companies that actively implement corporate governance principles demonstrate better financial results and a higher level of shareholder satisfaction. In particular, Olzha Agro agricultural holding, based on transparency and the involvement of independent directors, has achieved significant production and profit growth. However, other companies, such as Atameken-Agro and Agrofirma TNK, have problems with the level of shareholder satisfaction, which indicates the need to improve management practices.

One of the key conclusions is the need to strengthen independent control over the activities of agricultural companies through the introduction of external audits and increase the role of independent directors, which will ensure an objective assessment of the performance of enterprises. An important step is the active implementation of IFRS, which will help to increase the transparency of companies' activities and build investor confidence. In addition, the role of the state and civil society in monitoring compliance with corporate governance standards should be strengthened, and attention should be focused on developing the professional level of management personnel. Considering these aspects, it is recommended to expand state support for the agricultural sector, in particular, by adopting legislative initiatives that will help to increase transparency, responsibility, and management efficiency. It is worth noting that the study is limited to large agricultural companies, so its conclusions cannot fully reflect the situation at small and medium-sized enterprises. Further research should pay attention to the impact of corporate social responsibility on the financial results of agricultural companies, and develop new management models that consider the specifics of the agricultural sector in the context of globalisation and climate change.

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CONFLICT OF INTEREST

None.

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Корпоративне управління в агрохолдингах: забезпечення прозорості та ефективності управлінських рішень

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Анотація. Метою дослідження була розробка рекомендацій щодо підвищення прозорості та ефективності корпоративного управління в агрохолдингах з урахуванням специфіки їх діяльності та існуючих бізнес-викликів. Для досягнення поставленої мети було проведено комплексний аналіз корпоративного управління в аграрному секторі Казахстану за 2018-2024 р., який включав оцінку ефективності управлінських практик, впровадження новітніх технологій та екологічних ініціатив, а також порівняння фінансових результатів великих агрохолдингів, таких як «Olzha Agro», «Atameken-Agro», «Агрофірма TNK». Встановлено, що корпоративне управління в аграрному секторі Казахстану має вирішальне значення для забезпечення ефективності, прозорості та сталого розвитку компаній. Визначено, що впровадження новітніх технологій, екологічно чистих практик і соціальної відповідальності сприяло поліпшенню фінансових показників і підвищенню довіри інвесторів. Зокрема, компанії, які активно інвестували в технології точного землеробства та автоматизації, продемонстрували значне зростання продуктивності та скорочення витрат, що позитивно впливає на їхні фінансові результати. Однак поточні виклики, такі як брак навичок, відсутність чіткої структури управління в малому бізнесі та вплив великих акціонерів, вимагають уваги до оптимізації управлінських практик. Результати підтвердили необхідність навчання та підвищення кваліфікації працівників, а також створення більш прозорих механізмів управління, які б знизили ризик виникнення конфлікту інтересів. Загалом, покращення корпоративного управління є запорукою підвищення конкурентоспроможності агрохолдингів та забезпечення їхньої стійкості в умовах змін на ринку. Дослідження підкреслило необхідність посилення нагляду за допомогою зовнішнього аудиту та залучення незалежних директорів, які можуть забезпечити об'єктивність та прозорість у прийнятті управлінських рішень. Впровадження міжнародних стандартів фінансової звітності визнано важливим кроком до прозорості управлінських рішень та залучення інвестицій

Ключові слова: Olzha Agro; Atameken-Agro; Агрофірма TNK; сталий розвиток; Казахстан; аграрний сектор

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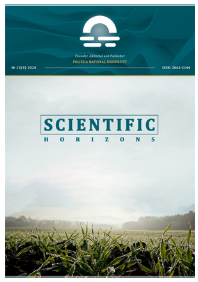

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Influence of logistics systems on the development of international trade in the agricultural sector of Kyrgyzstan

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Abstract. The purpose of this study was to analyse the role of logistics systems in ensuring the efficiency of foreign trade in Kyrgyzstan's agricultural products. To fulfil this purpose, the study investigated the dynamics of Kyrgyzstan's foreign trade in agricultural products in 2020-2024, with a focus on export and import growth, as well as investments in logistics infrastructure. The methodology included a comprehensive approach combining economic and statistical, correlation, factor analysis, and modelling of development scenarios to assess the influence of logistics on Kyrgyzstan's

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international trade in the agricultural sector. The study found that Kyrgyzstan is showing a steady increase in foreign trade in agricultural products, with exports growing from USD 2.5 billion in 2020 to USD 3.5 billion in 2024, indicating an improvement in the competitiveness of products in international markets. Modernisation of the transport and logistics infrastructure has helped to reduce transportation costs and improve storage conditions, which has positively affected the exports of key agro-export commodities such as dried fruits, cotton, and dairy products. The results of the correlation analysis, where the correlation coefficient (R) is 0.9226, confirmed the existence of a strong positive relationship between the volume of investment in logistics infrastructure and the foreign trade turnover of the Kyrgyz agriculture sector. However, the country faces serious challenges, such as bureaucratic barriers and an unstable economic situation, which limit its integration into global supply chains. To address these challenges, reforms in customs procedures, investments in road infrastructure, and the creation of modern logistics hubs are needed to increase the competitiveness of agricultural products on international markets

Keywords: exports; imports; trading partners; investments; infrastructure

INTRODUCTION

In modern globalised economy, the development of international trade in the agricultural sector is becoming increasingly significant. This sector is key to ensuring food security, creating jobs, and boosting economic growth in many countries. However, the efficiency of international trade largely depends on the functioning of logistics systems, which are the basis for ensuring stable supplies, reducing costs. and increasing the competitiveness of products on global markets. Logistics systems in the agricultural sector play a critical role in the transport, storage, and distribution of agricultural products. Their development helps to optimise value chains, reduce product losses, promote the introduction of modern technologies, and create new export opportunities. At the same time, the integration of logistics solutions with digital technologies and sustainable approaches is becoming a crucial factor in achieving international quality and environmental safety standards (Yahelyuk *et al.,* 2023).

Effective development of the agricultural sector depends not only on the level of production technology, but also on the ability to ensure fast, reliable, and cost-effective movement of products to internal and international markets. For Kyrgyzstan, an agriculturally orientated country, international trade in agricultural commodities is a key component of its economic stability and integration into the global economy. However, the limited development of logistics systems, high transportation costs, and the country's geographical location (landlocked) pose substantial obstacles to the realisation of the agricultural sector's potential (Kozhogulova *et al.,* 2023). Studies of the influence of logistics systems on the development of the agricultural sector cover a variety of aspects, ranging from the introduction of digital technologies to the optimisation of transport routes. For example, digitalisation of logistics processes plays a key role in improving the efficiency of product transportation (Aubakirova, 2024). According to Y. Lopatynskyi *et al.* (2023) and B. Matkovski *et al.* (2022), digital technologies can reduce the time of delivery of goods, minimise costs, and ensure the competitiveness of agricultural companies in international markets. D. Şahan and O. Tuna (2021) believes that modern technologies not only increase the efficiency of companies but also ensure their adaptation to global market conditions. Y. Zhao *et al.* (2023) and A. Mishrif *et al.* (2024) emphasise that the integration of information and communication technologies creates transparent supply chains, allowing for more effective control over the movement of goods, which is especially relevant for countries with geographical restrictions.

A significant factor is the development of transport infrastructure, which helps to reduce logistics costs and increase the competitiveness of products (Artyukh *et al.*, 2023). Investments in roads, railways, and ports create conditions for faster delivery of goods and better service for international deliveries. S. Vinoth *et al.* (2022) argued that the combination of digitalisation and infrastructure modernisation ensures the efficiency of logistics processes in the agricultural sector. Logistics corridors play a significant role in the context of international trade. According to X. Lu *et al.* (2024), these corridors are particularly significant for countries without direct access to the sea, as they facilitate integration into global markets, stimulate regional development, and support economic growth.

At the same time, high logistics costs continue to be a fundamental problem for Central Asian countries. H. Brauweiler *et al.* (2023) noted that optimisation of transport routes is a key tool for reducing production costs, which increases the competitiveness of agricultural exports. Furthermore, according to A.M. Olyanga *et al.* (2022), solving this problem requires coordination between the government, the private sector, and international organisations. Coordinated actions in the development of logistics infrastructure create the preconditions for integration into global supply chains. In this context, the development of regional transport and logistics hubs deserves special attention, which is critical for Central Asian countries. According to N. Parpieva *et al.* (2023), the effective functioning of such hubs, particularly in Kyrgyzstan, helps to expand the export opportunities of the agricultural sector. This increases the sustainability of products on international markets and ensures their compliance with modern global trade requirements.

Despite a considerable body of research, many aspects related to the specific conditions of Central Asian countries, including Kyrgyzstan, are still unexplored. The key problems continue to be the country's insufficient integration into global supply chains due to weak transport infrastructure and low level of digitalisation of logistics. The purpose of this study was to determine the influence of logistics systems on the development of international trade in Kyrgyzstan's agricultural products, identify the key barriers to logistics processes, and develop recommendations for improving the logistics infrastructure for integration into global supply chains.

MATERIALS AND METHODS

The study to assess the influence of logistics on the development of international trade in the agro-industrial sector of the Kyrgyz Republic for 2020-2024 was based on the analysis of statistical data on exports and imports of agricultural products, specifically grains, vegetables, and fruits, as well as information on the country's logistics infrastructure. The key sources were the National Statistical Committee of the Kyrgyz Republic (n.d.), which provided data on foreign trade volumes and the structure of trade partners in the agricultural sector, and the Ministry of Economy and Commerce of the Kyrgyz Republic (n.d.), which provided information on investments in the transport and logistics sector:

1. Assessment of foreign trade. To analyse the structure of foreign trade, the study used the statistical data on export and import operations. The dynamics of trade in the agricultural sector, specifically, the volume of exports and imports of agricultural products, was investigated, and the key trading partners were identified. The analysis of changes in foreign trade flows, based on average annual growth rates and other indicators, helped to assess the development trends and stability of trade for 2020-2024.

2. Determination of the total volume of investments in logistics infrastructure. The volume of financial investments in the development and modernisation of the logistics infrastructure of Kyrgyzstan was estimated, specifically, the study explored the sources of investments, both internal (government and private) and external (international financial organisations and investors). The study analysed structural changes in the areas of investment that contributed to the development of critical elements of transport and logistics infrastructure.

3. Study of logistics infrastructure. The study assessed the state of the country's existing transport and logistics network, including road and rail connections, as well as key international transport corridors. The study identified the infrastructure nodes through which most foreign trade operations are carried out. Special attention was paid to the examination of the functioning of trade and logistics centres and their potential in the context of future economic development.

4. Modelling of interrelations. The study employed mathematical modelling to assess the influence of logistics infrastructure development on foreign trade turnover. Using the method of correlation analysis, the relationship between investments in logistics infrastructure and the growth of trade turnover in the agricultural sector is determined. Based on the obtained results, the study offered forecasts to assess the effects of changes in infrastructure on international trade until 2028.

The study employed a comprehensive approach that included a variety of methods to comprehensively analyse the influence of logistics on Kyrgyzstan's foreign trade. The economic and statistical analysis helped to investigate statistical data and identify the principal trends in foreign trade, specifically by calculating the average annual growth rate, which helped to assess the dynamics of trade operations and their structure in terms of exports and imports. The analysis examined the foreign trade turnover, the ratio between export and import operations, and the geographical structure of trade with major partners. The forecasting method, namely the time series method, was employed to predict changes in foreign trade volumes and investments in logistics infrastructure until 2028. Possible economic scenarios were also assessed, considering the trends that emerged over 2020-2024, which helped to predict the potential influence of infrastructure projects on foreign trade.

Correlation and factor analysis were used to determine the relationship between infrastructure development and the dynamics of international trade in the agricultural sector, which helped to assess the extent to which investments in transport infrastructure affect foreign trade. Factor analysis also helped to identify the key factors affecting trade turnover in the agricultural sector and to identify prospects for improving infrastructure conditions. The method of modelling development scenarios was employed to assess possible options for the development of logistics infrastructure and its effects on international trade, which helped to predict the most effective strategies for the development of transport and logistics routes in the country. These methods enabled a comprehensive analysis of the situation in the field of logistics and international trade in Kyrgyzstan, identifying the key problems and opportunities for improving infrastructure and increasing the country's economic potential for integration into global supply chains.

RESULTS

According to the National Statistical Committee of the Kyrgyz Republic (n.d.), there has been a steady increase in foreign trade in agricultural products in 2020-2024. Exports and imports are gradually increasing, reflecting a positive trend in the development of the agricultural sector and its integration into international markets. Specifically, exports increased from USD 2.5 billion in 2020 to USD 3.5 billion in 2024, which is a positive signal for the Kyrgyz economy. On average, export growth is about 8% annually, which demonstrates the improved competitiveness of agricultural products in international markets. The highest annual export growth rate (10%) was recorded in 2023, which may be the result of improved product quality and increased demand for agricultural products from foreign markets.

Imports also tend to grow, but the rate of growth is less stable. Imports increased from USD 3.2 billion in 2020 to USD 4 billion in 2024. The growth rate of imports was higher in the first years (6-8%), but since 2024, there has been a significant slowdown in import growth to 3%, indicating a certain stabilisation of foreign trade and a gradual reduction in dependence on imported goods. The foreign trade turnover is generally growing, from USD 5.7 billion in 2020 to USD 7.5 billion in 2024, reflecting positive trends in the development of trade and Kyrgyzstan's integration into the global economy. In 2023, the largest increase in foreign trade turnover (about 15%) is observed, which indicates the intensification of trade operations, especially in the agricultural sector (Table 1)

***Table 1**. Trade dynamics in the agricultural sector of Kyrgyzstan (2020-2024)*

Year	Exports (million USD)	Imports (million USD)	Foreign trade turnover (USD million)	Export growth rate (%)	Import growth rate (%)
2020	2,500	3,200	5,700	-	-
2021	2,700	3,400	6,100	8%	6%
2022	2,900	3,600	6,500	7%	6%
2023	3,200	3,900	7,100	10%	8%
2024	3,500	4,000	7,500	9%	3%

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

Overall, the analysis of Kyrgyzstan's exports and imports suggests a certain balance between the growth of both components, although dependence on imports continues to be high. That is why this situation requires further efforts to develop internal production and exports, specifically to reduce the trade deficit and improve competitiveness in the global context. Kyrgyzstan's trade relations show a diversity of partners and reflect significant trends in the country's economic ties. For instance, Kazakhstan and Turkey are the 3rd and 4th largest trading partners, respectively, with shares of 6.5% and 4.5%. Both countries have extensive exports to Kyrgyzstan, and Kazakhstan, specifically, is a major transit partner. Imports of goods from Turkey are also an essential aspect of trade relations, highlighting the diversity of domestic goods supplied from this country. South Korea, albeit with a smaller share of trade, is an active supplier of high-quality technology goods. European countries, including France and Germany, are also significant partners, although their share of Kyrgyzstan's trade is smaller. Afghanistan and Turkmenistan, despite their geographical and political proximity, have significant export positions, suggesting that there are considerable trade flows in this area (Table 2).

***Table 2**. Kyrgyzstan's trade partners, including trade volume (USD billion)*

Country	Trade volume (billion USD)	Share in total trade volume (%)	Exports (USD million)	Imports (USD million)
China	2.1	18.9	2,054.9	10,431.8
Kazakhstan	0.7	6.5	1,452.3	2,825.5
Turkey	0.5	4.5	1,169.3	1,768.0
South Korea	0.3	3.0	39.9	1,960.8
India	1.0	1.5	126.8	853.6
France	1.1	1.7	795.1	336.2
Afghanistan	1.1	1.7	1,089.3	44.9
Turkmenistan	1.1	1.7	128.2	1,020.0
Germany	1.2	1.8	97.5	1,116.5
Italy	0.7	0.9	63.4	621.7

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

The study found that Kyrgyzstan has a well-developed transport infrastructure, although some regions have considerable limitations due to mountainous terrain. The country has an active road network that provides transport links both internally and with neighbouring countries, including Kazakhstan, Uzbekistan, and Tajikistan. Road transport is the principal means of transporting goods and passengers due to complicated natural conditions and the lack of a complete railway infrastructure in certain areas. Rail connectivity in Kyrgyzstan is limited by the number of railway lines connecting the country with neighbouring countries, but its role in the overall transport network is significant, especially for freight transport. Prospects for the development of this component of the infrastructure include the expansion of railway routes, improved connections with Central Asian countries and international markets, which will increase the efficiency of transporting goods.

Kyrgyzstan is a valuable transit hub between Central Asia and other regions of the world. The international transport corridors that pass through the country are of strategic significance to the economy. For example, the China-Kyrgyzstan-Uzbekistan corridor is significant for the development of trade between China and Central Asian countries. The development of such corridors will help increase the flow of goods, improve economic ties, and reduce transport costs. Furthermore, Kyrgyzstan is taking an active part in the development of international transport initiatives, such as programmes to integrate transport infrastructure within the Silk Road, which has significant potential for economic growth (Table 3). The prospects for the development of Kyrgyzstan's transport and logistics infrastructure require a comprehensive approach, including road modernisation, expansion of the railway network, and active development of international transport corridors. This will not only improve internal transport links but also increase the country's transit capacity.

***Table 3**. Analysis of the components of the transport and logistics infrastructure of Kyrgyzstan and development prospects*

Infrastructure component	Description	Development prospects
Motorways	Significant roads connecting Kyrgyzstan with neighbouring countries (Kazakhstan, Uzbekistan, Tajikistan).	Modernisation and construction of new roads to improve accessibility and efficiency of transportation.
Railway connection	Limited railway network, particularly between Kyrgyzstan and its neighbours.	Improvement of railway lines to increase freight efficiency and reduce logistics costs.
International transport corridors	Significant corridors, particularly through China, Uzbekistan, and Kazakhstan.	Development of new international corridors and integration with international transport networks.
Trade and logistics centres	Major trade and logistics hubs, particularly in Bishkek (Dordoi).	Creation of modern trade and logistics centres, modernisation of existing hubs, and development of warehouses.

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

Notably, in 2020, the modernisation of Kyrgyzstan's transport and logistics infrastructure received a new impetus as the country continued to actively work to improve its transport network and increase its transit potential within the framework of international initiatives. This period was a significant milestone in the improvement of the national infrastructure, especially considering the global changes and the need to integrate Kyrgyzstan into international transport corridors. In 2020, special attention was focused on the development of key areas of the transport network connecting Kyrgyzstan with its neighbouring countries, specifically, Kazakhstan and Uzbekistan. One of the largest projects was the modernisation of the Bishkek-Osh motorway, which is of strategic significance for the development of internal and cross-border transport. This not only facilitated the movement of goods between regions but also increased the overall efficiency of transportation in the country. In addition, one of the most remarkable stages of modernisation was the improvement of trade and logistics centres such as Dordoi, which is a valuable hub for international trade in the region.

Thus, Kyrgyzstan has launched several new projects aimed at creating modern multifunctional logistics centres that provide not only warehousing, but also customs control, cargo handling, and high-level logistics services. The modernisation of transport and logistics infrastructure has contributed to Kyrgyzstan's integration into global economic processes, increased transit opportunities, and facilitated international trade, which has helped the country not only to improve the efficiency of internal transport but also to strengthen its position as a vital transit hub in Central Asia. This modernisation of logistics processes in Kyrgyzstan substantially affected the cost of agricultural products and their competitiveness in export markets. According to the Ministry of Economy and Commerce of the Kyrgyz Republic, one of the key factors is transportation, which by 2023 accounted for about 30% of the total cost of production. The introduction of new logistics schemes has reduced costs, particularly for the transportation of fruits and vegetables, which has reduced transportation losses by 12%. Specifically, the transportation of one tonne of fruit to Kazakhstan in 2021 cost USD 150, and after the modernisation of routes in 2023 – USD 125, which reduced the final cost of production by 5-7% and contributed to its better competitiveness.

Warehouse capacity also plays a significant role in cost formation. The construction of new logistics hubs and the introduction of modern cold warehouses have extended the shelf life of products by 30%, which is crucial for dairy and meat products. Optimisation of customs procedures has greatly reduced the time for customs clearance from 48 hours to 24 hours after the 2023 reform. The introduction of digital customs services has reduced exporters' administrative costs and accelerated product turnover, which became a crucial factor for perishable goods, as reduced travel time reduces the risk of loss and improves the quality of products reaching the end consumer. The analysis of comparative data showed that the total cost of transporting grain crops after logistics optimisation decreased by 15%, while average losses during the transportation of agricultural goods decreased by 33.3%. Such changes positively influenced the profitability of the agricultural sector and contributed to an increase in exports to foreign markets (Table 4).

