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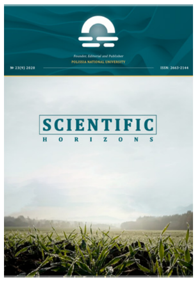

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Analysis of variability in gestation length in sows and its association with litter traits at birth

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Abstract. Gestation length is a complex polygenic trait in sows that significantly determines their productive characteristics and influences foetal development during the embryonic period. This study aimed to analyse the effects of genotypic factors (breed of the sow and sire boar) and environmental factors (year and season of farrowing) on the variability of gestation length in sows and to determine the nature of its association with litter traits at birth using a meta-analysis algorithm. The analysis was based on primary data regarding reproductive traits in the main herd of the private joint-stock company "Plemzavod "Stepnoi", Zaporizhzhia Region, collected from 2010 to 2013. The mean gestation length for the animals in the study herd was 115.9 ± 0.04 days, with a range of 110 to 121 days. Gestation length exhibited a very low level of inter-individual variability, with a coefficient of variation of only 1.65%. Duroc sows exhibited shorter gestation lengths, lower total litter sizes, and fewer live piglets per

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litter at birth compared to Landrace sows (in all cases: $P < 0.001$). A significant influence of the sire boar's breed on the reproductive traits of sows was established, except for gestation length and total litter size. The longest gestation lengths were recorded during the winter months, whereas the best performance in other reproductive traits was observed in the spring. Meta-analysis revealed that the "general" estimates of the phenotypic correlation coefficient between gestation length and total litter size, the number of live piglets, and total litter weight at birth were significant and negative. In contrast, the correlation between gestation length and the average birth weight of live piglets was significant and positive

Keywords: reproductive traits; genotypic and environmental factors; meta-analysis; pigs

INTRODUCTION

Modern pig farming increasingly focuses on improving the reproductive performance of sows and enhancing the survival of suckling piglets until weaning. However, selection aimed at increasing litter size often leads to a corresponding rise in piglet mortality rates at birth and during the suckling period. Therefore, to improve sow fertility, additional selection criteria must be developed to address the associated decline in the quality of neonatal and suckling piglets. As noted in the study by Z. Liu *et al.* (2022), gestation length is a key complex polygenic trait in sows that significantly influences their productivity and affects foetal development during the embryonic period. Gestation length is defined as the period from the last successful insemination to farrowing. In most cases, it spans approximately three months, three weeks, and three days (114-115 days) and is influenced by various factors such as the breed of the sow and sire boar, parity, year and season of farrowing. During the final days of gestation, the foetus undergoes critical organ development and weight gain. Consequently, an extended gestation period contributes to better piglet development and increased viability after birth.

The findings indicate a significant genotypic component influencing the variability of gestation length in sows. For instance, L. Shi *et al.* (2023) identified 1,002 SNPs significantly associated with gestation length during a genome-wide association study (GWAS) targeting genetic markers related to this trait. Additionally, a locus on pig chromosome 4 (ASGA0017859, SSC4, 7.8 Mb) was identified as being associated with substantial variability in gestation length across the first to fourth parities (See *et al.*, 2019). On the other hand, gestation length is also influenced by sow health. M. Parada Sarmiento *et al.* (2023) observed a tendency for reduced gestation length in animals exposed to stressors, such as laminitis. Furthermore, in crossbred animals (Large White × Landrace), conditions such as inadequate uterine involution, which can lead to postpartum disorders and negatively affect the reproductive cycle, were also linked to gestation length. M.I. Matsenko (2020) demonstrated that shortening the embryonic development period of piglets positively affects their growth rate, accompanied by improved haematological parameters, which should be considered in swine breeding programs (Egli *et al.,* 2022).

According to M. Ju *et al.* (2021), recent years have seen a gradual increase in litter size at birth in pig farming. This trend is significantly positively correlated with longer farrowing durations and gestation lengths. Additionally, a notable association was observed between gestation length and traits characterising the qualitative and quantitative properties of the litter at farrowing, possibly due to uterine capacity constraints and the length of the farrowing process. Interestingly, sows with the largest litters often exhibited the shortest gestation lengths. Furthermore, R. Bumpenkul and N. Imboonta (2021) demonstrated significant associations between gestation length and fertility traits, including total litter size, the number of live piglets, and stillbirths at birth. Overall, selection for increased litter size at birth in sows is accompanied by a tendency towards shorter gestation lengths.

Numerous findings reported by B. Medrado *et al.* (2021) demonstrate associations between gestation length and litter traits at birth. However, these results exhibit a degree of heterogeneity, as they were obtained from experimental groups of varying sizes, involving different breeds or crossbred animals, and under diverse management and feeding conditions for gestating and farrowing sows. Consequently, individual studies may either underestimate or overestimate the actual values. In such cases, meta-analysis (utilising a random-effects model) provides a means to assess the heterogeneity of individual studies and offers more reliable "general" results.

The study by D.M. Gathura *et al.* (2020) highlighted the advantages of using meta-analysis to investigate genetic parameters in beef cattle, while A.D. Hayward (2022) applied meta-analysis to explore genetic resistance to lung nematodes in sheep. In pig farming, meta-analysis has been employed to examine reproductive traits, such as the effects of oxytocin and carbetocin on farrowing characteristics and litter size, as reported by B.B.D. Muro *et al.* (2021). Similarly, R.H.R. Moreira *et al.* (2020) used meta-analysis to investigate factors affecting piglet birth weight variability. However, no comparable studies have yet been conducted on the key trait of sow gestation length and its association with litter traits at birth.

This study aimed to analyse the factors influencing sow gestation length and to establish the relationship between gestation length and litter traits at birth using meta-analysis.

MATERIALS AND METHODS

The analysis utilised primary data on the reproductive traits of sows from the main herd of the private joint-stock company "Plemzavod "Stepnoi" in the Zaporizhzhia Region. The sows belonged to the Duroc breed (DR; $n = 654$ heads) and the Landrace breed (LN; $n = 584$ heads), with an average parity of 2.25 ± 1.61 and 2.51 ± 1.70 (*Mean* ± SD), respectively, ranging from 1 to 9 parities. For each farrowing, the following traits were evaluated: gestation length (GL), total number of piglets born (TNB), number of piglets born alive (NBA), number of stillborn piglets (NSB), stillbirth rate (SBR) within the litter, total litter weight at birth (LWB), and mean piglet birth weight (MBW). Table 1 presents the descriptive statistics for the reproductive traits of the studied sows.

***Table 1**. Descriptive statistics for the reproductive traits of the studied sows (n = 2,863)*

Trait (unit of measurement)	*min*	*max*	*Mean ± SE*	*SD*	*As* ± SE_{As}	*Ex* ± SE_{Ex}
GL (days)	110	121	115.9 ± 0.04	1.92	-0.12 ± 0.05	-0.10 ± 0.09
TNB (heads)	3	21	10.06 ± 0.05	2.62	-0.05 ± 0.05	0.36 ± 0.09
NBA (heads)	1	17	8.60 ± 0.05	2.52	-0.40 ± 0.05	0.72 ± 0.09
NSB (heads)	0	15	1.46 ± 0.03	1.82	1.85 ± 0.05	4.77 ± 0.09
SBR (%)	0	100	13.7 ± 0.32	16.97	1.98 ± 0.05	5.86 ± 0.09
LWB (kg)	3.3	30.6	15,6 ± 0.08	4.27	-0.14 ± 0.05	-0.05 ± 0.09
MBW (kg)	1.0	2.0	1.803 ± 0.002	0.13	-0.72 ± 0.05	3.20 ± 0.09

***Note:** min, max – minimum and maximum values; Mean ± SE – arithmetic mean and its standard error; SD – standard deviation; As ± SEAs – skewness coefficient and its standard error; Ex ± SEEx – kurtosis coefficient and its standard error*
***Source:** developed by the authors*

The sows were inseminated with semen from sire boars of three breeds: Duroc (DR; $n = 38$), Landrace (LN; $n = 35$), and Large White (LW; $n = 39$). In total, data from 2,863 farrowings that occurred between 2010 and 2013 were included in the analysis. To evaluate the effects of genotypic factors (sow breed and sire boar breed) and environmental factors (year and season of farrowing) on the reproductive traits of the experimental group, the authors employed the General Linear Model (GLM) algorithm:

$$Y_{ijklm} = \mu + SB_i + BB_j + YoF_k + SoF_l + e_{ijklm}, \quad (1)$$

where Y_{ijklm} is the value of the corresponding trait for the *m*-th sow; μ is the overall mean; SB_i is the fixed factor "sow breed" with two levels (DR, LN); BB_j is the fixed factor "sire boar breed" with three levels (DR, LN, LW); YoF_k is the fixed factor "year of farrowing" with four levels (2010, 2011, 2012, 2013); SoF_l is the fixed factor "season of farrowing" with four levels: winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November); e_{ijklm} is the error term.