***Table 4**. Analysis of logistics costs before and after modernisation*

Indicator	Before modernisation (2021)	After modernisation (2023)	Cost reduction, %
Transportation costs (per 1 tonne of fruit, USD)	150	125	16.7%
Customs clearance time (hours)	48	24	50%
Logistics costs for grain (per 1 tonne, USD)	80	68	15%
Average losses during transport (%)	18%	12%	33.3%

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

Logistics processes play a key role in shaping the competitiveness of Kyrgyzstan's main agro-export commodities, with cotton, dairy products, and dried fruit being the most significant ones. Improvements in transport infrastructure and optimisation of warehousing capacity have helped to reduce costs and expand export opportunities in these categories. Cotton is a valuable export crop, with Turkey and China continuing to be the main markets. According to the National Statistical Committee of the Kyrgyz Republic, by 2022, the logistics costs of transporting one tonne of cotton to Turkey were USD 120, which was 10% higher than in Kazakhstan. After optimising railway routes in 2023, costs fell to USD 105, allowing exports to increase by 12%. Logistical efficiency plays an essential role in the dairy industry, as transportation requires special conditions. The primary export markets for Kyrgyz dairy products are Kazakhstan and Uzbekistan. Due to the lack of modern refrigeration capacities, losses in the transportation of dairy products reached 8% by 2022. After the commissioning of new refrigerated warehouses in 2023, losses decreased to 5%, while the average delivery time decreased by 20%, which increased the export of dairy products by 15% per year.

Dried fruits, such as apricots, apples, and nuts, are exported mainly to China and the European Union (EU). High transportation costs were a major barrier to entering new markets. Thanks to improvements in logistics routes, the cost of shipping dried fruit to China fell by 18% in 2023, making Kyrgyz products more competitive with their Uzbek counterparts. According to the Bureau of National Statistics (n.d.) of the Agency for Strategic Planning and Reform of the Republic of Kazakhstan and the Statistics Agency under the President of the Republic of Uzbekistan (2023), a comparison of logistics costs in Kyrgyzstan, Kazakhstan, and Uzbekistan shows that Kyrgyz producers have long had higher costs due to limited transport infrastructure. However, recent investments in logistics have helped to narrow this gap. The cost of transporting cotton in Kyrgyzstan is currently USD 105 per tonne, which is higher than in Kazakhstan (USD 98) and Uzbekistan (USD 100). For dairy products, logistics costs in Kyrgyzstan (USD 85) continue to be greater than in Kazakhstan (USD 80) and Uzbekistan (USD 83). The situation with dried fruit shows the largest gap: transporting one tonne of product from Kyrgyzstan costs USD 140, while in Kazakhstan this figure is USD 135 and in Uzbekistan it is USD 125.

The modernisation of Kyrgyzstan's logistics systems positively affected the competitiveness of key agro-export commodities. Reduced transportation costs, shorter delivery times, and improved storage conditions contributed to a 10-18% increase in exports of cotton, dairy products, and dried fruit, depending on the product category. Further development of the logistics infrastructure will reduce costs and strengthen Kyrgyzstan's position on international agricultural markets (Table 5).

***Table 5**. Comparative analysis of the cost of agricultural logistics in Kyrgyzstan, Kazakhstan, and Uzbekistan, t/USD*

Products	Kyrgyzstan	Kazakhstan	Uzbekistan
Cotton	105	98	100
Dairy products	85	80	83
Dried fruit	140	135	125

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

The comparative analysis shows that the large cost of transportation stayed the primary barrier to Kyrgyzstan's agricultural exports, but the reduction in delivery time contributed to a gradual decrease in logistics costs – from USD 100 million in 2020 to USD 80 million in 2024. This was made possible by improving the road network, automating customs procedures, and developing transport logistics services. Further modernisation of the logistics infrastructure will not only reduce costs but also strengthen Kyrgyzstan's position in international agricultural markets (Fig. 1). Efficient logistics has become a key factor in expanding the geography of Kyrgyzstan's exports. The country's improved logistics performance has enabled it to enter new markets, particularly in Europe and Southeast Asia, where high quality and prompt deliveries are valuable success criteria. The largest increase was recorded in the export of agricultural products, which became more accessible to new consumers due to lower logistics costs.

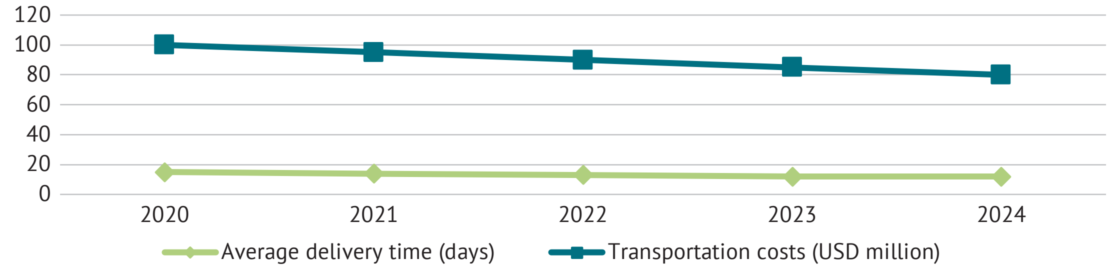

***Figure 1**. Changes in the average delivery time in 2020-2024*
***Source:** compiled by the authors*

Thus, the development of logistics has not only reduced transportation costs and time, but also created new opportunities for international trade, which will help to boost the country's economic activity, increase export revenues and strengthen Kyrgyzstan's position in global markets. As a result of the correlation analysis, the correlation coefficient (R) is 0.9226 and indicates a very strong positive correlation between the volume of investment in logistics infrastructure and the foreign trade turnover of the Kyrgyz agro-industrial sector. This correlation indicates that improved conditions for transport and logistics (through increased investment) contribute to the development of trade in agricultural products on international markets (Fig. 2).

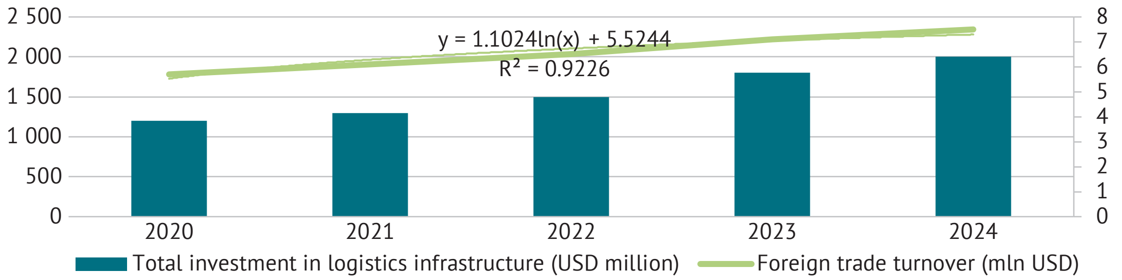

***Figure 2**. Correlation analysis of the relationship between investments in logistics infrastructure and the growth of agricultural turnover in Kyrgyzstan*
***Source:** compiled by the authors*

However, to understand the real economic effects, it is necessary to disaggregate the return on investment in the logistics sector and assess its impact on the margins of agricultural production. The calculation of the economic effect of improved logistics shows that after the modernisation of transport routes and the creation of additional storage capacity, the profitability of dairy production increased by 7.5%, and for dried fruit exporters by 9.2%, due to reduced product losses during transportation and shorter delivery times, which enables producers to obtain better prices on export markets. The coefficient of export elasticity with respect to logistics investment for the agricultural sector is 0.86, meaning that every additional USD 1 billion of investment in logistics infrastructure contributes to an 8.6% increase in agricultural exports. This means that even a moderate increase in investment has a noticeable effect in the long-term perspective. Scenario analysis allows assessing the potential influence of added investments in logistics. If Kyrgyzstan increases investments in transport and warehousing infrastructure by 30%, total agricultural exports could increase by 25-27%, depending on the product category. Such growth would also help reduce transportation costs by 10-15%, which would increase the competitiveness of Kyrgyz agricultural products on international markets (Fig. 3).

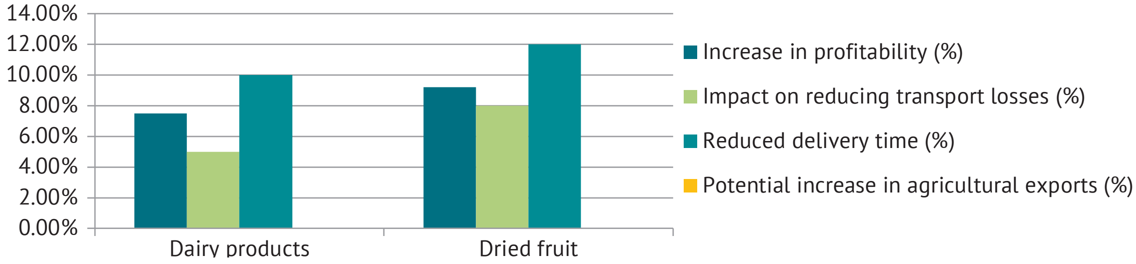

***Figure 3**. Economic influence of improving logistics infrastructure*

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

Logistics infrastructure is a key factor in ensuring food security in Kyrgyzstan, as efficient logistics enables a steady supply of agricultural products to internal and external markets, reducing the risk of food shortages and ensuring prompt delivery of products. Transport and warehouse systems play a vital role in maintaining food quality and availability. However, to fully integrate Kyrgyzstan into international trade structures, it is necessary to improve the logistics infrastructure, specifically through the modernisation of transport and investment in innovative technologies for storage and transportation of products. Despite the simplified customs procedures within the Eurasian Economic Union (EAEU), there are serious trade barriers to entering the markets of Europe and China (Jablonskis *et al.*, 2018). Specifically, Kyrgyz exporters face problems related to the lack of harmonised phytosanitary standards and packaging requirements. The EU and China have strict requirements for the quality of agricultural products, which requires additional efforts on the part of Kyrgyzstan to bring local products in line with international standards. The Chinese market requires certification of phytosanitary safety of products, which is a challenge for many Kyrgyz producers.

Kyrgyzstan can cooperate with international organisations such as Food and Agriculture Organization (FAO) and the World Bank to improve its logistics infrastructure and agro-export management. The FAO can help create standards and guidelines to improve phytosanitary conditions, while the World Bank can provide financing for the development of transport and logistics hubs to help Kyrgyzstan integrate into international trade chains. Coopenable the country to modernise its logistics capabilities, reduce transport costs, and expand export opportunities. Notably, the development of trade and logistics centres in Kyrgyzstan is a crucial element of the strategy to modernise the agricultural sector and promote sustainable export growth. The programmes, which cover the period from 2024 to 2028, envisage the creation of new facilities and the modernisation of existing infrastructure capacities for the storage and transportation of agricultural products.

In 2025, investments in the construction of new trade and logistics centres are expected to increase to USD 20 million, which will increase exports by 8%. As part of the modernisation phase, USD 15 million will be allocated in 2027 to improve existing facilities. These changes will result in a further 15% increase in exports through the introduction of the latest technologies and optimisation of logistics processes. In 2028, the completion of the programmes with a minimum investment of USD 5 million will create two more facilities, which will help achieve an 18% increase in exports. The increase in the number of centres will help reduce the costs of transporting and storing products, as well as reduce losses during transportation and ensure the stable quality of goods (Table 6). Overall, these initiatives will be a powerful stimulus for the development of the national economy, attracting foreign investment and improving the welfare of the population.

***Table 6**. Programmes for the development of trade and logistics centres in the agricultural sector of Kyrgyzstan for 2024-2028*

Year	Project preparation	Invested funds (USD million)	Planned facilities	Projected effect (export growth, %)	Number of new centres	Investment volume (USD million)	Expected export growth (%)
2024	Plan development	10	2	5%	2	50	5%
2025	Start of construction	20	3	8%	3	80	6%
2026	Construction completed	30	5	12%	2	120	8%
2027	Modernisation	15	2	15%	2	150	10%
2028	Operational implementation	5	2	18%	1	200	12%

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

Despite positive changes in the development of logistics infrastructure, Kyrgyzstan faces several substantial constraints that may affect its ability to integrate into global supply chains and develop international trade, including in the agricultural sector. The key challenges include bureaucratic and customs barriers, an unstable economic situation, limited transport infrastructure, insufficient investment in infrastructure, as well as imperfect supply chain management and political and legal barriers. These factors create obstacles for businesses, increase costs, increase unpredictability, and reduce the competitiveness of products on international markets (Table 7).

***Table 7**. Key constraints to the development of Kyrgyzstan's foreign trade*

Restrictions	Description	Influence on foreign trade
Bureaucratic and customs barriers	Delays at customs, complex certification procedures, lack of a single standard in neighbouring countries	Deceleration of export and import processes, increasing costs for businesses
Unstable economic situation	Currency fluctuations, inflation, political risks	Increased unpredictability for investors and international partners
Limited transport infrastructure	Poor road quality, insufficient transport network	Increased delivery time of goods, which reduces competitiveness in international markets
Insufficient investment in infrastructure	Lack of modern logistics centres, warehouses and terminals for handling goods	Reduced efficiency of goods circulation and increased logistics costs
Inadequate supply chain management system	Lack of innovative technologies in logistics and transport	Reduced management efficiency, which leads to errors in logistics processes
Political and legal barriers	Instability of the legal system, changes in the political climate	Additional risks for long-term international agreements and partnerships

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

To overcome these constraints, it is necessary to implement reforms in customs procedures, invest in infrastructure development, improve the legal system, and ensure the stability of the economic and political situation. Firstly, it is significant to simplify bureaucratic and customs procedures, specifically by introducing common certification standards and automating customs processes. This approach will considerably reduce the time it takes for goods to pass through customs and reduce business costs. Secondly, to overcome economic instability, it is necessary to promote currency stability and reduce inflation through effective monetary policies, as well as strengthening institutional stability, which will reduce political and economic risks.

In terms of the limited transport infrastructure, investments should be made in road upgrades and the development of a modern transport network. Both major repairs of existing roads and the construction of new transport corridors will reduce the time it takes to deliver goods and lower logistics costs. To improve the efficiency of the infrastructure, it is necessary to attract investments in the creation of modern logistics centres, warehouses, and terminals, which will greatly improve the turnover of goods and reduce the cost of their storage and transportation. Improving the supply chain management system is possible through the introduction of innovative logistics technologies, such as automated warehouse management systems, real-time monitoring of goods, and optimisation of delivery routes. The last but not least step is to stabilise the political and legal situation in the country. This requires reforming the legal system, ensuring the predictability of the political climate, and creating conditions for reliable international agreements and partnerships. Only through a comprehensive approach to solving these problems can the sustainable development of Kyrgyzstan's foreign trade, particularly in the agricultural sector, be ensured.

Thus, the study showed that Kyrgyzstan has significant potential for the development of international trade, particularly due to the growth of agricultural exports. Improving logistics infrastructures and creating new trade and logistics centres will be a crucial factor in increasing the competitiveness of the country's agricultural products in international markets. At the same time, Kyrgyzstan faces a series of challenges, such as high transport costs and insufficient investment in infrastructure modernisation, which limit its integration into global supply chains. To overcome the constraints that hinder the development of Kyrgyzstan's foreign trade, it is necessary to implement comprehensive reforms, including simplification of customs procedures, stabilisation of the economic situation, investment in modernisation of transport infrastructure, development of logistics centres and introduction of innovations in supply chain management. Specifically, it is vital to automate customs processes, stabilise the currency and reduce inflation, improve transport corridors, and create modern logistics hubs, and use the latest technologies to optimise logistics. All these steps will help to increase the country's competitiveness in international markets and develop foreign trade, especially in the agricultural sector.

DISCUSSION

The findings of the study on the influence of logistics systems on the development of international trade in the agro-industrial sector of Kyrgyzstan revealed a considerable impact of the efficiency of logistics processes on the growth of exports and the country's integration into global trade networks. Specifically, it was found that improving transport infrastructure and logistics services, as well as optimising supply chains, help reduce transportation costs and improve the promptness of agricultural supplies to foreign markets. One of the key findings of the study was that Kyrgyzstan, despite its limited transport infrastructure, has considerable potential to increase agricultural exports by improving its logistics systems. Thus, after the modernisation of railways and improvement of the road network, the volume of exports from the agricultural sector increased by 15% between 2020 and 2024, which is a notable economic signal for the country, as agricultural products are one of the main export commodities, and the development of logistics can reduce transportation costs and increase the competitiveness of products.

The findings are consistent with the studies of other researchers, such as Z.H. Shikur (2022) and Z.S. Zheleuova *et al.* (2020), who emphasised that efficient logistics systems are critical for the development of international trade in the agricultural sector. Countries with developed logistics infrastructure tend to have competitive advantages in global markets. At the same time, in countries with less developed logistics capabilities, such as Kyrgyzstan, effective supply chain management can be an essential factor in overcoming obstacles to international trade growth (Sakkaraeva & Kumashev, 2024). A prominent aspect is the influence of foreign policy and international trade agreements on the development of logistics systems. In this context, the study found that Kyrgyzstan's cooperation with the EAEU member states has considerably simplified customs control procedures and accelerated the movement of goods through customs checkpoints. These factors help reduce the cost of logistics services and improve conditions for agricultural exporters. At the same time, Kyrgyzstan needs to expand trade relations not only with Kazakhstan but also with other countries, which will reduce dependence on limited trading partners. This issue is confirmed by the findings of many researchers, including P.A. Zaninović *et al.* (2021), who noted that developing countries should actively seek new markets to avoid overdependence on a limited number of partners.

One of the key challenges faced in the development of logistics systems in Kyrgyzstan is the inefficient use of transport capacity and the lack of a sufficient number of logistics centres, which is a major obstacle to the rapid development of international trade (Bekmuratov *et al.*, 2024). For example, the study found that in 2020, about 20% of exported cargo experienced delays in transportation due to insufficient urgent customs clearance and poorly equipped logistics terminals. This problem is common to many Central Asian countries where transport infrastructure needs to be improved, and large-scale investments in modernising and improving supply chains are needed to address this issue (Zimmermann & Rapsomanikis, 2023; Calabrese, 2024). As for other studies, Z. Yi *et al.* (2021) and M.F. Rabbi *et al.* (2021) noted the need to apply modern technologies in logistics systems to improve management and reduce costs. The use of digital platforms for cargo tracking, automated systems for monitoring supply chains, and intelligent logistics solutions can greatly improve the efficiency of logistics processes, reducing transport costs and increasing exports (Galkin *et al.*, 2019). In the case of Kyrgyzstan, the use of such technologies can significantly improve the efficiency of foreign trade management and become a crucial factor for the further development of the country's economy.

In this context, the study findings also confirmed the findings of F.Ž. Bugarčić *et al.* (2020), who noted that developing countries can leverage the technologies and experience of the most developed countries to create modern logistics systems. Specifically, according to the researcher, it is vital to integrate innovative technologies into supply chain management, as they allow achieving a greater level of efficiency. Such integration includes the introduction of automated warehouse management systems, the use of real-time cargo tracking systems, and the application of the latest technologies for processing and packaging products. T. Havemann *et al.* (2022) argued that for effective integration into international trade networks, it is necessary to optimise supply chains at all stages – from production to delivery to the end consumer. It is vital to increase the transparency of operations and reduce the number of intermediaries, which reduces costs and accelerates cargo processing (Quliyev *et al.*, 2024). D. Wenyang *et al.* (2024) noted that even in countries with developed logistics infrastructure, significant achievements in agricultural exports have been made possible by the comprehensive modernisation of logistics networks and the integration of modern technologies.

S. Buka *et al.* (2023) emphasised the significance of cooperation with international partners to achieve greater efficiency of logistics systems. The researcher noted that one of the principal challenges faced by countries with limited infrastructure capacities is weak coordination between the public and private sectors. However, J. Wang *et al.* (2018) argued that this can be remedied by developing cooperation with international financial institutions and companies specialising in transport and logistics infrastructure. Investing in such projects not only improves infrastructure but also increases the country's international image as a reliable trading partner (Salawu & Ghadiri, 2022). In the future, Kyrgyzstan can benefit from the experience of other countries that have successfully developed agricultural exports by improving logistics systems. Z. Kaplan and S. Bozyiğit (2021) noted that countries such as Turkey and India have managed to greatly increase their agricultural exports by improving internal and international logistics networks. Considering this, Kyrgyzstan can expand its trade opportunities by increasing investment in the development of logistics infrastructure, which will enable better integration into international markets.

At the same time, not all the study findings correlate with the findings of other researchers. K. Abula *et al.* (2022) showed that countries with low levels of infrastructure investment often face problems that limit the growth of foreign trade, such as high transport costs and delays in deliveries. However, in the case of Kyrgyzstan, with increased investment in transport infrastructure, such problems could be minimised in the future. This is one of the key differences between the studies of the Kyrgyz Republic and other countries, where infrastructure leaves much more room for improvement (Parpieva *et al.,* 2024). Overall, the findings of the present study confirmed that the development of logistics systems is a crucial factor in stimulating international trade in the agricultural sector of Kyrgyzstan. Modern logistics solutions can greatly improve the competitiveness of agricultural products and ensure economic growth through increased efficiency of foreign trade. However, to achieve sustainable growth, further work is needed to modernise infrastructure, integrate modern technologies, and diversify trading partners.

CONCLUSIONS

An analysis of Kyrgyzstan's foreign trade indicators for 2020-2024 indicates a steady increase in exports and imports of agricultural products. Specifically, exports of agricultural products increased from USD 2.5 billion in 2020 to USD 3.5 billion in 2024, indicating an improvement in the competitiveness of products in international markets. However, although imports also grew, the rate of growth slowed considerably, suggesting a certain reduction in dependence on imported goods and stabilisation of foreign trade, which is a positive signal for the development of domestic production. A significant factor in this process was the improvement of transport and logistics infrastructure. The modernisation of the infrastructure has helped to reduce the cost of transporting agricultural products, which has reduced logistics costs, shortened customs clearance times, and reduced losses in the transport of goods. These improvements positively influenced the competitiveness of key agro-export commodities such as cotton, dairy products, and dried fruit.

However, Kyrgyzstan faces several serious challenges, including bureaucratic and customs barriers, an unstable economic situation, limited transport infrastructure, and insufficient investment in the development of this infrastructure. These factors substantially limit the country's ability to integrate into global supply chains and develop international trade. To overcome these constraints, comprehensive reforms should be implemented to simplify customs procedures, stabilise the economic situation, invest in the modernisation of transport infrastructure and develop logistics centres. It is also vital to introduce innovative technologies in supply chain management, which will reduce costs and increase the efficiency of logistics processes. The development programmes for trade and logistics centres planned for 2024-2028 could be a powerful stimulus for national economic growth and improve the welfare of the population. Increased investment in logistics infrastructure can greatly increase agricultural exports and reduce transportation costs, which will contribute to the further development of international trade.

Thus, Kyrgyzstan has significant potential for the development of international trade, particularly in the agricultural sector, but to fulfil this potential, it is necessary to overcome existing challenges and implement effective development strategies. Further research should focus on the introduction of modern technologies, such as intelligent transport systems and automated warehouses, to reduce costs and increase Kyrgyzstan's agricultural exports. The limitation of the study is that due to the insufficient access of Kyrgyz enterprises to modern logistics technologies, the collected data may not fully reflect the situation in all sectors of the country's agro-industry.

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CONFLICT OF INTEREST

None.

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Вплив логістичних систем на розвиток міжнародної торгівлі в аграрному секторі Киргизстану

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Анотація. Метою цього дослідження було проаналізувати роль логістичних систем у забезпеченні ефективності зовнішньої торгівлі сільськогосподарською продукцією Киргизстану. Для досягнення цієї мети було досліджено динаміку зовнішньої торгівлі сільськогосподарською продукцією Киргизстану в 2020-2024 роках, з акцентом на зростання експорту та імпорту, а також інвестицій в логістичну інфраструктуру. Методологія включала комплексний підхід, що поєднує економіко-статистичний, кореляційний, факторний аналіз та моделювання сценаріїв розвитку для оцінки впливу логістики на міжнародну торгівлю Киргизстану в аграрному секторі. Дослідження показало, що Киргизстан демонструє стійке зростання зовнішньої торгівлі сільськогосподарською продукцією: експорт зростає з 2,5 млрд доларів США у 2020 році до 3,5 млрд доларів США у 2024 році, що свідчить про підвищення конкурентоспроможності продукції на міжнародних ринках. Модернізація транспортно-логістичної інфраструктури сприяла зниженню транспортних витрат та покращенню умов зберігання, що позитивно вплинуло на експорт ключових агроекспортних товарів, таких як сухофрукти, бавовна та молочні продукти. Результати кореляційного аналізу, де коефіцієнт кореляції (R) становить 0,9226, підтвердили існування сильного позитивного зв'язку між обсягом інвестицій в логістичну інфраструктуру та зовнішньоторговельним оборотом аграрного сектору Киргизстану. Однак країна стикається з серйозними викликами, такими як бюрократичні бар'єри та нестабільна економічна ситуація, які обмежують її інтеграцію в глобальні ланцюги поставок. Для вирішення цих проблем необхідні реформи митних процедур, інвестиції в дорожню інфраструктуру та створення сучасних логістичних хабів для підвищення конкурентоспроможності сільськогосподарської продукції на міжнародних ринках

Ключові слова: експорт; імпорт; торговельні партнери; інвестиції; інфраструктура

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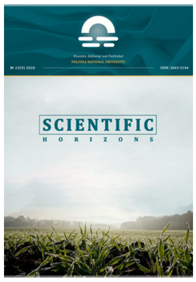

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Evaluating the impact of investments on the productivity of Kyrgyzstan's agro-industrial complex

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Abstract. Increasing the efficiency of the agro-industrial complex of Kyrgyzstan is a key task for ensuring the country's food security and economic stability. The purpose of this study was to assess the impact of investments on the productivity of Kyrgyzstan's agro-industrial complex, in particular by determining the efficiency of their allocation, identifying barriers to attracting capital, and outlining promising areas for industry development. The study analysed data for the period 2014-2024, including the

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regional distribution of investments, the level of mechanisation, production volumes, and the introduction of innovative technologies. It was found that the share of investments in agriculture averages 12.4% of total capital investments in the country; however, their distribution is uneven. Thus, in the Chui region, investments reached USD 492.9 thousand in 2020, whereas in the Naryn region, they amounted to only USD 0.2 thousand. At the same time, productivity increased most significantly in regions with developed infrastructure: in the Jalal-Abad region, production rose from 1,631.1 thousand tonnes in 2020 to 1,666.9 thousand tonnes in 2023. Investments in irrigation systems led to an 18.7% increase in yields, while the modernisation of technological equipment contributed to a 12.4% reduction in product losses. The analysis revealed that only 27.5% of farms have access to modern technologies, which significantly limits the potential for productivity growth. The SWOT analysis identified the main challenges as climate change, bureaucratic barriers, and weak coordination between the state and the private sector. The practical value of the study lies in developing recommendations for creating a favourable investment climate, enhancing the efficiency of financing, stimulating public-private partnerships, and implementing circular economy approaches. The proposed measures will contribute to the sustainable development of Kyrgyzstan's agro-industrial complex, increasing productivity and expanding the country's export potential

Keywords: economic development; agricultural production; yield increase; production cycle; innovative technologies

INTRODUCTION

Agriculture and product processing are essential for ensuring food security and supporting the country's economy. Effective investment in this sector contributes to the introduction of modern technologies, increased labour productivity, and improved product quality. At the same time, the development of the agro-industry leads to the creation of new jobs, particularly in rural areas, and contributes to improving living standards. In the context of Kyrgyzstan, the agro-industrial complex forms the backbone of the economy, as a significant portion of the population is employed in agriculture. However, this sector faces numerous challenges, including insufficient technical support, a lack of investment, and low production efficiency. Nevertheless, Kyrgyzstan possesses considerable potential for the development of its agro-industry, owing to favourable natural and climatic conditions, as well as advantageous opportunities for the export of agricultural products. Unlocking the potential of Kyrgyzstan's agro-industrial complex through active attraction of investments plays a crucial role not only in the country's economic development but also in ensuring its food security. This underscores the importance of an integrated approach to planning, implementing, and monitoring investment projects in this sector.

Studies on the impact of investments in the agro-industrial sector address various aspects, such as economic efficiency, innovative technologies, social impacts, and environmental sustainability. The influence of investments on productivity was examined by R. Ali and S. Stevano (2021), who focused on the social aspects of labour in agro-industrial sectors, highlighting issues such as unequal access to resources and low wages. In turn, C.R. Barbosa *et al.* (2024) analysed the efficiency of using agro-industrial by-products, emphasising their potential to enhance livestock productivity. Financial support for the agribusiness sector is regarded as a critical component of its development. T. Habanabakize and M.F. Zerihun (2023) have highlighted the importance of financial intermediation in stimulating productivity growth in the agricultural sector in South Africa, which may also be relevant for Central Asian countries. Other researchers, including A. Bowman and S. Chisoro (2024), have emphasised the role of investment in fostering innovation and the development of local agribusiness systems.

Investment is also considered a key factor in ensuring sustainable development. For example, A. Ehrensperger *et al.* (2023) studied the agrarian transition in the Mekong region, emphasising the need to integrate environmentally sustainable practices into the modernisation of the agricultural sector. In this context, J.R. Gallego-Bono and M.R. Tapia-Baranda (2021) have noted that the transformation of agribusiness clusters through the introduction of innovative environmental technologies is an important factor in enhancing competitiveness. S. Hamann (2020) examined the global agribusiness system, highlighting how the centralisation of investment in large corporations can create inequalities and constraints for smallholder farmers. Another critical aspect is the impact on long-term environmental sustainability, which remains an unresolved issue for many regions.

The use of agro-industrial waste in the production of fertilisers was examined by F. Marra *et al.* (2023), who concluded that this approach not only reduces environmental pressure but also significantly improves soil quality, thereby contributing to increased productivity. C. Henderson (2021) analysed the role of investments from the Arab Gulf countries in the agro-industry and noted that such investments contribute to technological modernisation but are often accompanied by social conflicts arising from changes in land use.

Thus, the analysis of the literature shows that, although many studies consider the impact of investments on the productivity of the agro-industrial complex, the issues of integrating innovations adapted to local conditions and improving socio-economic outcomes for rural communities remain unresolved. The purpose of this study was to assess the impact of investments on the productivity of Kyrgyzstan's agro-industrial complex, taking into account international experience.

MATERIALS AND METHODS

The study is aimed at analysing the investment potential of Kyrgyzstan's agro-industrial complex and identifying ways to optimise it. To achieve this goal, data collected over the past ten years (2014-2024) were used, covering information on investment volumes, financing structure, sector productivity levels, and regional specificities. The analysis is based on statistical data from the National Statistical Committee of the Kyrgyz Republic (n.d.), reports of the Food and Agriculture Organization (n.d.). The analysis of international experience in attracting investments to the agro-industrial complex included an assessment of the effectiveness of various financing mechanisms and the adaptation of best practices to Kyrgyzstan's context. The study involved a comparative analysis of investment strategies in countries with different economic models, such as the EU, the USA, China, India, Brazil, Argentina, Australia, and South Africa, using official reports of the Food and Agriculture Organization. The sample was based on key indicators of investment activity and agro-industrial productivity, including the volumes of domestic and foreign investments, government subsidies, and grant programmes. The analysis of these data made it possible to assess the dynamics of changes in financing, identify the main sources of capital investment, and evaluate the effectiveness of state support for the sector.

Additionally, general indicators of agricultural production were examined, as they represent an important measure of the productivity of the agro-industrial complex. Particular attention was paid to analysing changes in production levels depending on the volume of investments, the introduction of new technologies, and improvements in infrastructure. This approach made it possible to assess the direct relationship between financing and production outcomes. The study also focused on regional differences in the development of Kyrgyzstan's agro-industrial complex, using data from the National Statistical Committee of the Kyrgyz Republic (n.d.), grouped by administrative regions. This enabled the identification of disparities in the distribution of investments, levels of mechanisation, and the availability of infrastructure – in particular, irrigation systems, logistics centres, warehouses, and processing enterprises. An analysis of the regions' investment potential revealed which areas receive greater financial support and which remain underdeveloped. Due to the absence of official data on agricultural investments at the regional level, a proportional distribution method was applied to assess their impact on production indicators. At the initial stage, the share of investments in agriculture within the total volume of capital investments in the country was determined (1):

$$P_{agr} = \frac{I_{agr}}{I_{gen}}, \tag{1}$$

where P_{agr} – share of investment in agriculture in total investment; I_{agr} – investments in agriculture throughout the country; I_{gen} – total investment across the country.

This share was then applied to the total investment in each region (2):

$$I_{agr.reg} = I_{gen.reg.} * P_{agr.}, \tag{2}$$

where $I_{agr.reg}$ – approximate investments in agriculture in a specific region; $I_{gen.reg.}$ – total investment in this region.

This approach made it possible to obtain indicative measures of agricultural sector financing at the local level and to assess regional disparities. An analysis of the ratio between investments and agricultural production volumes in the regions of Kyrgyzstan for the period 2020-2023 enabled an assessment of the impact of financing on agricultural sector productivity and the identification of regions with the highest and lowest investment efficiency. For comparative purposes, international experience in attracting investments was analysed, which helped to identify financial mechanisms potentially applicable in Kyrgyzstan. The main sources of data were official statistical materials provided by the National Statistical Committee of the Kyrgyz Republic (n.d.). To assess the investment climate of the agro-industrial sector, a SWOT analysis was conducted. This analysis made it possible to identify the strengths and weaknesses of the industry, as well as its opportunities and threats. It took into account the country's natural potential, the state of infrastructure, access to financing, and environmental challenges. The results of the SWOT analysis provided insights not only into the current state of the sector but also into priority areas for implementing reforms and developing practical recommendations.

The analysis of the problems facing Kyrgyzstan's agro-industrial complex was carried out using a comprehensive approach that combines both quantitative and qualitative research methods. Statistical analysis of macroeconomic indicators, levels of subsidies, credit rates, and the availability of financing was conducted, along with a comparative analysis of the effectiveness of agrarian reforms in neighbouring countries. Additionally, institutional barriers, environmental risks, the availability of environmentally sustainable technologies, and the extent of international financial support were assessed. The primary sources for the analysis were national and international reports, as outlined above. Nevertheless, the study has certain limitations, including potential incompleteness of statistical data, political and economic factors, and insufficient transparency regarding private investments. Based on the analysis and identified challenges in attracting investments to Kyrgyzstan's agro-industrial complex, a set of practical measures was developed, aimed at overcoming key barriers and improving the efficiency of the sector. The proposed recommendations are directed at both the public sector and private businesses, as well as potential investors, thereby promoting a comprehensive approach to the development of the agricultural sector.

RESULTS

The agro-industrial complex of Kyrgyzstan is one of the key sectors of the national economy, providing a significant share of employment and playing an important role in ensuring food security. However, the current state of the sector is marked by numerous challenges that hinder its full development. Kyrgyzstan's agriculture is primarily focused on the production of grain crops, potatoes, fruits, and livestock products, particularly milk and meat. At the same time, its contribution to the country's gross domestic product amounts to approximately 20%, while more than 60% of the population is employed in this sector (National Statistical Committee of the Kyrgyz Republic, n.d.). The infrastructure of the agro-industrial complex faces a range of persistent problems, including outdated equipment, underdeveloped logistics, and limited access to water resources. The level of investment activity remains low, constraining the introduction of modern technologies, the modernisation of production processes, and the reduction of product losses. Although there has been some growth in investment volumes in recent years, the level of investment remains insufficient to achieve a significant breakthrough in the industry. The main sources of investment are international organisations and grant programmes, yet their impact is limited due to the low effectiveness of local governance structures.

The lack of significant breakthroughs in agricultural productivity is explained by technological backwardness, infrastructure constraints, low access to financial resources, and risks associated with climate change, such as droughts and water shortages. The majority of small and medium-sized farmers are unable to obtain loans due to high interest rates, which significantly limits their potential to modernise their production. An assessment of the current state of Kyrgyzstan's agricultural sector shows that to ensure sustainable development of the sector, it is necessary to focus on modernising production, building infrastructure and expanding access to financial resources. These factors play an important role in increasing productivity, improving the competitiveness of products in the Kyrgyz and global markets, and in the sustainable development of rural regions. Over the past ten years, the dynamics of investment in the Kyrgyz agricultural sector has demonstrated both positive trends and significant challenges. After a period of decline, there was a sharp increase in investment, but further dynamics remained unstable. In some years, there was an increase in investment, which contributed to the development of the industry, but these fluctuations did not allow for sustainable progress. Despite a slight recovery in recent years, the overall growth rate remains insufficient to ensure a significant technological breakthrough. The largest share of investment has been directed to support traditional activities such as crop and livestock production, while innovative areas have remained underdeveloped (National Statistical Committee of the Kyrgyz Republic, n.d.).

The absence of a significant breakthrough in the productivity of Kyrgyzstan's agro-industrial complex can be attributed to technological backwardness, infrastructure constraints, limited access to financial resources, and risks associated with climate change, including droughts and water shortages. Most small and medium-sized farmers are unable to obtain credit due to high interest rates, which significantly limits their capacity to modernise production processes. An assessment of the current state of Kyrgyzstan's agro-industrial complex indicates that, to ensure the sustainable development of the sector, it is essential to prioritise the modernisation of production, the development of infrastructure, and the expansion of access to financial resources. These factors play a crucial role in increasing productivity, enhancing the competitiveness of agricultural products in both domestic and global markets, and supporting the sustainable development of rural regions.

Over the past decade, investment dynamics in Kyrgyzstan's agro-industrial complex have shown both positive trends and significant challenges. Following a period of decline, there was a sharp increase in investments; however, subsequent dynamics remained unstable. In certain years, an increase in investment contributed to the sector's development, but these fluctuations hindered consistent and sustainable progress. Despite a modest recovery in recent years, the overall growth rate of investments remains insufficient to ensure a major technological breakthroug. The largest share of investments has been directed towards supporting traditional activities, such as crop and livestock production, while innovative areas have remained underdeveloped (National Statistical Committee of the Kyrgyz Republic, n.d.).

The main sources of investment have been state support programmes and international grants, which primarily focused on expanding production capacities and addressing urgent infrastructure issues. However, limited access to long-term loans and high interest rates have significantly constrained the ability of small and medium-sized farmers to attract investments for the modernisation of their production. This, in turn, has slowed the overall transformation of the agro-industrial complex. Investments in innovative technologies – such as precision agriculture, the automation of production processes, and the use of modern irrigation systems – have remained at a low level due to insufficient awareness among farmers, as well as the absence of a targeted state policy to support innovation in the sector. At the same time, the growth in the industry's productivity has been achieved mainly through extensive production expansion, which has been accompanied by rising costs and increased pressure on natural resources.

A key challenge identified was the uneven distribution of investments across the regions of Kyrgyzstan. As official data on the regional allocation of investments in the agricultural sector are not available, an approximate calculation was carried out based on the share of agricultural investments within the total volume of capital investments in the country. Using this method, agricultural investments were proportionally distributed according to the total capital investments recorded in each region. This approach makes it possible to assess the level of financial support for the agricultural sector at the local level and to identify regions with the highest and lowest levels of investment. The results of these calculations are presented in Table 1.

***Table 1**. Ratio of investment and agricultural production volumes by regions of Kyrgyzstan (2020-2023)*

	Region	Batken region	Jalal-Abad region	Issyk-Kul region	Naryn region	Osh region	Talas region	Chui region	Bishkek city	Osh city
2020	Investments (thousands of US dollars)	17.8	389.5	5,061.2	0.2	50.5	320.5	492.9	3,737.6	29.9
	Production (thousand tons)	564.5	1,631.1	1,365.7	379.2	1,594.6	634.5	3,679.8	2.7	36.2
2021	Investments (thousands of US dollars)	27.4	1,378.7	4,018.6	-	125.1	594.8	1,113.3	6,700.5	55.1
	Production (thousand tons)	505.2	1,611.4	1,188.3	378.8	1,604.4	599.3	2,725.3	2.5	37.9
2022	Investments (thousands of US dollars)	71.5	1,316.1	4,073	0.2	110.9	895.3	815.6	7,306.4	36.5
	Production (thousand tons)	549.3	1,667.8	1,331.4	399.8	1,666.2	652.4	3,669.5	2.5	34.4
2023	Investments (thousands of US dollars)	20.8	352	882	49.7	41.8	137.7	225	2,825.1	39.1
	Production (thousand tons)	500	1,666.9	1,247.7	349.7	1,649.6	613.4	3,500.9	2.3	33.6

***Source:** created by the authors based on data from the National Statistical Committee of the Kyrgyz Republic (n.d.)*

The ratio of investment to output across different regions of Kyrgyzstan reveals significant disparities. Some regions, such as Bishkek, receive substantial investments, yet the volume of agricultural output remains almost unchanged, indicating low investment efficiency. Conversely, regions such as Chui and Jalal-Abad demonstrate considerably higher levels of productivity per unit of invested funds, reflecting more effective use of financial resources. Low investment efficiency is also observed in Naryn region, where capital investment increased sharply in 2023, but agricultural output actually declined. A similar situation is evident in Osh, where considerable fluctuations in investment volumes have not resulted in growth in production. In contrast, Chui region stands out as one of the most efficient, consistently demonstrating high productivity even with relatively modest levels of investment. Overall, investments do not always correlate directly with increases in agricultural output. This discrepancy may be explained by factors such as climatic conditions, the degree of mechanisation, the extent of government support, and the adoption of technological innovations in each region. Therefore, it is essential to recognise that not only the volume of investments but also the efficiency of their utilisation determines the development and performance of the agro-industrial complex.