For each subgroup (based on sow breed, sire boar breed, year, and season of farrowing), the mean values were calculated using the least squares means (LSM) method with corresponding errors (± *SE*), as well as the significance level of the influence of each factor included in the model (1). To analyse the combined effect of sow breed and sire boar breed on reproductive traits, a twofactor analysis of variance (with fixed factors) was employed. Pairwise comparisons of subgroup means were carried out using Tukey's *post-hoc* analysis (for unequal group sizes). All mathematical and statistical analyses of the data were performed using STATISTICA v.7 software. To analyse the relationship between gestation length and both qualitative and quantitative traits of the litter and individual piglets at birth, estimates of the phenotypic correlation coefficient (*r*) were calculated for animal groups based on sow breed. Subsequently, a meta-analysis was conducted, incorporating both the authors' own results and the estimates of the phenotypic correlation coefficient between gestation length and other reproductive traits of sows, as reported in the literature.

The literature search was conducted using the bibliographic databases PubMed and Google Scholar based on the key terms (and their combinations) "pig, swine", "sow", "reproductive traits", and "gestation length" from 2019 to 2023. A total of 101 publications meeting these criteria were analysed. Subsequently, based on the obtained values of the phenotypic correlation coefficient, a meta-analysis was performed using the online programme Meta-Mar v. 3.5.1. A test for data heterogeneity was conducted using the χ^2 test (with corresponding significance level *P*) and the heterogeneity index I^2. In cases where the initial data showed low heterogeneity ($I^2 \leq 50\%$ and $P > 0.05$), a fixed-effects model was used, whereas, for high heterogeneity in the data ($I^2 > 50\%$ and $P < 0.05$), a random-effects model was applied. The results of the meta-analysis represented the "general" estimate of the correlation coefficient and its 95% confidence interval (Borenstein *et al.*, 2021). The care and handling of the experimental animals and all related procedures were carried out by the Law of Ukraine No. 249 "On the Procedure for Carrying out Experiments and Experiments on Animals by Scientific Institutions" (2012) and the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986).

RESULTS AND DISCUSSION

General characteristics of the reproductive traits of sows. The average number of piglets per litter in the sows studied at the private joint-stock company "Plemzavod "Stepnoi" in the Zaporizhzhia Region from 2010 to 2013 was 10.06 ± 0.05 (ranging from 3 to 21 piglets), with an average gestation length of 115.9 ± 0.04 days (ranging from 110 to 121 days) (Table 1). The average number of stillborn piglets was 1.46 ± 0.03, and the percentage of stillborn piglets in the litter varied from 0 to 100%, with a mean of 13.7 ± 0.32%. The average birth weight of live piglets ranged from 1.0 to 2.0 kg (with a mean of 1.80 ± 0.002 kg), while the average litter weight was 15.6 ± 0.08 kg. Notably, for all reproductive traits (except for the total number of piglets in the litter at birth), there was significant skewness in the distribution, particularly for the number and percentage of stillborn piglets in the litter.

Gestation length exhibited very high levels of both between- and within-breed variability (Table 2). The shortest average gestation length was observed for the indigenous Croatian breed, Banija spotted pig (113.0 days), the Chinese Qingping pig (113.6 days), and crosses between the European Hampshire and Indian Desi breeds (113.6 days). In contrast, Berkshire sows had an average gestation length of nearly five days longer (118.4 days).

Table 2*. Gestation length by breed/genotype of the sow and country of origin, days*