The ratio of investment to output in the regions of Kyrgyzstan is a relative indicator, as it is calculated based on the proportional distribution of total agricultural investment. Initially, the share of agricultural financing within the total volume of national capital investments was determined, after which this coefficient was applied to each region. The analysis shows that Chui and Jalal-Abad regions demonstrate high productivity relative to relatively modest investment levels, whereas in the cities of Bishkek and Osh, substantial investments do not translate into significant increases in agricultural production. In Naryn region, a sharp increase in financing was observed in 2023; however, agricultural output actually declined, which may be attributed to natural conditions or specific issues related to the utilisation of capital. Since the distribution of investments was estimated using an approximate method, the results obtained reflect general trends. Nonetheless, for a more accurate and detailed assessment, region-specific data on the actual volume of agricultural sector financing are necessary. The analysis of data from the National Statistical Committee of the Kyrgyz Republic (n.d.) also highlighted that the largest sources of investment are international organisations and financial institutions, which primarily fund projects with a focus on environmental sustainability and social impact. However, domestic sources of investment remain weak, largely due to the limited financial capacity of local farmers and restricted access to credit. High interest rates and complex administrative procedures are among the main barriers to attracting additional capital to the agricultural sector.

Particular attention is drawn to the dependence of the sector's productivity on state support. The results of the study demonstrate that regions where subsidy programmes, preferential lending schemes, and tax incentives for farmers have been implemented show higher rates of yield and profitability growth. Conversely, in areas lacking such programmes, there is a decline in productivity and a low level of private investor engagement. Overall, the analysis confirmed that achieving stable growth of the agro-industrial complex requires not only an increase in the total volume of investments but also a revision of their structure. Priority should be given to the introduction of innovative technologies, the development of export-oriented sectors, and improving the efficiency of financial resource use through greater transparency in management decisions. Such an approach would foster more balanced regional development and enhance the competitiveness of Kyrgyzstan's agro-industrial complex in international markets. To identify the key strengths, weaknesses, opportunities, and threats of Kyrgyzstan's agro-industrial complex, a SWOT analysis was conducted, serving as a tool to assess the sector's investment potential (Table 2).

***Table 2**. SWOT analysis of the investment climate of the agro-industrial complex of Kyrgyzstan*

Strengths	Weaknesses
▪ significant natural potential, including fertile land and water resources; ▪ a large proportion of the population employed in agriculture, which provides an available workforce; ▪ orientation towards the production of environmentally friendly products that are in demand on the international market.	▪ low level of mechanisation and outdated equipment; ▪ limited access to financing for small and medium-sized farmers; ▪ imperfect infrastructure: problems with logistics, storage and processing of products; ▪ high level of bureaucracy and corruption, which complicate investment processes.
Opportunities	**Threats**
▪ attracting international investors through tax breaks and the creation of special agricultural zones; ▪ introducing innovative technologies to increase productivity; ▪ expanding the export of agricultural products to international markets; ▪ using grants and programs of international organisations to develop the industry.	ᴍclimate change, which negatively affects crop yields and water supply; ▪ instability of the economic and political situation in the country; ▪ high competition from neighbouring countries, which have better infrastructure capabilities; ▪ lack of a long-term state strategy for the development of the agro-industrial sector.

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

The strengths of Kyrgyzstan's agro-industrial complex provide a foundation for further development, while its weaknesses significantly constrain investment potential. Successful exploitation of available opportunities, particularly through the introduction of modern technologies and the expansion of cooperation with international partners, could contribute to overcoming existing threats. At the same time, it is essential to consider environmental challenges, which remain among the key risks to the stability and long-term sustainability of the agro-industrial sector. Kyrgyzstan's agro-industrial complex accounts for approximately 20% of the country's gross domestic product and provides over 40% of jobs in rural areas (National Statistical Committee of the Kyrgyz Republic, n.d.). Despite its considerable potential, the sector faces serious challenges that hinder investment attraction. These challenges are multifaceted and encompass technological, financial, institutional, and environmental dimensions.

One of the key problems facing the sector is its technological backwardness. The majority of agro-industrial enterprises continue to rely on outdated equipment, with only approximately 27% utilising modern machinery. This significantly undermines production efficiency, increases operational costs, and complicates the processes of product processing and storage. As a result, product losses due to inefficient storage reached 35% of the total harvest in 2024. The insufficient adoption of modern agricultural technologies – such as precision agriculture, automated farm management systems, digital field monitoring, and the use of biotechnologies – further reduces the competitiveness of Kyrgyz agricultural products in international markets. This issue is particularly critical in the context of increasing global integration, where international product quality standards are becoming stricter and consumers increasingly demand environmentally friendly and certified products.

This technological lag also limits the potential for expanding Kyrgyzstan's export capacity. Due to the low quality and limited processing of agricultural produce, local farmers are often forced to sell their products at reduced prices, thereby lowering the overall profitability of the sector. Furthermore, the lack of access to modern equipment and advanced technologies diminishes the resilience of agricultural enterprises to climate change impacts, such as droughts and sudden frosts, which result in substantial crop losses. Technological backwardness also negatively affects the investment climate: international investors are reluctant to invest in enterprises that are unable to ensure high production standards and effective management practices. To address this issue, it is essential to develop a clear strategy for the modernisation of the agro-industrial complex, focusing on improving access to modern technologies, supporting scientific research in agriculture, and creating favourable conditions for both foreign and domestic investment. For example, in Uzbekistan, the government introduced a programme to subsidise farmers for equipment modernisation, which led to a 40% increase in agricultural productivity over five years. Kyrgyzstan should consider adopting a similar approach.

Financial barriers also play a significant role in constraining the investment process. Small and medium-sized farmers face substantial difficulties in accessing credit due to high interest rates and stringent banking requirements. The lack of long-term financing options and the prevalence of high credit rates (ranging from 10% to 24% per annum) severely limit opportunities for modernising production facilities and adopting innovations (Pomerlyan & Belitski, 2023). State subsidies currently reach less than 15% of farmers, and the absence of grant programmes aimed at agricultural development further exacerbates this problem. Institutional barriers, such as bureaucracy, corruption, and weak legal frameworks, significantly hinder the attraction of both domestic and foreign investment. According to the Doing Business 2020 ease of doing business ranking, Kyrgyzstan is ranked 80th, whereas Uzbekistan holds the 69th position and Azerbaijan ranks 34th. This suggests that the regulatory environment for entrepreneurship in Azerbaijan is more favourable compared to Uzbekistan and Kyrgyzstan. Higher rankings typically indicate more streamlined procedures for starting a business, obtaining permits, and conducting commercial activities. Kyrgyzstan should consider implementing reforms aimed at improving its business climate, drawing on the experiences of neighbouring countries. The unsatisfactory level of legal regulation creates unstable investment conditions, which deter potential investors, particularly from the international community. Furthermore, insufficient transparency in the management of investment projects increases risks for investors, as the absence of clear rules and effective control mechanisms heightens the likelihood of fund misappropriation and delays in project implementation.

The underdevelopment of market infrastructure, including logistics, storage, and processing facilities, also limits the full realisation of investment projects. The uneven distribution of infrastructure across regions means that in some areas the essential conditions for the efficient transportation and storage of agricultural products are lacking. This situation leads to an increase in transportation costs by 15-20%. Additionally, the lack of a developed network of processing enterprises reduces the added value of agricultural products, thereby lowering farmers' profits by an average of 25%. Additionally, institutional barriers limit small and medium-sized farmers' access to government support programmes and financial instruments, such as loans and subsidies. In many cases, the application process for such programmes is overly complex, which reduces their effectiveness and limits the participation of potential beneficiaries. The absence of a unified database and a transparent system for monitoring investment flows also creates significant obstacles to evaluating the effectiveness of already implemented projects.

An example of a government initiative aimed at financing the agro-industrial complex is the "Agricultural Financing-13" project, approved for 2025. This programme provides loans at an annual interest rate of 10%, with a total allocated amount of 4,092,769,440 soms. The implementation period is set at 36 months for enterprises engaged in livestock, crop production, and water-saving irrigation technologies, and 84 months for farmers requiring financing through the leasing of agricultural machinery. This programme has been in operation for over ten years, and although there were initial plans to terminate it in 2025, a decision was made to extend its duration, which underscores its significance for the development of the agricultural sector. Nevertheless, despite substantial allocated funds, small farmers continue to face difficulties in accessing these resources due to persistent administrative and procedural barriers. Environmental challenges also play a crucial role in shaping the investment climate. Climate change is already exerting a significant impact on the agricultural sector: over the past decade, the average annual temperature in Kyrgyzstan has increased by 1.2°C, and the number of dry periods has risen by 30%. This has resulted in a 15% reduction in water resources and a marked decline in wheat and barley yields in several regions. For instance, in Batken region, a 20% decrease in grain yields was recorded in 2022 compared to 2015 (National Statistical Committee of the Kyrgyz Republic, n.d.).

These factors not only reduce overall agricultural output but also complicate long-term investment planning due to the high degree of uncertainty regarding natural conditions. Moreover, the increasing frequency of extreme weather events – such as heavy rainfall, frosts, and hail – causes substantial production losses. For example, in 2021 alone, hail damage in Chui region was estimated at over 250 million soms, significantly undermining the financial stability of local farms. The low level of adaptation to these changes increases the vulnerability of Kyrgyzstan's agro-industrial complex to external factors, making it less attractive to potential investors. Currently, only 18% of agricultural land in the country has access to modern irrigation systems, and more than 40% of irrigation canals require repair or reconstruction. This significantly limits farmers' capacity to cope with climate-related challenges. For instance, within the framework of the "Rehabilitation of Irrigation Systems in the Fergana Valley" project, supported by the World Bank during 2021-2023, more than 200 km of irrigation canals were repaired, enabling increased productivity on approximately 15,000 hectares of agricultural land. Nevertheless, the scale of such initiatives remains insufficient to ensure the long-term sustainability of the agricultural sector.

Furthermore, investments in environmentally sustainable technologies remain at a low level. For example, the share of land under drip irrigation does not exceed 3% of the total agricultural area, whereas in neighbouring Kazakhstan this figure reaches 12% (Food and Agriculture Organization, n.d.). Programmes to support the cultivation of drought-resistant crops, the development of agroforestry, and the use of agro-industrial waste for fertiliser production are also still limited. In addition, the absence of comprehensive government programmes for climate change adaptation and the insufficient involvement of international organisations further exacerbates existing problems. For instance, in 2022, Kyrgyzstan received only USD 4 million in international financial assistance for environmental projects, whereas neighbouring Uzbekistan attracted over USD 50 million from the World Bank and the Asian Development Bank. This disparity is particularly critical in light of the growing global demand for environmentally friendly products, which require adherence to stringent standards of sustainable production.

Coordination problems between government agencies, the private sector, and international organisations also remain significant. For example, the "Green Economy for Sustainable Development" project, which aimed to finance the modernisation of irrigation systems, faced serious implementation challenges: due to bureaucratic obstacles and the absence of a unified coordination centre, only 35% of the allocated funds were utilised during the first year of implementation. Such a lack of coordination leads to the duplication of efforts, inefficient use of resources, and a lack of synergy in addressing key challenges within the agro-industrial complex. Moreover, uncertainty for potential investors is aggravated by conflicting regulations and inconsistent government policies. For instance, in 2023, the Kyrgyz government introduced changes to the tax regime for agribusiness, which compelled more than 15% of farm enterprises to revise their business models or temporarily suspend operations. In addition, international organisations – which could serve as important sources of funding and expert support – currently lack a clear platform for interaction with the government and the private sector, limiting their participation in strategic initiatives. To improve this situation, it is necessary to establish transparent mechanisms for monitoring and evaluating the implementation of investment projects, enabling the timely identification of problems and the adoption of corrective measures.

All these issues create additional risks for investors, thereby reducing overall trust in the country's institutional system. Addressing these challenges requires a comprehensive approach, including the improvement of legislation, increased public investment in sustainable agricultural practices, and more active engagement with international donors. Thus, the main barriers to attracting investment in Kyrgyzstan's agro-industrial complex are technological backwardness, limited access to financial resources, institutional shortcomings, and environmental challenges. The following section will present recommendations for overcoming these barriers and creating a favourable investment climate. Based on the analysis conducted and the identified problems and barriers to attracting investment in Kyrgyzstan's agro-industrial complex, a set of practical recommendations has been developed to address these issues and enhance the sector's overall efficiency. These recommendations are aimed at both the public sector and private businesses, including potential domestic and foreign investors, and are designed to promote a comprehensive and coordinated approach to the development of the agricultural sector.

The primary task for the state is to create a favourable institutional environment, which includes simplifying administrative procedures for investors, increasing transparency of processes, and reducing the level of corruption. It is crucial to develop a national programme for the modernisation of the agro-industrial complex, which should incorporate subsidies for the purchase of modern equipment, preferential loans for farmers, and financing of innovative projects within the sector. Another key priority is infrastructure development. Investments are required to create and modernise irrigation systems, logistics centres, storage facilities, and processing plants. Such improvements would significantly reduce crop losses, enhance product quality, and expand export opportunities. To raise the technological level of the agro-industrial complex, it is recommended to establish specialised training programmes for farmers and agro-industry workers, focusing on the application of modern agricultural technologies. In addition, the creation of state or public-private research centres dedicated to the development of innovations specifically adapted to Kyrgyzstan's climatic conditions is essential.

From the private sector perspective, it is important to promote cooperation among small and medium-sized farmers, which would enable more efficient use of resources, knowledge sharing, and improved access to financing. Investors, in turn, should focus on long-term projects that consider not only economic benefits, but also social and environmental impacts. This approach would help to foster a positive perception of investors within local communities and support the sustainability of investments. International organisations can play a significant role in the development of the agro-industrial complex by providing grants, technical assistance, and facilitating Kyrgyzstan's integration into global agricultural markets. An important avenue for development is also the attraction of international expertise and the adaptation of successful practices from other countries to the local context. Table 3 systematises practical recommendations for the development of Kyrgyzstan's agro-industrial complex.

***Table 3**. Comparison of international practices for attracting investment in agro-industry*

Sector	Recommendations	Expected results
Public policy	Simplification of administrative procedures and reduction of corruption	Improving the investment climate and increasing transparency
	Development of a state programme for the modernisation of the agricultural sector: subsidies, preferential loans, financing of innovative projects	Increasing investments, modernising equipment, and enhancing productivity
	Investments in infrastructure: irrigation systems, logistics centres, warehouses, facilities for product processing	Reducing crop losses, improving product quality, and expanding exports
	Introduction of incentives for investors: tax breaks, support for public-private partnerships	Attracting international and domestic investors
Financing	Expanding access to credit resources for small and medium-sized farmers	Increasing investment in production modernisation
	Introduction of preferential financial instruments, such as long-term loans and grants	Expanding the availability of investments for farmers
Cooperation	Development of farmers' cooperatives to share resources and obtain more favourable financing conditions	Enhancing the efficiency of resource use and reducing costs
	Establishment of cooperation between the state, the private sector, and international organisations	Developing a coordinated industry strategy and incorporating international experience
Ecology	Introduction of sustainable agricultural practices to preserve natural resources	Reducing the impact of climate change on yields and promoting environmental sustainability
	Use of agro-industrial waste for the production of fertilisers or energy	Reducing costs and increasing production efficiency

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

Table 3 summarises the main areas of reform and specific measures that can be implemented to overcome existing barriers and ensure the sustainable development of Kyrgyzstan's agro-industrial complex. In conclusion, the implementation of these recommendations will enhance the efficiency of Kyrgyzstan's agro-industrial complex, increase its attractiveness to investors, ensure sustainable economic growth, and contribute to improving the living standards of the rural population. These measures will lay the foundation for the development of an agricultural sector that is adapted to modern challenges and opportunities, fostering long-term resilience and competitiveness.

DISCUSSION

The agro-industrial complex of Kyrgyzstan is a strategically important sector of the economy; however, low investment levels, outdated infrastructure, and insufficient implementation of modern technologies remain key challenges to its development. Similar conclusions are drawn in the work of J.G. Djokoto (2021), who argues that although foreign investment holds significant potential for transforming the agricultural sector, it may crowd out domestic investment if there is insufficient integration and coordination. Effective attraction of investments into Kyrgyzstan's agricultural sector is critical for increasing productivity, modernising infrastructure, and adopting innovative approaches. This conclusion is consistent with the research of T. Joltreau (2024), who highlights the positive impact of state grants and subsidies on the development of precision agriculture in European Union countries. The adoption of similar approaches in Kyrgyzstan could contribute to enhancing the competitiveness of its agricultural products.

Furthermore, the integration of circular economy principles into the agro-industrial complex demonstrates significant potential (Golub *et al.*, 2020). As examples from the Netherlands and Denmark show, the use of agricultural waste for energy and fertiliser production increases the efficiency of production processes and reduces the environmental impact. Similar concepts are explored by A. Vastolo *et al.* (2022), who highlight the substantial benefits of using agro-industrial waste for feed production. Such practices could be adapted to Kyrgyzstan's specific conditions, taking into account local environmental and economic characteristics. At the same time, the study by X. Xu and Y. Yan (2014) demonstrates that public investment, if not accompanied by proper planning and coordination, can crowd out private investment. This issue is particularly relevant for Kyrgyzstan, where the attraction of private capital should play a key role in transforming the agro-industrial complex.

The introduction of circular economy principles in the agro-industrial sector represents a crucial element for increasing production efficiency and reducing environmental impact. Research confirms that integrating circular practices, such as the use of biogas plants for processing agricultural waste, contributes to diversifying farmers' income sources and provides additional opportunities for economic growth. For instance, in Germany, a significant proportion of farms generate income from the sale of biogas and processed organic fertilisers, which allows for more efficient resource use. Similar conclusions are presented in the works of A. Vastolo *et al.* (2022), who emphasise that the use of agro-industrial waste for feed purposes and energy production enhances the economic profitability of farms. Beyond economic benefits, the circular economy also addresses key environmental issues, including the reduction of greenhouse gas emissions, prevention of soil degradation, and preservation of water resources (Khryk *et al.*, 2024). These aspects are particularly critical for regions facing severe natural challenges, such as Kyrgyzstan, where water scarcity and soil quality issues limit agricultural productivity. In this context, the experience of the Netherlands and Denmark can serve as an important model for adaptation, as confirmed by the studies of B.I. Koura *et al.* (2024).

It has been identified that different countries apply unique approaches to the development of their agro-industrial sectors, depending on their natural, economic, and social conditions. For example, in EU countries, as noted by T. Joltreau (2024), government subsidies and grants are directed towards supporting innovations such as precision agriculture, which significantly enhances the competitiveness of the agricultural sector. In the USA and Canada, public-private partnerships facilitate the rapid integration of new technologies, aligning with the findings of M. Böhme (2020), who emphasises the importance of strategic cooperation between government and business in implementing large-scale agricultural projects.

For Kyrgyzstan, adapting such approaches requires careful consideration of local specificities, including infrastructure constraints, low levels of mechanisation, and insufficient government support. As highlighted by N.U. Wani *et al.* (2024), it is essential to take into account the potential for regional integration and diversification of investment sources to support the agro-industrial complex under the specific conditions of Central Asia. Kyrgyzstan's agro-industrial sector plays a crucial role in employment and food security, but its development is hindered by numerous structural challenges. The analysis confirms that low levels of mechanisation, limited infrastructure, and insufficient adoption of modern technologies represent the main barriers to increasing productivity in the sector. These conclusions are consistent with the study by V. Yarashevich (2020), who notes that countries of the Eurasian Economic Union, to which Kyrgyzstan belongs, are marked by significant disparities in agricultural development due to uneven investment distribution and infrastructure limitations.