Sow breed/crossbreed	Country	*n*	*Mean*	*min – max*	*SD*	*CV, %*	Source
Berkshire	Poland	58	118.4	-	2.54	2.15	B. Nowak *et al.*(2020b)
Large White	Thailand	9,655	116.7	110 – 122	1.38	1.18	R. Bumpenkul & N. Imboonta (2021)
Large White	China	19,306	115.1	105 – 127	1.81	1.57	G. Yu *et al.* (2022)
Large White	Poland	258	114.9	-	1.41	1.23	B. Nowak *et al.* (2020b)
Large White	Japan	8,649	114.0	110 – 118	1.30	1.14	S. Ogawa *et al.* (2019)
Large White × Landrace	USA	473	115.8	113 – 119	0.80	0.69	K.M. Gourley *et al.* (2020)
Large White × Landrace	USA	728	115.5	113 – 119	1.30	1.13	K.M. Gourley *et al.* (2020)
Hampshire	Poland	32	115.1	-	1.24	1.08	B. Nowak *et al.* (2020b)
Hampshire × Desi	India	149	113.6	-	1.40	1.23	T. Aeir *et al.* (2020)
Duroc	Thailand	5,042	115.6	110 – 122	1.49	1.29	R. Bumpenkul & N. Imboonta (2021)
Duroc	China	1,887	115.6	108 – 119	1.20	1.04	Y. Yang *et al.* (2023)
Duroc	Poland	99	114.6	-	2.15	1.88	B. Nowak *et al.* (2020b)
Duroc	Ukraine	1,333	114.9	110 – 120	1.68	1.46	own data
Yorkshire	China	74,796	114.1	104 – 124	1.48	1.30	Y. Yang *et al.* (2023)
Yorkshire	Poland	139	115.4		1.86	1.61	B. Nowak *et al.* (2020b)
Landrace	Thailand	14,112	116.8	110 – 122	1.34	1.15	R. Bumpenkul & N. Imboonta (2021)
Landrace	China	21,787	115.9	106 – 124	1.45	1.25	Y. Yang *et al.* (2023)
Landrace	Poland	150	114.7	-	1.64	1.43	B. Nowak *et al.* (2020b)
Landrace	Japan	10,637	114.0	110 – 118	1.30	1.14	S. Ogawa *et al.* (2019)
Landrace	Ukraine	1,530	116.7	110 – 121	1.71	1.47	own data
Landrace × Yorkshire	Thailand	13,421	114.8	109 – 120	1.80	1.57	P. Tospitakkul *et al.* (2019)
Landrace × Yorkshire	Poland	556	117.6	113 – 121	1.30	1.11	A. Pietruszka *et al.* (2020)
Landrace × Yorkshire	Vietnam	210	115.3	110 – 120	1.80	1.56	N.H. Nam & P. Sukon (2020a)
Landrace × Yorkshire	Vietnam	1,020	114.8	105 – 126	1.60	1.39	N.H. Nam & P. Sukon (2020b)
Banija spotted pig	Croatia	69	113.0	-	1.63	1.44	S. Menčik *et al.* (2019)
Qingping pig	China	398	113.6	110 – 117	1.23	1.08	Z. Liu *et al.* (2022)

Note: *CV – coefficient of variation*
Source: *developed by the authors*

On the other hand, the estimates obtained from different countries and herds also varied significantly. For example, for a Large White herd in Japan, the average gestation length was estimated at 114.0 days, while in Thailand, for animals of the same breed, the estimated gestation length was 116.7 days. Gestation length was characterised by a very low level of individual variability. The coefficient of variation for this trait varied within a range of only 1-2% for different herds (Table 2). For the animals in the experimental herd, this estimate was 1.65%. The widest range of gestation length values obtained for individual sows included an interval from 104 to 127 days, although most sows farrowed 110-120 days after insemination.

Gestation length is characterised by relatively high heritability (h^2) and repeatability estimates compared to other reproductive traits in sows. For example, for Large White, Landrace, and Duroc sows, heritability estimates ranged from 0.26 to 0.32, while similar estimates for the total number born and number born alive were significantly lower (0.05-0.13 and 0.07-0.12, respectively). Notably, gestation length also exhibited a higher level of repeatability compared to other reproductive traits. In the study by Y. Yang *et al*. (2023), heritability estimates for gestation length were even higher – 0.43, 0.28, and 0.33 for Duroc, Landrace, and Yorkshire sows, respectively. For Landrace and Large White sows in Japan, heritability estimates for gestation length were 0.29 and 0.34, and repeatability estimates were 0.38 and 0.40, respectively. In contrast, for other traits characterising litter size, these estimates were significantly lower, ranging from 0.08 to 0.18 and 0.13 to 0.24, respectively.

The influence of sow and sire boar breed on the variability of reproductive traits. A significant effect of the sow breed on the expression of her reproductive traits included in the analysis was established, except for the number and proportion of stillborn piglets in the litter (Table 3).

Table 2*. LSM estimates (± SE) of sow reproductive traits depending on their breed*

Trait (unit of measurement)	Sow breed		*P*
	DR (*n* = 1,309)	LN (*n* = 1,508)	
GL (days)	114.9 ± 0.05a	116.6 ± 0.05b	< 0.001
TNB (heads)	9.36 ± 0.08a	10.74 ± 0.08b	< 0.001
NBA (heads)	8.07 ± 0.07a	9.30 ± 0.08b	< 0.001
NSB (heads)	1.29 ± 0.05a	1.44 ± 0.06a	ns
SBR (%)	12.8 ± 0.46a	12.5 ± 0.49a	ns
LWB (kg)	14.5 ± 0.13a	16.6 ± 0.13b	< 0.001
MBW (kg)	1.80 ± 0.004a	1.79 ± 0.004b	< 0.001

Note: *P – significance level. ns – P > 0.05. Significant differences between means of individual subgroups (P < 0.05) based on Tukey's multiple comparison test are indicated by different letters*
Source: *developed by the authors*

Duroc sows performed less favourably than Landrace sows in terms of gestation length, total number of piglets born, number of piglets born alive, and consequently, total litter weight at birth (in all cases: $P < 0.001$). However, the average birth weight of piglets from Duroc sows was significantly higher ($P < 0.001$) compared to those from Landrace sows. Previous studies have already established that sow breed has a significant impact on gestation length. For instance, R. Bumpenkul and N. Imboonta (2021) demonstrated that Large White sows (116.7 days) and Landrace sows (116.7 days) had significantly longer gestation lengths ($P < 0.001$) compared to Duroc sows (115.6 days). Furthermore, significant differences were also observed between the studied breeds in terms of total number of piglets born, as well as the number of live and stillborn piglets. Landrace and Large White sows exhibited the highest values for these traits. In the study by Y. Yang *et al.* (2023), the average gestation length for Duroc, Landrace, and Yorkshire sows was 115.6, 115.9, and 114.1 days, respectively. Similar differences were observed in terms of the total number of piglets born, the number of live and stillborn piglets, total litter weight, and average birth weight. In the study by B. Nowak *et al.* (2020a), it was also shown that sow breed had a significant impact on reproductive traits related to litter size (total number born, number born alive, proportion of stillbirths, etc.). However, no significant effect of sow breed on the number of stillborn piglets was demonstrated, as in the current study. Large White and Landrace sows exhibited the best reproductive performance. A significant effect of the sire boar breed on sow reproductive traits was established, except for gestation length and total number born (Table 4).

Table 4*. LSM estimates (± SE) of sow reproductive traits depending on sire boar breed*

Trait (unit of measurement)	Sire boar breed			*P*
	DR (*n* = 827)	LN (*n* = 1,353)	LW (*n* = 637)	
GL (days)	115.7 ± 0.07a	115.9 ± 0.05a	115.8 ± 0.07a	ns
TNB (heads)	10.10 ± 0.11a	9.93 ± 0.08a	10.12 ± 0.10a	ns
NBA (heads)	8.48 ± 0.10a	8.53 ± 0.07a	9.05 ± 0.09b	< 0.001
NSB (heads)	1.62 ± 0.07c	1.40 ± 0.06b	1.08 ± 0.07a	< 0.001
SBR (%)	15.1 ± 0.61c	12.9 ± 0.48b	9.9 ± 0.59a	< 0.001
LWB (kg)	14.9 ± 0.17b	15.4 ± 0.13a	16.3 ± 0.16a	< 0.001
MBW (kg)	1.76 ± 0.005b	1.81 ± 0.004a	1.80 ± 0.005a	< 0.001

Note: *P – significance level. ns – P > 0.05. Significant differences between means of individual subgroups (P < 0.05) based on Tukey's multiple comparison test are indicated by different letters*
Source: *developed by the authors*

The average number of live piglets in the litter at birth, as well as the total litter weight at birth, was significantly ($P < 0.001$) higher in sows inseminated with semen from Large White sire boars (9.05 piglets and 16.3 kg, respectively) compared to those inseminated with semen from Duroc or Landrace sire boars. Birth losses (i.e., the number and percentage of stillborn piglets) were highest in sows inseminated with Duroc sire boar semen (1.62 piglets and 15.1%, respectively), and lowest in sows inseminated with Large White sire boar semen (1.08 piglets and 9.9%, respectively). Sows inseminated with Landrace sire boar semen occupied an intermediate position and differed significantly from both groups (1.40 piglets and 12.9%, respectively). The average birth weight of a live piglet was significantly ($P < 0.001$) higher in sows inseminated with semen from Landrace sire boars (1.81 kg) and Large White boars (1.80 kg) compared to those inseminated with Duroc sire boar semen.