At the same time, despite the low level of investment activity, international organisations and grant programmes play an important role in providing financing for Kyrgyzstan's agro-industrial complex (Sakkaraeva & Kumashev, 2024). As noted by J. Rodenbiker (2022), infrastructure projects, such as initiatives under the framework of the "Green Silk Road", can serve as significant stimuli for regional economic development. However, as the experience of other countries demonstrates, the effectiveness of such initiatives depends largely on the state's ability to create transparent mechanisms for resource management and adapt them to local conditions. A comparison with neighbouring countries, such as Kazakhstan and Uzbekistan, reveals that the level of mechanisation in Kyrgyzstan's agricultural sector remains considerably lower. For instance, in Kazakhstan, due to substantial investments in technology and strong state support, agricultural productivity is significantly higher (Manatovna *et al.*, 2023). This comparison underscores that for Kyrgyzstan, the modernisation of production processes must be a priority task to ensure the competitiveness of the sector at the regional level.

Particular attention should also be given to access to financial resources, as high interest rates and insufficient financial support severely limit farmers' capacity to modernise their production. As evidenced by V. Yarashevich (2020), overcoming these constraints requires the development of low-interest credit programmes and the promotion of cooperation between the state and the private sector. An analysis of the dynamics of investment in the agro-industrial complex of Kyrgyzstan over the past ten years has shown that although the volume of investments is gradually increasing, their overall level remains insufficient to achieve a technological breakthrough. The findings confirm that priority is still given to supporting traditional sectors, such as crop production and livestock, while innovative areas are developing slowly. This trend aligns with the conclusions of A. MacMillan (1991), who emphasises that limitations in the design of investment programmes and a focus on short-term goals significantly hinder progress in the agricultural sector.

Although state programmes and international grants continue to play an important role in supporting Kyrgyzstan's agro-industrial sector, their impact is limited by the weak effectiveness of management structures and insufficient integration of private investment. As highlighted by A. Vilas-Franquesa *et al.* (2023), the introduction of innovations, particularly in the field of agro-industrial by-product utilisation, is a key avenue for enhancing the sectors efficiency while also addressing environmental challenges. However, in Kyrgyzstan, such technologies remain in the early stages of limited implementation, due to low levels of awareness and insufficient state support. Furthermore, the uneven distribution of investments across regions remains a serious challenge, exacerbating socio-economic inequalities (Krylova *et al.*, 2023). This finding is consistent with the study of V. Zubok *et al.* (2021), which emphasises that structural disparities in regional development significantly reduce the overall effectiveness of state policy. In Kyrgyzstan, regions with better-developed infrastructure receive a disproportionately higher share of investments, while less developed areas remain largely neglected.

The direct relationship between investment volumes and agricultural productivity is clearly evident in regions where access to modern technologies and irrigation systems enables significant increases in yields. At the same time, stagnation is observed in areas with limited access to financing and low levels of mechanisation, confirming the critical importance of integrating innovative approaches. As A. MacMillan (1991) highlights, investments in infrastructure modernisation are essential for ensuring the sustainable development of the agro-industrial sector. The results of this study also underline the need to develop a comprehensive strategy that considers not only the total volume of investments, but also their structure and targeted allocation. Furthermore, the SWOT analysis conducted in this study identified key aspects of the investment climate within Kyrgyzstan's agro-industrial complex. While substantial natural potential and an available labour force create favourable conditions for industry development, low levels of mechanisation, inadequate infrastructure, and restricted access to finance remain serious constraints. As observed by S.K. Wegren and F. Nilssen (2021), such challenges are characteristic of economies in transition, where structural barriers significantly hinder the attraction of investment.

The direct relationship between investment volumes and agricultural productivity is clearly evident in regions where access to modern technologies and irrigation systems enables significant increases in yields. At the same time, stagnation is observed in areas with limited access to financing and low levels of mechanisation, confirming the critical importance of integrating innovative approaches. As A. MacMillan (1991) highlights, investments in infrastructure modernisation are essential for ensuring the sustainable development of the agro-industrial sector. The results of this study also underline the need to develop a comprehensive strategy that considers not only the total volume of investments, but also their structure and targeted allocation. Drawing on international experience, particularly in the field of agro-industrial waste processing innovations, as noted by A. Vilas-Franquesa *et al.* (2023), could significantly enhance both the efficiency and profitability of the sector. Furthermore, the SWOT analysis conducted in this study identified key aspects of the investment climate within Kyrgyzstan's agro-industrial complex. While substantial natural potential and an available labour force create favourable conditions for industry development, low levels of mechanisation, inadequate infrastructure, and restricted access to finance remain serious constraints (Kerimkulova *et al.*, 2023). As observed by S.K. Wegren and F. Nilssen (2021), such challenges are characteristic of economies in transition, where structural barriers significantly hinder the attraction of investment.

Institutional barriers and environmental challenges continue to pose significant obstacles to the development of Kyrgyzstan's agro-industrial complex. Complex procedures for applying for state support and the absence of a transparent system for monitoring investment projects limit small and medium-sized farmers' access to financial resources, including loans and subsidies. Similar issues are identified by J.G. Díaz-Cueva and R. Guevara-Moncada (2023), who emphasise that ineffective management and lack of coordination in supporting small businesses in the agro-industrial sector led to reduced competitiveness and financial sustainability of the sector. Environmental challenges, including climate change, water scarcity, and frequent extreme weather events, introduce additional risks for agriculture (Oliynyk *et al.*, 2021). The lack of modern water management and irrigation systems, along with ongoing soil degradation, severely constrains farmers' capacity to adapt to these changes. As T. Salerno (2014) notes, effective natural resource management and the implementation of adaptation practices are crucial for ensuring sustainable agricultural development, especially in the context of growing global demand for environmentally friendly products. Investment in innovative, environmentally sustainable technologies, such as drip irrigation, cultivation of drought-resistant crops, and the use of agro-industrial waste for fertiliser production, remains at a low level. The absence of incentives to attract investments in these areas creates a vicious cycle, limiting the sector's capacity to address climate risks and enhance productivity. A similar situation is observed in other countries, where, according to T. Salerno, imperfect investment regulation and insufficient state support hinder the development of the agro-industrial sector.

Coordination between government agencies, the private sector, and international organisations remains weak, leading to the inefficient use of resources and duplication of efforts. This is supported by the findings of J.G. Díaz-Cueva and R. Guevara-Moncada (2023), who argue that the absence of an integrated development strategy creates uncertainty for investors and significantly complicates the implementation of long-term projects. Creating a favourable institutional environment is a key condition for attracting investment. As T. Joltreau (2024) notes, the introduction of transparent governance mechanisms and support for investors through tax incentives significantly increase investment activity. In Kyrgyzstan, the implementation of measures such as simplifying administrative procedures and developing state support programs for farmers can provide the necessary basis for attracting both domestic and international investors.

Infrastructure modernisation is another important area of reform. Investments in irrigation systems, logistics centres and processing facilities will reduce crop losses and improve product quality, which, in turn, will contribute to expanding export potential. Similar examples of effective infrastructure solutions are given in the study by M. Benegiamo (2020), which emphasises the importance of integrating logistics chains in the development of the agro-industry. The creation of training programs and research centres is recommended to introduce modern technologies and improve the skills of agricultural workers. Creating a favourable institutional environment is a key condition for attracting investment. As J.R. Caradus (2022) highlights, the introduction of transparent governance mechanisms and support for investors through tax incentives significantly increase investment activity. In the context of Kyrgyzstan, the implementation of measures such as simplifying administrative procedures and developing state support programmes for farmers can establish a necessary foundation for attracting both domestic and international investors.

Infrastructure modernisation represents another critical area of reform. Investments in irrigation systems, logistics centres, and processing facilities will help to reduce crop losses and improve product quality, thereby enhancing the country's export potential. Similar examples of effective infrastructure development are provided in the study by M. Spies (2021), which emphasises the importance of integrating logistics chains for the successful development of the agro-industrial sector. Furthermore, the creation of specialised training programmes and research centres is recommended to facilitate the adoption of modern technologies and to improve the skills of agricultural workers. As noted by A. Mahmoud *et al.* (2024), the development of technologies adapted to local conditions significantly enhances resource efficiency and ensures environmental sustainability. In Kyrgyzstan, such initiatives should focus on addressing specific challenges related to climate change and soil degradation, thereby supporting the long-term resilience and productivity of the agro-industrial complex.

CONCLUSIONS

Kyrgyzstan's agro-industrial complex plays a key role in the national economy, accounting for approximately 20% of gross domestic product and providing over 40% of rural employment. However, its development is constrained by technological backwardness, limited access to finance, institutional barriers, and environmental challenges. Although overall investment in the sector has increased in recent years, both the structure and efficiency of these investments remain problematic. In 2023, total investment in the agro-industrial sector amounted to USD 7.3 million, but its distribution was uneven. For instance, USD 2.8 million was invested in Bishkek, while the Chui region, despite demonstrating high productivity indicators, received only USD 225,000.

Technological backwardness continues to be one of the most pressing issues, resulting in high product losses, which reach up to 35% of the harvest. The lack of access to modern technologies also reduces the resilience of the agricultural sector to climate change, which is already having a marked impact on yields. Over the past decade, Kyrgyzstan's average annual temperature has increased by 1.2°C, while the frequency of droughts has risen by 30%. These changes have led to a 15% reduction in water resources and a decline in the yields of key crops, such as wheat and barley. Furthermore, financial barriers significantly constrain farmers' capacity to invest in modernisation. High credit rates, ranging from 10% to 24% per annum, make production modernisation unaffordable for most small and medium-sized agricultural enterprises. In addition, state subsidies currently reach less than 15% of farmers, which is substantially lower than the level of support provided in neighbouring countries.

Weak infrastructure remains another critical factor holding back the development of Kyrgyzstan's agro-industrial sector. Currently, only 18% of agricultural land has access to modern irrigation systems, while over 40% of irrigation canals are in critical condition and require reconstruction. For example, the Fergana Valley Irrigation Rehabilitation Project successfully modernised 200 km of irrigation canals, leading to increased productivity on 15,000 hectares of agricultural land. However, such measures remain insufficient to ensure the sustainable development of the sector on a national scale. Institutional barriers, including high levels of bureaucracy and corruption, pose additional challenges for attracting investment. According to the Doing Business 2020 ranking, Kyrgyzstan is ranked 80th, while Uzbekistan and Azerbaijan are ranked 69th and 34th, respectively. This reflects a less favourable business climate in Kyrgyzstan, which significantly reduces its attractiveness to potential investors. Moreover, the inconsistency of state policy and frequent changes in tax legislation compel agricultural enterprises to repeatedly revise their business strategies, thereby slowing down the sector's overall development.

An analysis of the regional distribution of investments further reveals significant disparities in the efficiency of their utilisation. For instance, in Naryn region, investments rose from USD 0.2 thousand to USD 49.7 thousand in 2023, yet agricultural production declined, indicating inefficient resource management. In contrast, the Chui region, despite receiving relatively modest investment volumes, continues to demonstrate stable productivity growth, confirming its higher investment efficiency. To ensure the sustainable development of Kyrgyzstan's agro-industrial complex, the implementation of comprehensive reforms is essential. Improving access to financing, reducing credit rates to 5-7% per annum, expanding state subsidies for modernisation from 15% to 30% of farms, and simplifying administrative procedures will contribute significantly to attracting both domestic and foreign investors. Investments in technological innovations, including precision agriculture, automated farm management systems, and drip irrigation, should be increased from the current 3% to 15% of total capital investments in the sector. A critical priority remains the modernisation of infrastructure, particularly the reconstruction of at least 500 km of irrigation canals over the next five years, which is expected to substantially improve agricultural yields. Overall, the implementation of these proposed measures will enhance the efficiency of Kyrgyzstan's agro-industrial complex, increase its attractiveness to investors, boost the competitiveness of agricultural products in international markets, and contribute to the sustainable economic development of the country.

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CONFLICT OF INTEREST

None.

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Оцінка впливу інвестицій на продуктивність агропромислового комплексу Киргизстану

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Анотація. Підвищення ефективності агропромислового комплексу Киргизстану є ключовим завданням для забезпечення продовольчої безпеки та економічної стабільності країни. Метою даного дослідження була оцінка впливу інвестицій на продуктивність агропромислового комплексу Киргизстану, зокрема шляхом визначення ефективності їх розподілу, виявлення бар'єрів для залучення капіталу та окреслення перспективних напрямів розвитку галузі. У дослідженні проаналізовано дані за період 2014-2024 рр., зокрема регіональний розподіл інвестицій, рівень механізації, обсяги виробництва та впровадження інноваційних технологій. Виявлено, що частка інвестицій у сільське господарство в середньому становить 12,4 % від загального обсягу капітальних інвестицій в країні, проте їх розподіл нерівномірний. Так, у Чуйській області інвестиції досягли 492,9 тис. доларів США у 2020 році, тоді як у Наринській області вони склали лише 0,2 тис. доларів США. У той же час, продуктивність зросла найбільш суттєво в регіонах з розвиненою інфраструктурою: в Джалал-Абадській області виробництво зросло з 1631,1 тис. тон у 2020 році до 1666,9 тис. тон у 2023 році. Інвестиції в зрошувальні системи призвели до зростання врожайності на 18,7 %, а модернізація технологічного обладнання сприяла зниженню втрат продукції на 12,4 %. Аналіз показав, що лише 27,5 % господарств мають доступ до сучасних технологій, що значно обмежує потенціал зростання продуктивності. SWOT-аналіз визначив основні виклики: зміна клімату, бюрократичні бар'єри та слабка координація між державою та приватним сектором. Практична цінність дослідження полягає у розробці рекомендацій щодо створення сприятливого інвестиційного клімату, підвищення ефективності фінансування, стимулювання державно-приватного партнерства та впровадження підходів циркулярної економіки. Запропоновані заходи сприятимуть сталому розвитку агропромислового комплексу Киргизстану, підвищенню продуктивності та розширенню експортного потенціалу країни

Ключові слова: економічний розвиток; сільськогосподарське виробництво; підвищення врожайності; виробничий цикл; інноваційні технології

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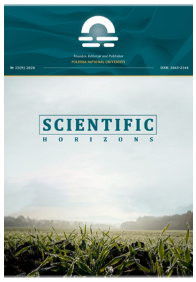

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Impact of decentralisation and war on land cover in the Zhytomyr Region of Ukraine

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Abstract. This study aimed to examine land cover transformations in the Zhytomyr Region of Ukraine in response to decentralisation and war. It focused on assessing how shifts in local governance and the full-scale invasion have influenced land use dynamics, particularly changes in agricultural expansion, reductions in natural land cover types, and fluctuations in forested areas and water bodies. The study analysed land use patterns from 2016 to 2023 using Google Earth Engine's Dynamic World V1 data, combining geospatial data with qualitative semi-structured interviews. The

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results showed that the decentralisation process launched in 2014 has strengthened local self government and empowered communities to manage land resources. This period was characterised by the expansion of agricultural land and the reduction of natural land cover types, such as grasslands and scrublands. By contrast, the full-scale invasion that began in 2022 resulted in a shift in land use priorities due to labour shortages, rising resource costs, and limited access to markets, which led to shrinking agricultural land and partial restoration of natural ecosystems. Particularly significant fluctuations are noted in forested areas and water bodies because of energy demands and restrictions on activities in conflict zones. The findings underscored the need for adaptive land resource management in the context of socio-economic and political challenges, as well as the importance of land cover monitoring for regional planning and the sustainable use of natural resources. By analysing geospatial data from Google Earth Engine's Dynamic World V1 and qualitative semi-structured interviews, the study identified key trends from 2016 to 2023, evaluates the socio-economic and political drivers behind these changes, and highlights the challenges of adaptive land resource management in the face of instability. The findings contribute to a better understanding of the implications of land cover changes for regional planning and sustainable land use strategies

Keywords: land use change; GIS land monitoring; socio-economic impact; territorial reform; war effects

INTRODUCTION

Land cover analysis is a crucial tool for studying structural socio-economic transformations across different territories, ranging from local communities and districts to regional and national levels. In the context of decentralisation and armed conflict, the effective management of land resources has become particularly important. Decentralisation empowers communities to autonomously manage their territories, influencing land use patterns, infrastructure development, and agricultural expansion. At the same time, war introduces additional challenges, such as the disruption of economic networks, loss of human capital, and shifting land use priorities. Therefore, studying land cover changes in this context is essential for understanding the dynamics of socio-economic processes, their impact on regional development, and the formulation of policies for the sustainable use of land resources.

In Ukraine, the decentralisation process was officially launched in 2014 with the approval of the Concept of Reforming Local Self-Government and Territorial Organisation of Power in Ukraine, as outlined in Order No. 333-p of the Cabinet of Ministers of Ukraine (2014). The main goal of the reform was to strengthen local self-government and devolve powers and resources from the central government to the regions (OECD, 2018). This reform has contributed to improving the quality of public service delivery, increasing the financial autonomy of communities, and strengthening local democracy (Romanova & Umland, 2021). Notably, the amalgamation of territorial communities (ATCs) has influenced approaches to the management of socio-economic territories at the community, district, and regional levels, allowing for more efficient resource management and regional development. This has been particularly significant in enhancing Ukraine's resilience in times of war (Harus & Nivyevskyi, 2020).

On 24 February 2022, Russia launched a full-scale military invasion of Ukraine, resulting in widespread destruction, thousands of deaths, and the displacement of millions of people. This invasion had a profound impact on the territorial structure and governance of Ukraine, disrupting the functioning of local authorities, leading to the occupation of territories, altering land use, and forcing Ukraine to adapt its governance structures to wartime conditions (OCHA, 2023; UNHCR, 2024). Research on land use change traditionally relies on spatial data analysis and the identification of key socio-economic drivers. Many studies focus on urbanisation, demographic shifts, and economic development as primary factors shaping land cover transformations. For example, Zh. Yang *et al.* (2020) examined land use change in rural China between 1995 and 2015, concluding that industrialisation and urban expansion were the dominant forces driving these transformations. Similarly, Q. Xie *et al.* (2023) analysed land cover changes in Wuhan, China, and demonstrated that economic growth and infrastructure expansion contributed to the loss of arable land and an increase in built-up areas.

In the European context, A. Allan *et al.* (2022) conducted a systematic review, emphasising that land use change results from a combination of economic, political, and environmental factors. P. Pyvovar *et al.* (2023) highlighted that land cover transformations have a direct impact on local tax revenues, which is particularly relevant to territorial communities in Ukraine. Their study confirmed that decentralisation has led to improved land resource management, contributing to agricultural land expansion. Meanwhile, J. Wang *et al.* (2021) demonstrated that in China, agricultural land-use changes were closely linked to economic policies and social transformations. M. Kutia *et al.* (2023) investigated land cover changes in Changsha City, China, between 2005 and 2020, employing Landsat time-series satellite images and the Random Forest classification algorithm. Their study demonstrated a substantial increase in urban areas, which expanded from 3.23% to 15.95%, while forest cover declined until

2015, followed by a slight recovery. Cropland remained a dominant land type, peaking at nearly 50% in 2010, whereas water bodies showed little variation. The study confirmed the effectiveness of the applied classification method, highlighting its potential for sustainable urban planning. Similarly, S. Bulygin *et al.* (2021) examined strategies for improving saline and erosion-prone lands in Donetsk Region through prairie restoration. Their findings indicated that introducing salt-tolerant forage grasses significantly enhanced biomass productivity and nutritional value, with an increase in crude protein and essential nutrients. The research underscored the importance of adaptive agricultural practices for restoring degraded lands and ensuring sustainable fodder production.

This study aimed to determine the impact of decentralisation and military conflict on land cover dynamics in the Zhytomyr Region. The analysis focused on changes in the use of agricultural and natural lands, identifying key socio-economic drivers of these transformations between 2016 and 2023, and assessing the challenges associated with land resource management under crisis conditions.

MATERIALS AND METHODS

Study area. Zhytomyr Region is located in the north of the Right Bank of Ukraine, primarily within the Zhytomyr Polissia area (Fig. 1). The administrative centre is the city of Zhytomyr. The region is the fifth largest in Ukraine, covering 29,832 km^2. It extends 170 kilometres from west to east and 230 kilometres from north to south. Zhytomyr Region borders the Rivne, Vinnytsia, and Kyiv regions of Ukraine, as well as the Gomel Region of the Republic of Belarus. The region is situated at the junction of two natural zones: the southern part lies within the forest-steppe zone, while the northern part belongs to the mixed forest zone. The population of the region was 1,179,801 as of 1 January 2022 (SSSU, 2023).

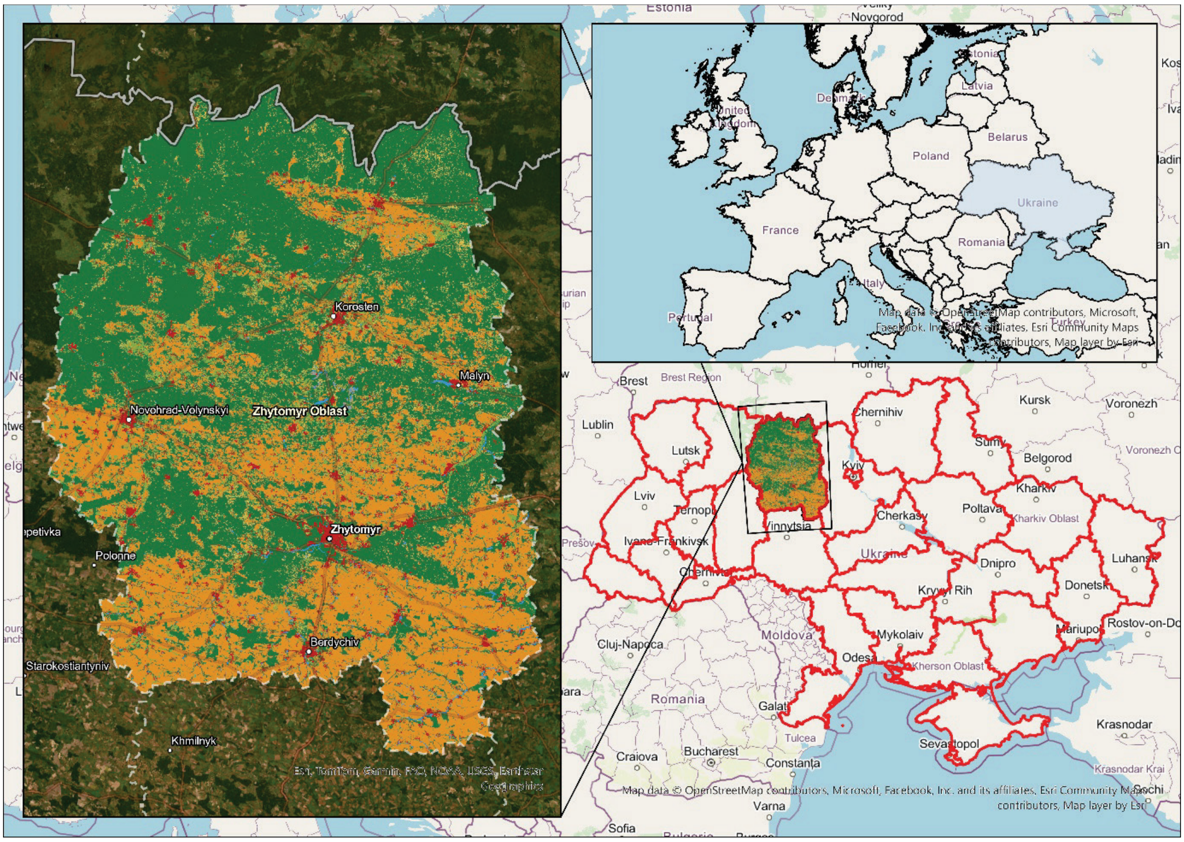

Figure 1. *Geographical location of Zhytomyr Region and its land cover, 2022*
Source: *compiled by the authors based on the method of C. Brown et al. (2022)*

The selection of Zhytomyr Region for this study is based on several important factors. The region encompasses two natural zones – Polissia and Forest-Steppe – offering unique conditions for examining land use change, as the diversity of natural environments influences the structure and dynamics of land cover. Over the past decade, the composition of crops grown in the Zhytomyr Region has shifted towards southern crops, which are not typically cultivated in this region. This trend has sparked interest in investigating the impact of such changes on land use and the local economy. The study was conducted at Polissia National University, enabling the testing of hypotheses and discussions with local experts. This approach ensured a comprehensive understanding of regional conditions and specific land use characteristics. In 2022, Russian troops invaded the Zhytomyr Region, temporarily occupying five villages. This created a unique opportunity to analyse the impact of military operations on land use and land cover dynamics.

Research design. This study adopts a mixed-methods approach that integrates geospatial analysis of land cover changes with qualitative research methods to assess the socio-economic and political drivers of land use transformation in the Zhytomyr Region. The research is structured into three main components:

1. Geospatial analysis of land cover change (2016-2023) using satellite data from Google Earth Engine's Dynamic World V1
2. Quantitative assessment of land use dynamics through geostatistical processing in ArcGIS Pro.
3. Qualitative validation and interpretation of changes via semi-structured interviews with local stakeholders, including community members, local authorities, and land use experts.

The geospatial analysis was conducted across three distinct periods:

- pre-decentralisation (2016-2019) – baseline trends prior to administrative ;
- decentralisation period (2020-2021) – assessment of land use transformation under new governance policies;
- wartime period (2022-2023) – analysis of the impact of military conflict on land cover dynamics.

The analysis focused on land cover trends and growth/decline rates, calculated as the ratio of each land cover category's area in a given year relative to the previous year. The study examined the following land cover categories:

- general land cover trends (overall transformations in land use);
- trees (forested areas and woody vegetation) – assessed for deforestation, afforestation, and stability in coverage;
- crops (agricultural land and cultivated fields) – analysed for expansion, contraction, and shifts in cultivated areas;
- grass (meadows, pastures, and other non-woody vegetation) – studied for natural ecosystem restoration or degradation;
- water, flooded vegetation, bush and scrub (water bodies, wetlands, and transitional vegetation types) – examined for seasonal and long-term variations;
- land cover transitions(detection of changes between different land cover types over time).

By integrating geospatial and qualitative approaches, the study provides a comprehensive understanding of land cover transformations and their socio-economic implications.

Collecting data. In cooperation with the World Resources Institute (WRI), Google provides the so-called "Dynamic World" tool. Dynamic World is an open and freely available dataset that can be used by scientists, governments, and companies (Brown *et al.,* 2022). Datasets for the Zhytomyr Region were generated on Google Earth Engine using GOOGLE/DYNAMICWORLD/V1 for the period 2016-2023. Based on satellite images, Dynamic World provides detailed data on the condition and use of land in real time at a resolution of ten metres. This means that Dynamic World can be used to quantify and analyse land cover conditions and changes in a region over a short period. Dynamic World V1 offers information on the following types of land cover in the so-called "Land Use/Land Cover Classification" (LULCC): water, trees (forested area), grass (meadows), flooded vegetation, crops (arable land), scrubs and bushes, built-up surfaces, bare soil, snow, and ice. Satellite image data for 2016-2023 were downloaded from the Google Earth Engine platform for further analysis of land use changes.

The algorithm for processing data and obtaining results was implemented in ArcGIS (Fig. 2) and consisted of the following steps:

1. Downloading data – Satellite images for 2016-2023 were obtained through the Google Earth Engine platform.
2. Importing tools – Tools from the Data Management Tools and Conversion Tools modules were imported to manage and process geospatial data.
3. Loading data – Raster images for 2016-2023 were imported for further analysis of land use changes.
4. Cropping raster images – The raster images were cropped according to the boundaries of the Zhytomyr Region, ensuring a focus on the study area.
5. Converting of raster data into polygons – The cropped raster images were converted into vector format (polygons) for a detailed analysis of land cover changes.
6. Polygon merging – Polygons were grouped by GRIDCODE values to simplify the data structure and optimise further processing.
7. Adding attribute fields – New fields were added to the attribute table to store information about the territory areas, allowing for quantitative analysis.
8. Intersecting polygons – The spatial intersection of land parcels between 2016-2021 and 2021-2023 was performed to identify and analyse changes in land use.
9. Calculating areas – For each polygon obtained from the intersection, the area in hectares was calculated, enabling a quantitative assessment of the scale of changes.
10. Exporting data – The results were exported to Excel for further statistical analysis and visualisation.

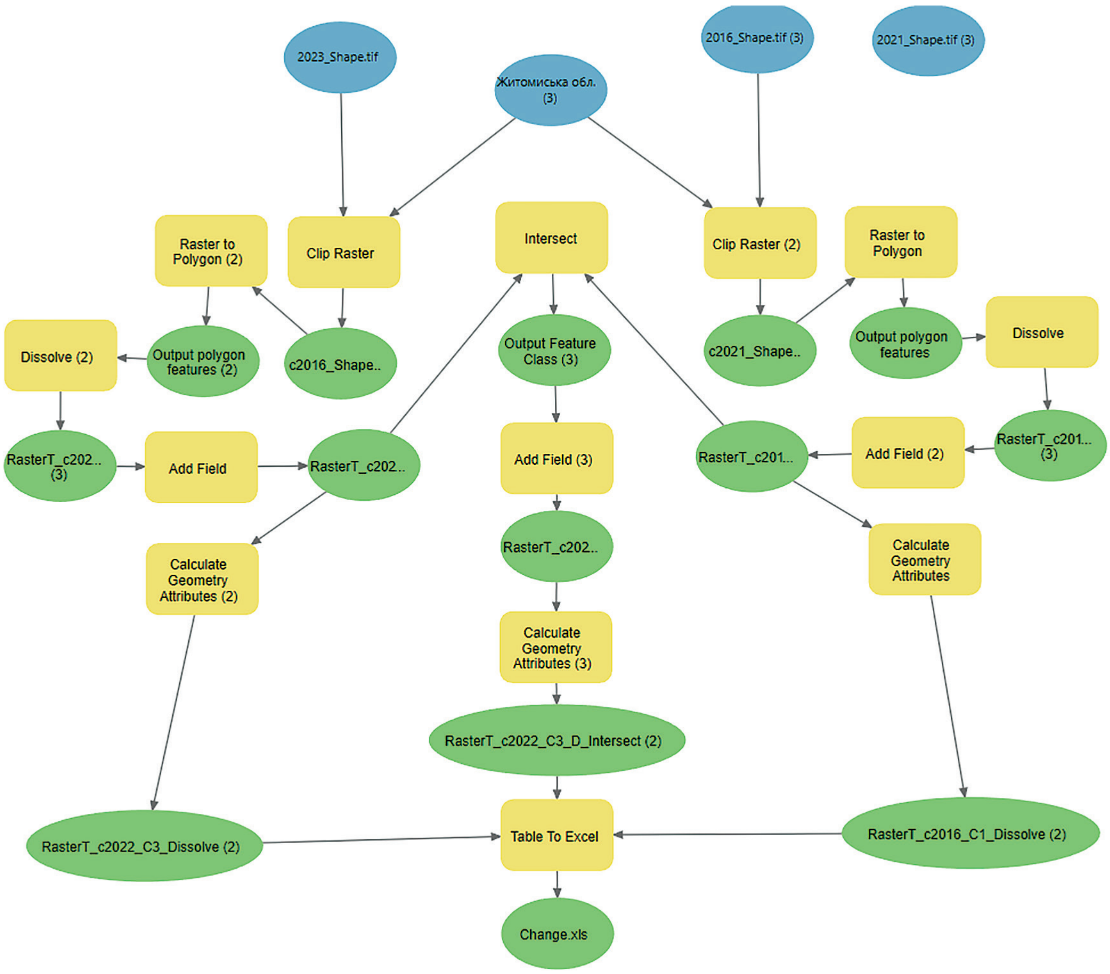

Figure 2. *Algorithmic scheme for determining land cover change in ArcGIS Pro ModelBuilder*
Source: *compiled by the authors*

The GOOGLE/DYNAMICWORLD/V1 dataset was chosen for the analysis because it provides images with a resolution of 10 metres and frequent updates, allowing for a detailed analysis of land cover changes at the level of individual sites. Continuous updates provide access to the most up-to-date data, which is critical for analysing rapid changes caused by decentralisation and military operations. The use of modern machine learning algorithms improves the accuracy of identifying different types of land cover. Integration with Google Earth Engine simplifies the process of data collection and processing, allowing for scalable analysis without loss of quality. In addition, the standardised land cover classification facilitates comparison with other studies and integration with additional data sources.

As part of the study, a series of semi-structured oral interviews were conducted in 36 settlements across the Zhytomyr Region with local residents, representatives of local authorities, and land use experts. The interviews were conducted in person where possible and remotely (via telephone or online platforms) in cases where physical access was restricted due to security concerns. Participation in the study was entirely voluntary, and respondents provided verbal, informed consent before the interview. During the interviews, participants were shown maps and visualised geospatial data, including satellite imagery and land cover change maps, to facilitate discussion and validate the observed transformations. Interviewers provided explanations of the detected changes, and respondents shared their insights into the underlying socio-economic and political factors driving these shifts. This approach ensured data triangulation, enhancing the reliability of the findings by integrating geospatial analysis with local knowledge and expert assessments. The study adhered to ethical research standards, ensuring confidentiality and anonymity for respondents (ASA's Committee on Professional Ethics (COPE), 1997). No personally identifiable information was recorded, and participants had the right to withdraw from the interview at any stage without providing a reason. The collected qualitative data were used solely for research purposes, contributing to a more comprehensive understanding of land cover changes in the region.

Research limitations. This study analyses land cover changes in Zhytomyr Region from 2016 to 2023 using high-resolution geospatial data. While incorporating 2024 data could enhance the findings, maintaining methodological consistency was prioritised. Qualitative data collection was limited to the central and southern parts of the region due to restricted access in the north caused by military operations, potentially introducing geographical bias. Additionally, while the Dynamic World dataset provides high-resolution classification, certain land cover types, such as seasonally flooded vegetation, may require further field validation. Expanding ground-truthing and qualitative surveys in inaccessible areas could improve future assessments.

RESULTS AND DISCUSSION

Land cover, as an indicator of landscape transformation, plays a critical role in biogeochemical and hydrological cycles, influencing biodiversity and ecosystem productivity. In 2023, the land cover structure of the Zhytomyr Region comprised a diverse range of natural and artificial surfaces, which, according to geoinformation analysis, covered29,500 km² (official data indicate 29,800 km² (ZHOVA, 2023)). Among these, the largest proportion consisted of forested areas, which covered 55% of the region's territory, or approximately 16,340 km² (Fig. 3). Agricultural land, including cultivated areas, accounted for a significant share – 31%, or 9,275 km². Built-up areas, which included urban and industrial zones, covered 4% of the total area (1,098 km²). The land cover also featured bush and scrub thickets, which covered 4% of the territory (1,148 km²). Water resources, represented by rivers, lakes, and other water bodies, covered 1% of the region's area (177 km²). Areas with flooded vegetation were minimal, comprising 0.04% of the total area (12.8 km²). Grassy areas accounted for 5% (1,402 km²). Less significant land cover categories included bare land with minimal vegetation, covering only 46 km². Given the above, the land cover structure in 2023 reflects a dynamic balance between natural and anthropogenic landscapes, which is essential for land use planning and environmental monitoring in the region.

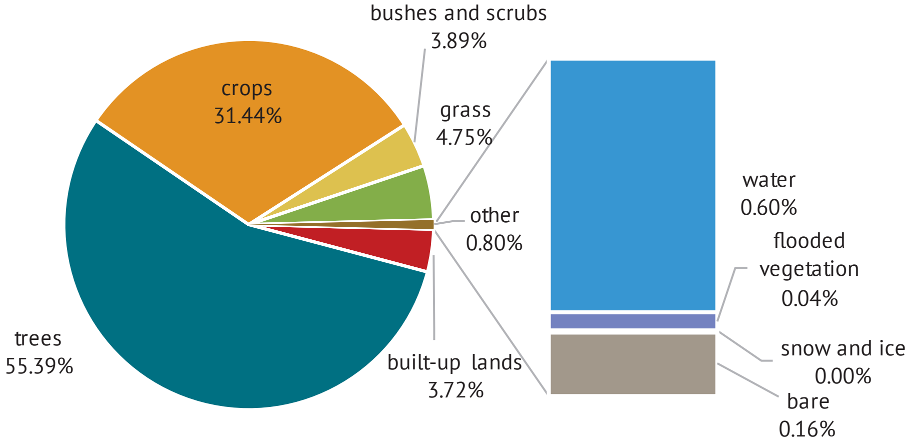

Figure 3. *Structure of land cover in 2023*
Source: *compiled by the authors based on the method of C. Brown et al. (2022)*

It should be noted that the land cover structure, according to data obtained using the GOOGLE/DYNAMICWORLD/V1 classifier and official statistical data (ZHOVA, 2023), differs slightly (Table 1). This discrepancy arises because satellite image analysis classifies the Earth's surface based solely on the spectral characteristics of pixel imagery, whereas official statistics are based on the legal designation of land plots. At the same time, official statistical data (ZHOVA, 2023) do not capture dynamic land cover changes, as they rely on the legal status of land rather than actual spectral characteristics, which have remained unchanged over the past seven years. This results in inconsistencies, particularly in the context of rapid land use changes that are not promptly reflected in legal documents, rendering official statistics unsuitable for in-depth scientific analysis. Satellite imagery analysis for land cover research offers several advantages, including high spatial resolution and frequent data updates, enabling real-time monitoring of landscape changes. Additionally, advanced machine learning algorithms enhance the accuracy of land cover classification, and the ability to detect small-scale and short-term changes provides greater flexibility for natural resource research and management.

Table 1. *Dynamics of land use in Zhytomyr Region based on official statistics (km2), 2016-2022*

Year / Main types of land cover	2016	2017	2018	2019	2020	2021	2022
Total	29,827	29,827	29,827	29,827	29,827	29,827	29,827

Table 1. Continued

Main types of land cover \ Year	2016	2017	2018	2019	2020	2021	2022
Agricultural lands, of which:	15,101	15,101	15,101	15,101	15,101	15,101	15,101
Forests and other wooded areas	11,234	11,234	11,234	11,234	11,234	11,234	11,234
Built-up lands	890	890	890	890	890	890	890
Open wetlands	1,012	1,012	1,012	1,012	1,012	1,012	1,012
Open lands without vegetation cover or with insignificant vegetation cover	383	383	383	383	383	383	383
Water	486	486	486	486	486	486	486
Bushes and scrubs	552	552	552	552	552	552	552
Other lands	169	169	169	169	169	169	169

Source: *ZHOVA (2023)*

The land cover map (Fig. 4) provides insights into the distribution of land cover classes in the Zhytomyr Region. The land cover map of the Zhytomyr Region is dominated by vast forests primarily in the central and northern parts, indicating the presence of protected areas. Agricultural land, concentrated in the south-western part of the region, reflects a high level of agricultural activity, supported by proximity to transport routes and settlements. Built-up areas are situated along major transport corridors and intersections, reflecting the region's administrative and industrial hubs. Water bodies are unevenly distributed, with a higher concentration in the northern part, influencing the microclimate and land use. The largest rivers in the region – Teteriv, Sluch, and Uzh – form a significant part of these water bodies. Meanwhile, scrubland zones act as transitional ecosystems between forests and agricultural areas, playing a key role in biodiversity restoration and conservation.

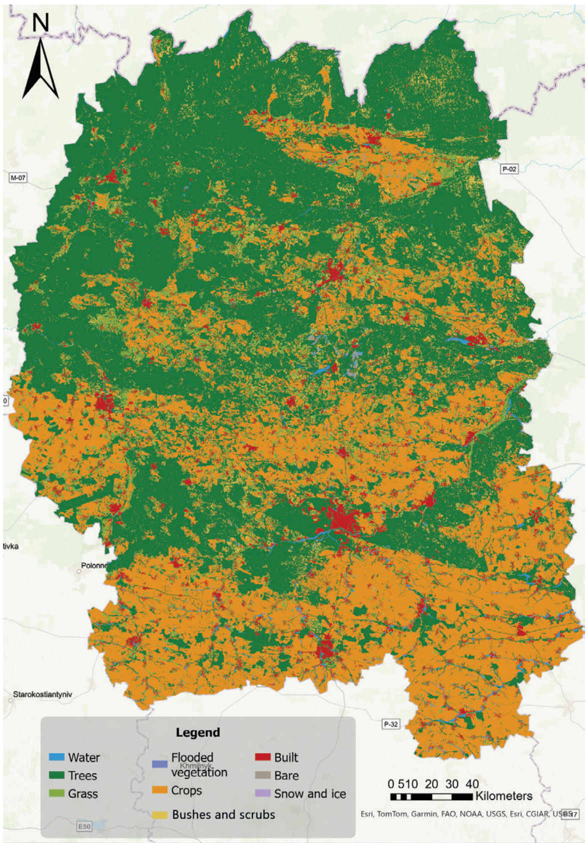

Figure 4. *Land cover of the Zhytomyr Region for 2023*
Source: *compiled by the authors based on the method of C. Brown et al. (2022)*

Further quantitative analysis of different land cover classes reveals the dynamics and changes from 2016 to 2023 for each of the nine classes defined by the Google Dynamic World V1 classifier. During the study period, a clear upward trend is observed in the expansion of forested areas, agricultural land,

and bare land compared to 2016. Conversely, the proportion of other key land cover classes – such as wetlands, scrubs and bushes, and herbaceous coenoses, which contribute to ecological balance – has significantly declined (Table 2). The land cover structure during the analysed period, highlighting two key phases –decentralisation and full-scale war – is presented in Figure 5.

Table 2*. Dynamics of land use in Zhytomyr Region based on the analysis of satellite images (km²), 2016-2023*

Indicator	2016	2017	2018	2019	2020	2021	2022	2023
Water	↓0.6	→0.6	↑0.7	↑0.7	→0.6	↑0.7	↑0.7	↓0.6
Flooded vegetation	↓0.0	↓0.0	→0.0	↓0.0	↓0.0	↓0.0	↑0.1	↓0.0
Built-up lands	↑3.9	↑3.9	↑3.8	→3.8	↓3.7	→3.8	↓3.6	↓3.7
Trees	↓52.7	→54.2	→54.4	↓53.3	↓53.2	→53.7	↓52.4	↑55.5
Crops	↓26.2	→28.9	→30.6	→31.1	↑32.0	↑32.7	↑33.8	↑31.5
Bushes and scrubs	↑7.3	↓4.3	↓3.5	↓4.7	→5.1	↓4.1	↓4.5	↓3.9
Snow and ice	↑0.1	↓0.0	↑0.1	↓0.0	↓0.0	↓0.0	↓0.0	↓0.0
Bare	→0.1	↓0.1	↓0.1	↑0.2	↑0.2	↓0.1	→0.1	↑0.2
Grass	↑9.0	↑8.2	→6.9	→6.4	↓5.4	↓5.2	↓4.9	↓4.8

Note: *↑ – increase, ↓ – decrease, → – stabilisation*
Source: *compiled by the authors based on the method of C. Brown et al. (2022)*

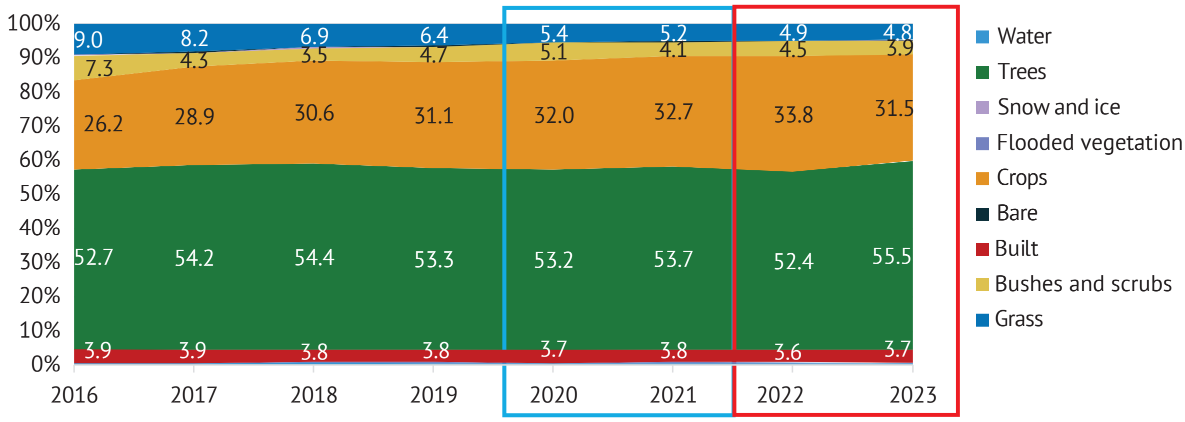

Figure 5*. Dynamics of land cover changes in Zhytomyr Region*
Note: *Blue rectangle – decentralisation; Red rectangle – war*
Source: *compiled by the authors based on the method of C. Brown et al. (2022)*

It is evident that the region has experienced land cover changes in both analysed subperiods. A detailed examination of changes in individual land cover classes and underlying the reasons is necessary.Recognising that reforms not only influence these changes but also drive their development, expert interviews were conducted to understand the preconditions for these transformations.

Forested areas remained the dominant land cover class in the Zhytomyr Region during the study period. Between 2016 and 2019, notable changes were observed in the forested areas of the Zhytomyr Region. The initial year (2016) was characterised by 1,549,515 hectares of forests, accounting for 52.7% of the total area. During 2017-2018, the forested area gradually increased, reaching 1,601,088 hectares in 2018, with its share rising to 54.4%. This growth was driven by active afforestation, the natural expansion of forests, and the successful implementation of digitalisation programmes for forest protection. However, in 2019, the forested area declined by 2%, or 33,000 hectares. This sharp decrease resulted from the abnormally dry autumn of 2019, which led to frequent and severe fires (Skydan *et al.*, 2021).

Based on qualitative semi-structured interviews, it was found that at the beginning of the decentralisation process in 2020, a decline in both the total forested area and its proportion was observed. With communities assuming power, control over forest resources significantly improved, leading to more effective measures against illegal logging. Additionally, communal forests were established to preserve community-owned woodlands. During this period, the local population gained greater influence over decisions regarding the allocation of local finances. Notably, one of the primary concerns raised by communities was the clearance of wild forest areas, particularly around cemeteries, roadsides, and solid waste dumps. The implementation of these measures, funded by local budgets, resulted in a reduction in forested areas, as wild vegetation was cleared to enhance public spaces and improve safety.

The full-scale invasion of Ukraine by the Russian Federation has had a significant impact on land cover composition, particularly in forested areas. In 2022, the forested area decreased sharply, reaching its lowest level during the study period – 1,541,392 hectares (Table 2), while the proportion of forested areas fell to 52.4%. This decline was linked to the energy crisis in Ukraine, triggered by Russian missile attacks on energy facilities, which led the rural population to collect firewood for heating private homes. However, in 2023, the situation changed: the forested area expanded to 1,634,015 hectares, and the proportion of forested areas rose sharply to 55.5%. This growth can be attributed to several factors: 1) a significant portion of the territories bordering Belarus in Zhytomyr Region (a buffer zone of 357,000 hectares (Prospects of return to economic use..., 2024)) was closed not only to the public but also to any production activity, meaning no forest management operations were carried out in these areas; 2) limited export opportunities from Ukraine during the period of martial law; 3) the rural population had already harvested sufficient firewood in 2022 for three to five years, meaning this factor no longer influenced the forested area in 2023 (Fig. 6).

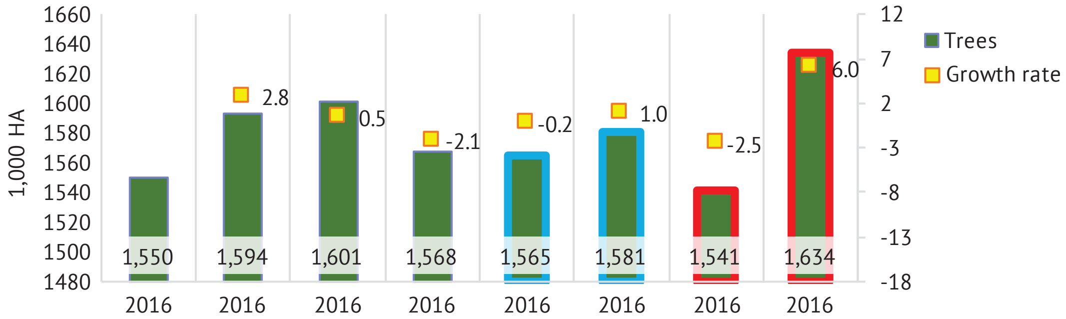

Figure 6. *Dynamics and rate of change of forest-covered areas in Zhytomyr Region*
Source: *compiled by the authors based on the method of C. Brown et al. (2022)*

The analysis indicates that decentralisation, as a process of transforming local governance, has significantly affected the extent and composition of forested areas by strengthening control over the use of local natural resources and clearing wild vegetation. Meanwhile, during the full-scale invasion by the Russian Federation, the forested area reached its lowest level of the study period, due to the energy crisis and increased firewood collection, as well as the clearance of wild forests around villages and towns. However, in 2023, a sharp recovery in forest cover was observed, driven by restricted access to territories bordering Belarus, reduced exports, and a diminished demand for additional firewood.

Cultivated land is the second-largest class of land cover by area, which exhibited a stable upward trend from 2016 and 2022, followed by a sharp decline in 2023. Between 2016 to 2019, there was a significant increase in the extent and proportion of cultivated land, averaging 43,000 hectares or 3.3% annually. This period was characterised by the active expansion of agricultural areas due to the growing demand for energy crops (rapeseed, soybean, and sunflower) in export markets, the introduction of new technologies, and the intensification of agricultural activity in the region. From 2020 to 2021, when territorial communities became operational, the cultivated land area continued to expand, although the growth rate slightly declined: the average increase over this period was approximately 20,000 hectares (2.8%) annually. The decentralisation reform contributed to more favourable economic conditions for agribusiness and increased investment in the region's agricultural sector. This is evidenced by data on capital investments in agriculture in Zhytomyr Region: in 2019, they amounted to 1.797 billion UAH; in 2020, 1.990 billion UAH (an 11% increase); in 2021, 2.294 billion UAH (a 15%increase); and in 2022, 1.655 billion UAH (a 28% decrease) (SSSU, 2024).

During the wartime period of 2022-2023, fluctuations were observed in the cultivated land area (Fig. 7). In 2022, the area expanded significantly to 996,000 hectares, marking the highest level recorded during the entire analysis period – an increase of 35,000 hectares (2.9%). This growth was influenced by strong internal and regional migration trends. Internally, many urban residents moved to rural areas to live with their parents and relatives during the war in 2022. Regionally, some migration flows from conflict zones and frontline areas also sought refuge in rural settlements, including abandoned houses. These demographic shifts encouraged the rural population to increase cultivated areas. Additionally, agricultural enterprises continued operating out of inertia – winter sowing was completed, and fertilisers, plant protection products, and fuel had already been purchased, sustaining agricultural activity. However, in the second year of the full-scale war (2023), the situation changed dramatically: the cultivated land area decreased by

68,000 hectares (nearly 7% compared to the previous year). This sharp decline was driven by several war-related factors (Fig. 7):

1) In 2022, a significant proportion of the rural population was mobilised into the army, resulting in a shortage of labour for the operation of rural households. This severely reduced the possibility of cultivating fields and keeping livestock, as there were not enough workers to perform the full cycle of agricultural work for the following year. Consequently, large areas remained uncultivated, leading to an overall decrease in cultivated land.

2) The salaries paid to soldiers during mobilisation partially reduced the economic pressure on rural families, allowing them to survive without the need to maintain subsistence farms with an agricultural focus.

3) Russian missile attacks on ports disrupted agricultural supply and export chains, which significantly reduced the profitability of certain crops as access to international markets was limited. As a result, agricultural enterprises and farmers reduced the area under cultivation, further contributing to the overall reduction in cultivated land.

4) Due to the depreciation of the national currency, higher transport costs, and other economic pressures, prices for seeds, crop protection products, and fuel and lubricants rose significantly. The high cost of agricultural inputs limited their accessibility to farmers, resulting in a decrease in cultivated land area, as many were unable to afford to continue farming under these conditions.

5) The six-month export blockade in 2022 led to the accumulation of agricultural products within the country. This caused a decline in domestic prices, making production less profitable for farmers. Consequently, many farmers chose to lower production volumes or cease cultivating certain crops entirely, leading to a reduction in the overall area of cultivated land.

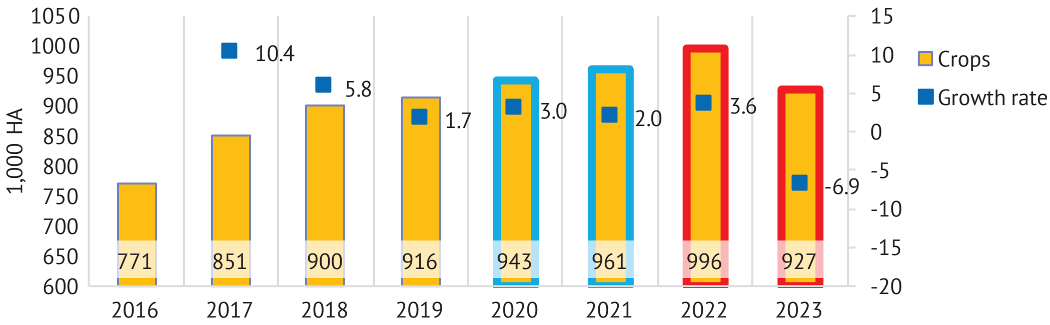

Figure 7. *Dynamics and rate of change of cultivated land in Zhytomyr Region*
Source: *compiled by the authors based on the method of C. Brown et al. (2022)*

These factors demonstrate that the war has had a significant impact on the agricultural sector, particularly the extent of cultivated land. The combined effects of mobilisation, high input costs, infrastructure destruction, and export restrictions have resulted in a sharp decline in cultivated land area in 2023, with serious economic and social consequences.

From 2016 to 2023, the area of grassy communities in the Zhytomyr Region showed a steady decline, with a decrease in absolute area and a reduction in its share of the total land cover from 9% in 2016 to 4.8% in 2023. The average rate of decline over this period was approximately 8.6% per year, with an average annual reduction of around 17.8 thousand hectares. Notably, between 2016 and 2019, the share of grassy communities in the total land cover decreased significantly, from 9.0% in 2016 to 6.4% in 2019. Such a pronounced downward trend reflects a notable increase in the extensification of agricultural development and a substantial decline in cattle numbers, both in agricultural enterprises and rural households (Prospects of return to economic use..., 2024). In the period 2020-2021, the decline in grassy communities continued, although the rate of decrease slowed. The area fell from 157.800 hectares in 2020 to 151.600 hectares in 2021, while its share of the total land structure decreased from 5.4% to 5.2%. During this period, a slowdown in the reduction of the cattle population was recorded, which was reflected in the extent of grassy communities, as they serve which serves as a fodder base for cattle. At the same time, local authorities began implementing programmes to support livestock production as a strategic development priority, which contributed to a moderation in the decline of the cattle population and, consequently, to the stabilisation of grassland areas. The war period of 2022-2023 was also characterised by the continuation of negative trends in grassy communities: the area decreased by 4.1% in 2022 and by 3.5% in 2023 compared to the previous year. The slight apparent stabilisation in the rate of decline can be attributed to several factors: disruptions in regional food supplies and the migration of people from cities to rural areas prompted rural residents to maintain their cattle herds instead of reducing them, which in turn impacted the extent of grassland (Fig. 8).

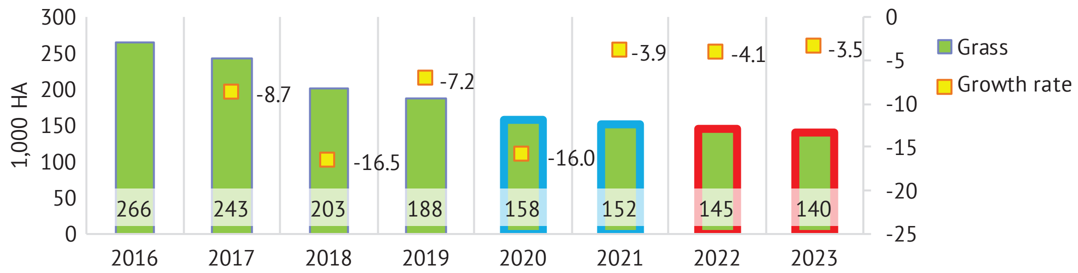

Figure 8. *Dynamics and rate of change of grassland communities in Zhytomyr Region*
Source: *compiled by the authors based on the method of C. Brown et al. (2022)*

The land cover of the Zhytomyr Region includes ecologically important classes such as water bodies (water), wetlands (flooded vegetation), and scrublands (bush and scrub), which provide the ecological basis for biodiversity and ecosystem resilience. These categories play a key role in maintaining water balance, regulating the climate, and preventing erosion processes. During the period 2020-2021, the area of water bodies, wetlands, and scrublands in the Zhytomyr Region experienced significant fluctuations (Fig. 9). The area of water bodies initially decreased by 5.2% in 2020, but in 2021, it expanded by 4.1%, which may have resulted from changes in climatic conditions and water resource regulation. Wetlands also showed a decline: in 2020, the area decreased by 3.2%, and in 2021, it reached its lowest level during the period, with a further 15.1% decrease, which may suggest increased human impact, including land reclamation and agricultural development. The area of scrublands increased by 19.4% in 2020, likely due to natural regeneration, but in 2021, it decreased again by 19.5%.

The period 2022-2023 was critical for the balancing of land cover classes in the Zhytomyr Region, as evidenced by significant changes in their areas. In 2022, there was a sharp increase in the area of water bodies to 19,648 hectares, marking the highest figure over the last three years. However, by 2023, the area of water bodies had decreased to 17,744 hectares. This significant reduction can likely be attributed to military operations, including the release of water from dams to slow the advance of Russian troops. In 2022, the area of wetlands increased sharply to 1,723 hectares, a rise of 60%, as a result of the expansion of water bodies. However, in 2023, the area of flooded vegetation decreased again to 1,275 hectares, indicating the instability of this class and its sensitivity to external influences. In 2022, the area of scrublands increased to 132,188 hectares, indicating a temporary recovery of this class. However, in 2023, the area decreased again to 114,827 hectares, which may be linked to the intensified use of land for agricultural or forestry purposes (Fig. 9).

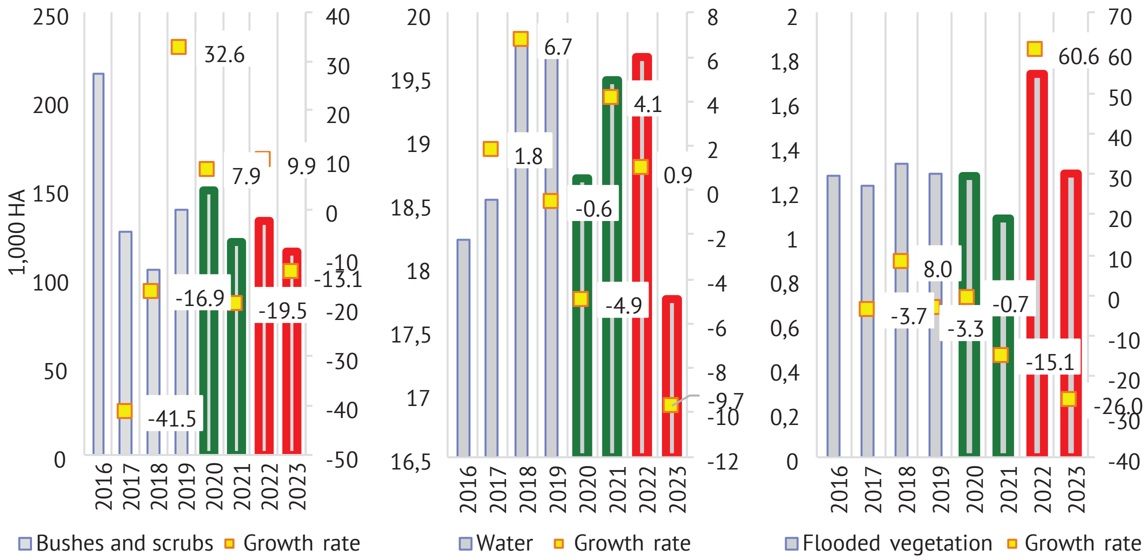

Figure 9. *Changes in balancing land cover classes*
Source: *compiled by the authors based on the method of C. Brown et al. (2022)*

A general analysis of the balancing land cover classes in the Zhytomyr Region from 2016 to 2023 reveals significant fluctuations in the areas of water bodies, wetlands, and scrublands. These land cover types have proven to be particularly vulnerable to anthropogenic impacts, including defence-related measures and industrial-scale land use for agricultural and forestry purposes. A decrease in the area of these classes, especially in critical periods, may have serious environmental consequences for the region, such as deterioration in water quality, soil degradation, and reduced ecosystem resilience to climate change. Therefore, it is essential to consider these factors when planning land use and developing strategies for the conservation of natural resources in the Zhytomyr Region (Fig. 10).

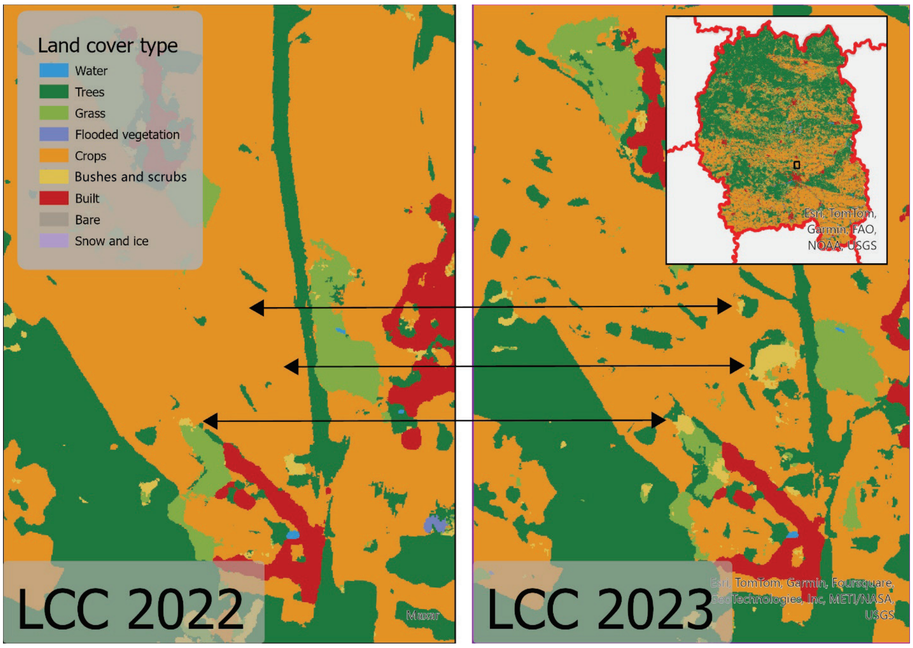

Figure 10. *Transition of cultivated lands into scrublands and forested areas (2022-2023)*
Source: *compiled by the authors based on the method of C. Brown et al. (2022)*

Changes. An important element in the study of land cover structure and its transformation is analysing the transition of land from one class to another. Taking into account the previous results of this study, an examination was conducted on the transition of land from the 2016 classifications to those of 2021 (decentralisation) and from 2021 to 2023 (war). The study of such changes reveals significant transformations in land cover under the influence of both administrative and military factors. The period of decentralisation was marked by significant changes in wetlands, flooded vegetation, and scrublands due to land reclassification (Fig. 11). Wetlands expanded due to the conversion of part of the forested areas (1,762 hectares (9.7%)), including an additional 390 hectares (2.1%) from bare land and herbaceous coenosis. Further expansion occurred through the conversion of some forested areas (394 hectares (28.4%)) and cultivated land (31 hectares (2.2%)). In contrast, scrublands contracted significantly, as large areas were converted into forested areas (41,057 hectares (18.6%)) and cultivated land (54,140 hectares (24.5%)).

Cultivated land increased primarily at the expense of scrublands (54,140 hectares (24.5%)), herbaceous coenosis (134,541 hectares (17.2%)), and to a lesser extent at the expense of forested areas (42,107 hectares (2.7%)). This increase reflects the intensified development of land for agricultural purposes, resulting in the reduction of natural ecosystems and alterations in land cover across the region. Forested areas also experienced significant changes during the decentralisation period. Although a substantial proportion of forested land remained within its original classification (1,454,291 hectares (93.5%)), some areas were reclassified into other land cover categories. For example, a portion of forested areas was converted into cultivated land (42,107 hectares (2.7%)), scrublands (41,057 hectares (2.8%)), and herbaceous coenosis (27,874 hectares (1.9%)). At the same time, the forested area expanded due to the reclassification of land from other categories, including scrublands (76,887 hectares (34.8%)) and cultivated land (16,800 hectares (2.3%)). These changes indicate active reforestation processes and the utilisation of land previously occupied by other land cover types to expand forest plantations.

Thus, changes in land cover structure during the decentralisation period highlight significant transformations in ecologically important land categories, including forested areas, water bodies, scrublands, and cultivated lands. These processes reflect both natural trends and the influence of anthropogenic factors, including agricultural and forestry activities, which have contributed to the transformation of Zhytomyr Region's natural landscapes. The war period (2022-2023) was characterised by substantial changes in the land cover structure of the Zhytomyr Region, particularly in key categories, such as wetlands, scrublands and forested areas, which were affected by both military operations and human activities. These ecosystems remained relatively stable during this period, with 16,306 hectares (85.5%) remaining within this classification. However, it is important to note that some land transitioned from other categories, particularly forested areas (415 hectares (2.3%)) and scrublands (80 hectares (0.4%)). Despite these transfers, the total area of water bodies declined slightly, primarily due to lower water levels resulting from military operations and the release of water from dams to impede military forces. Wetlands also underwent changes during the war period, with only 533 hectares (42.5%) remaining within this classification. Some areas, including 503 hectares (40%) of forested land and 69 hectares (5.5%) of cultivated land, were converted into wetlands. This suggests instability in the region's hydrological regime, which may be attributed to both military operations and climate change. The rise in waterlogging levels could also result from the destruction of infrastructure and a decline in land reclamation activities.

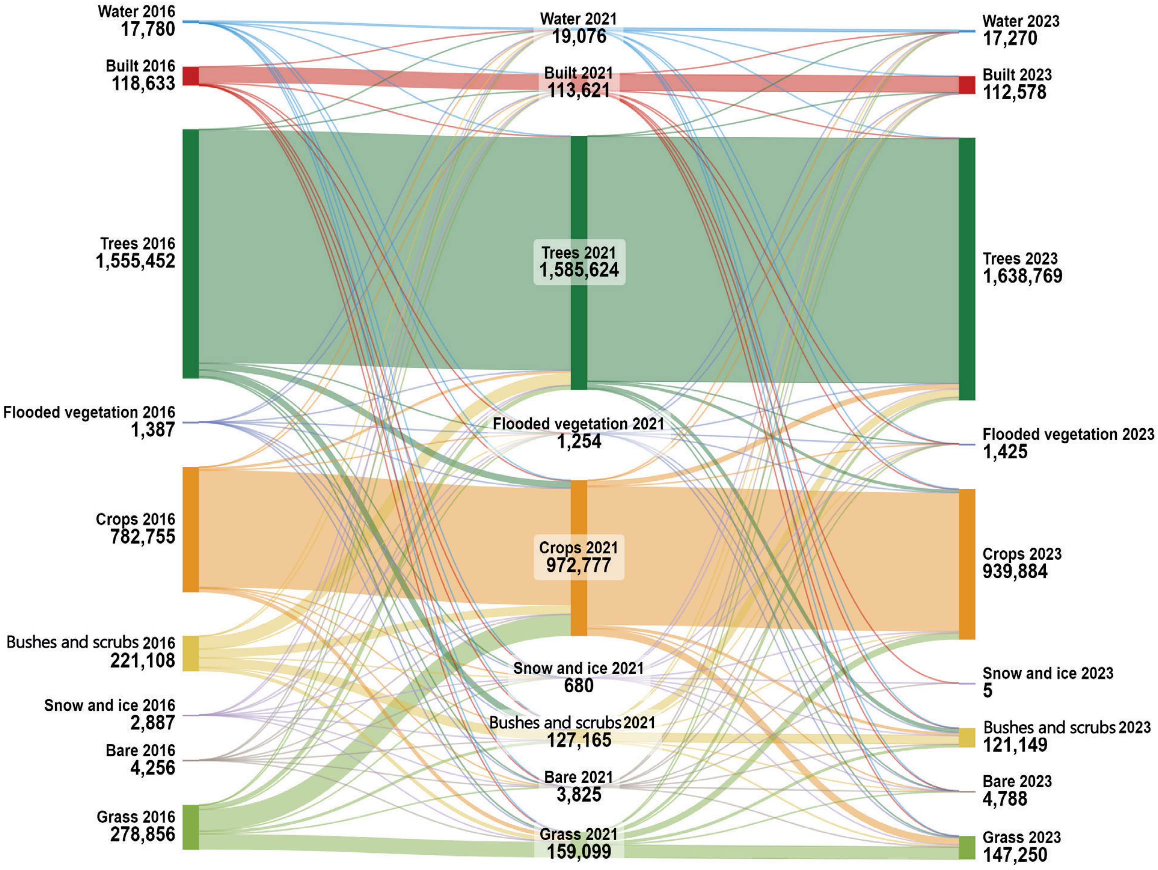

Figure 11. *Sankey diagram of the period of decentralisation and war, ha*
Source: *compiled by the authors based on the method of C. Brown et al. (2022)*

Scrublands continued to decline in area, with 55,187 hectares (43%) remaining within this classification. A significant portion was reclassified as forested land (25,457 hectares (19%)) and cultivated land (18,834 hectares (14.2%)). This reduction in scrublands reflects the intensified use of land for agriculture and other industrial purposes, which escalated during the war. Forested areas also experienced significant changes during the war. While 1,526,170 hectares (94.1%) of forested land remained within this classification, some areas were reclassified into other land cover categories. In particular, 34,317 hectares (2.2%) of forested land were converted into cultivated land, 50,555 hectares (3.3%) into scrublands, and 19,464 hectares (1.3%) into herbaceous coenosis. At the same time, forested land expanded due to the reclassification of land previously classified as scrublands (50,555 hectares (3.3%)) and cultivated land (34,317 hectares (2.2%)). These changes indicate that, despite the challenges of wartime, forests underwent regeneration, possibly due to reduced human activity in certain areas.

During the war period, cultivated land in the Zhytomyr Region also underwent significant transformations, reflecting the impact of military operations on agricultural land. Over this period, cultivated land retained a substantial portion of its area, with 867,244 hectares (89.5%) remaining within this classification. However, some land was reclassified into other categories. For instance, 18,949 hectares (2.2%) became forested land, and 18,834 hectares (2.2%) were converted into scrublands. Additionally, 46,044 hectares (5.3%) of cultivated land were reclassified as herbaceous coenosis. These transformations reflect substantial changes in the use of agricultural land, which may be attributed to both the destruction of infrastructure and the temporary inaccessibility of certain areas, as well as shifts in agricultural priorities during the war. Simultaneously, cultivated land expanded through the incorporation of land from other classifications. For example, 41,541 hectares (4.3%) were reclassified from scrublands, which may indicate increased agricultural activity in certain areas. Land reclassification from other categories also included 18,949 hectares (2.2%) of forested land and 4,141 hectares (0.5%) of built-up land.

Comparing the two periods and focusing on differences among donor categories reveals that the role of donor categories changed between the decentralisation and wartime periods. During decentralisation, natural ecosystems such as scrublands and herbaceous coenoses served as the primary donor categories, whereas during the war, anthropogenic categories, particularly cultivated land and forested areas, assumed this role. The driving forces behind these transformations differ: decentralisation stimulated intensive land development and the expansion of agricultural and forest plantations at the expense of natural areas, whereas the war resulted in a reduction in economic activity, land abandonment, and the regeneration of natural ecosystems in formerly cultivated areas. The environmental consequences of these processes vary: during decentralisation, the decline of natural ecosystems may have negatively impacted biodiversity and ecosystem services, whereas, during the war, the restoration of natural categories may have had positive environmental effects. However, such regeneration also signals economic decline and social challenges.

Previous studies on land use change have primarily focused on natural factors, urbanisation, and climate change, but have rarely addressed the combined impact of administrative reforms (such as decentralisation) and external shocks (such as war) on land cover dynamics. While many researchers analyse the effects of decentralisation on governance, local budgets, and economic development, few investigate its influence on land cover transformation, particularly in conflictaffected regions. This study seeks to bridge this gap by examining land use changes in the Zhytomyr Region under the influence of both decentralisation and military conflict, using an integrated geospatial and qualitative approach. The following findings reveal significant land use changes in Zhytomyr Region, with distinct trends observed during the decentralisation (2020-2021) and wartime (2022-2023) periods. During decentralisation, local communities gained greater control over land management, leading to an increase in agricultural land and a decline in natural land cover categories. These results align with P. Pyvovar *et al.* (2023), who demonstrated that decentralisation in Ukraine facilitated the expansion of arable land as local governments took a more active role in land administration. Similar findings were reported by X. Li *et al.* (2016) in their study of Wuhan, China, where local governance policies significantly influenced land use priorities.

However, during the wartime period (2022-2023), these trends reversed. The total area of cultivated land decreased due to labour shortages, economic uncertainty, and supply chain disruptions, aligning with the conclusions of M. Forleo *et al.* (2017), who found that economic crises and social instability contribute to the contraction of agricultural areas. Simultaneously, the reduction of human activity led to a partial recovery of forested areas and water bodies, a trend also observed by Q. Xie *et al.* (2023), who noted that land use restrictions and decreased industrial activity facilitated the regeneration of natural landscapes in restricted zones. The authors' findings also suggest that war-induced instability in land use differs from land cover changes driven by natural disasters or internal conflicts. For instance, F. Krausmann *et al.* (2003) analysed land use trends in Austria, demonstrating that socio-economic transformations, particularly industrialisation, had longterm effects on land use. In contrast, in Zhytomyr Region, war-related disruptions resulted in temporary fluctuations in land cover rather than permanent conversions.

J. Bekere *et al.* (2023) explored the socio-economic drivers of land use and land cover (LULC) change in western Ethiopia, identifying both natural and anthropogenic factors. Their study found a sharp decline in forest cover, from 12.1% in 1990 to 2.6% in 2020, driven by demographic and economic variables. Through Pearson correlation and binary logistic regression, they demonstrated that education and land-holding size were negatively correlated with LULC drivers, while age and gender had a positive correlation. The findings highlight the necessity of integrated policy measures to mitigate human-induced landscape changes. Similarly, K. Cegielska *et al.* (2023) developed an LULC conflict risk assessment model, integrating spatial and social perspectives to examine the impact of suburbanisation in the peri-urban zones of Kraków. Their research revealed that agricultural land is particularly vulnerable to conflict due to unplanned urban expansion, demonstrating a methodological approach that combines GIS-based spatial analysis with public perception surveys. Meanwhile, P. Di Marzio *et al.* (2023) analysed land cover and socioeconomic changes over five decades in Molise, Italy, using CORINE Land Cover data alongside historical aerial imagery. They found that agricultural expansion and human disturbances had fragmented the landscape, with natural vegetation confined to riparian formations. The study underscores the tension between agricultural intensification and biodiversity conservation in regions with a long history of land use transformation.

Another notable finding is that a significant portion of Zhytomyr Region's forested land was incorporated into buffer zones during the war, where economic activity was heavily restricted, leading to a measurable increase in forest cover. This phenomenon has been observed in other regions as well; for example, Q. Xie *et al.* (2023) found that the establishment of restricted zones in China led to similar increases in natural vegetation. Despite these insights, this study faces certain limitations. First, the classification of land cover is based on spectral characteristics rather than legal land use status, which may lead to discrepancies in the interpretation of agricultural and natural land categories. Second, restricted access to some areas due to military operations may have affected the accuracy of local observations, particularly regarding forested areas and water bodies. Lastly, while semi-structured interviews provided valuable qualitative insights, the geographical scope of interviews was limited to the central and southern parts of the Zhytomyr Region, potentially introducing regional bias in the interpretation of land use changes.

CONCLUSIONS

The analysis has shown that decentralisation and military conflict have significantly influenced land use changes in the Zhytomyr Region. During the local governance reforms (2020-2021), communities gained more control over land resources, enabling them to clear scrublands and naturally regenerated forests, reducing their area by over 5%, as these landscapes hindered infrastructure development, land management, and agricultural expansion. At the same time, natural landscapes – including meadows and scrublands – declined by an average of 5% per year. However, the full-scale war in 2022 drastically altered this trend: the area of cultivated land decreased by 7% in 2023, primarily due to mobilisation, rising agricultural costs, and restricted market access. In contrast, forest cover expanded by 3% in 2023, mainly due to the creation of buffer zones where economic activity was restricted, while water bodies increased by 19% in 2022, partly as a consequence of militaryrelated hydrological changes.

A detailed analysis of specific land cover categories highlights significant trends and processes over the study period. Forested areas experienced major fluctuations, with firewood collection driving deforestation in 2022, while restrictions on logging in border regions resulted in 92,600 hectares (5.7%) increase in forested land in 2023. Cropland expanded during the period of decentralisation but declined by 68,000 hectares (7%) in 2023 due to labour shortages, decreasing agribusiness profitability, and economic instability. Meadows and pastures underwent a significant reduction, shrinking from 9% of total land cover in 2016 to 4.8% in 2023, primarily due to a decline in livestock farming. Water bodies and wetlands expanded by 19% in 2022 but contracted again in 2023. Scrublands were mostly converted into croplands and forests over the study period; however, in 2023, a decline in agricultural activity led to a 14% increase in scrubland areas.

The findings indicate that economic and political instability necessitate adaptive land-use strategies at the local level. The war has resulted in the reversion of significant areas of cultivated land to their natural state due to the decline in agricultural activities. These dynamics underscore the critical need to incorporate external factors into land use planning and to develop sustainable land management strategies. Geospatial technologies have demonstrated their high effectiveness in monitoring land cover transformations. The applied methodologies not only facilitate the assessment of current land use conditions but also enhance long-term decision-making processes, contributing to more informed and data-driven land management practices. Further research should focus on the long-term impacts of administrative reforms and military action on land use and its broader socioeconomic and ecological implications, including potential changes in land use legislation. Research could also examine the environmental and economic impacts of land cover transformations in post-conflict recovery, as well as the development of adaptive land management models that take into account socio-economic and political factors.

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CONFLICT OF INTEREST

None.

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Вплив децентралізації та війни на рослинний покрив у Житомирській області України

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Анотація. Це дослідження мало на меті вивчити трансформації ґрунтового покриву в Житомирській області України у відповідь на децентралізацію та війну. Основна увага приділялася оцінці того, як зміни в місцевому управлінні та повномасштабне вторгнення вплинули на динаміку землекористування, зокрема, на зміни в сільськогосподарській експансії, скорочення природних типів земного покриву та коливання лісових масивів і водних об'єктів. У дослідженні проаналізовано моделі землекористування з 2016 по 2023 рік з використанням даних Dynamic World V1 сервісу Google Earth Engine, поєднуючи геопросторові дані з якісними напівструктурованими інтерв'ю. Результати показали, що процес децентралізації, розпочатий у 2014 році, зміцнив місцеве самоврядування та розширив можливості громад в управлінні земельними ресурсами. Цей період характеризувався розширенням площ сільськогосподарських угідь і скороченням природних типів земельного покриву, таких як луки та чагарники. Натомість повномасштабне вторгнення, яке розпочалося у 2022 році, призвело до зміни пріоритетів у землекористуванні через дефіцит робочої сили, зростання вартості ресурсів та обмежений доступ до ринків, що спричинило скорочення сільськогосподарських угідь та часткове відновлення природних екосистем. Особливо значні коливання спостерігаються щодо лісових масивів та водних об'єктів, що пов'язано з енергетичними потребами та обмеженнями на діяльність у зонах конфлікту. Отримані результати підкреслюють необхідність адаптивного управління земельними ресурсами в умовах соціально-економічних та політичних викликів, а також важливість моніторингу рослинного покриву для регіонального планування та сталого використання природних ресурсів. Аналізуючи геопросторові дані з Google Earth Engine's Dynamic World V1 та якісні напівструктуровані інтерв'ю, дослідження виявило ключові тенденції з 2016 по 2023 рік, оцінило соціально-економічні та політичні чинники, що стоять за цими змінами, а також висвітлило виклики адаптивного управління земельними ресурсами в умовах нестабільності. Отримані результати сприяють кращому розумінню наслідків змін земного покриву для регіонального планування та стратегій сталого землекористування

Ключові слова: зміни у землекористуванні; ГІС-моніторинг земель; соціально-економічний вплив; територіальна реформа; наслідки війни

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