In the study by M.L.M. Pedersen *et al.* (2019), it was found that sows inseminated with semen from Pietrain sire boars had, on average, 0.5 more live piglets in the litter at birth compared to those inseminated with Duroc sire boar semen. However, the mortality rate of suckling piglets before weaning was higher in the offspring from Pietrain sire boars. In the study by A. Kramarenko *et al.* (2023), it was previously shown that the percentage of stillborn piglets in litters from sows inseminated with Duroc sire boar semen was significantly higher ($P < 0.001$) compared to those inseminated with semen from Ukrainian Meat breed, Large White, or Landrace sire boars. S. Menčik *et al.* (2020) demonstrated a significant ($P < 0.05$) influence of the sire boar on the number of stillborn piglets in the litter from crossbred sows (Landrace × Large White) during the second, while the duration of gestation was significantly associated with the total number of piglets born. This influence can partly be explained by the characteristics of the ejaculate, which significantly differ between boars of different breeds (Kamanova *et al.*, 2021). In the study by H. Petrocelli and C. Batista (2019), it was shown that the origin of the boar affected both the fertility of the sows and the total number of piglets born. A significant combined effect of both sow breed and sire boar breed on the reproductive traits of sows was also established, again, except for gestation length and total number of piglets in the litter (Table 5).

***Table 5**. Variability estimates (Mean ± SE) of reproductive traits in sows depending on their breed and sire boar breed*

Trait (unit of measurement)	Sow breed						$P_{S/B}$
	DR			LN			
	Sire boar breed						
	DR	LN	LW	DR	LN	LW	
n	797	235	301	42	1,139	348	
GL (days)	114.8 ± 0.06a	115.1 ± 0.11a	114.9 ± 0.09a	116.7 ± 0.25b	116.7 ± 0.05b	116.6 ± 0.09b	ns
TNB (heads)	9.39 ± 0.08a	9.47 ± 0.15a	9.27 ± 0.13a	10.45 ± 0.39ab	10.60 ± 0.08b	10.81 ± 0.15b	ns
NBA (heads)	7.78 ± 0.08a	8.09 ± 0.16ab	8.19 ± 0.13ab	9.43 ± 0.34bcd	9.01 ± 0.07c	9.74 ± 0.14d	0.006
NSB (heads)	1.61 ± 0.06b	1.38 ± 0.13ab	1.08 ± 0.08a	1.02 ± 0.24ab	1.60 ± 0.06b	1.07 ± 0.08a	0.009
SBR (%)	16.4 ± 0.64c	13.3 ± 1.24abc	11.5 ± 0.95ab	8.4 ± 1.96abc	14.0 ± 0.48bc	9.5 ± 0.78a	0.010
LWB (kg)	13.9 ± 0.13d	15.3 ± 0.27a	14.9 ± 0.22a	16.8 ± 0.64abc	16.4 ± 0.13b	17.6 ± 0.24c	< 0.001
MBW (kg)	1.77 ± 0.004b	1.85 ± 0.009c	1.81 ± 0.007a	1.79 ± 0.025abc	1.81 ± 0.004a	1.80 ± 0.008ab	0.013

***Note:** PS/B – significance level for the combined effect of the factors "sow breed" and "sire boar breed". ns – P > 0.05. Significant differences between means of individual subgroups (P < 0.05) based on Tukey's multiple comparison test are indicated by different letters*
***Source:** developed by the authors*

The best reproductive performance (highest number of live piglets in the litter, highest total litter weight at birth, and the lowest number and percentage of stillborn piglets in the litter) was observed in Landrace sows inseminated with semen from Large White or Landrace sire boars. In contrast, the poorest performance was observed in Duroc sows inseminated with Duroc sire boar semen. The highest average birth weight was found in piglets born to Duroc sows inseminated with semen from Landrace sire boars.

The study by O.L. Bondoc *et al.* (2019) demonstrated that the reproductive qualities of sows and the traits of piglets at birth and weaning were influenced by the combination of the sow and sire boar breeds (Large White and Landrace). Offspring from crossbred litters exhibited better performance than purebred animals. For instance, crossbred animals of Large White × Landrace showed significantly ($P < 0.05$) more teats than animals of Landrace × Large White. In the case of Chinese-origin crossbred pigs (Shanxia black pig and Lulai black pig), direct crosses had better reproductive traits than reciprocal crosses (Yan *et al.*, 2021). Similarly, the research by J.K. Hagan and N.N. Etim (2019) showed that purebred Large White sows produced fewer piglets at birth (12.5 piglets) compared to crossbred animals (Large White × Duroc), which had an average of 14.2 piglets. However, the study by H. Jankowiak *et al*. (2020) indicated that the genotype of the piglets (whether purebred or crossbred) had a lesser impact than the genotype of the sow itself.

The influence of the year and season of farrowing on the reproductive traits of sows. Sows that farrowed in different years significantly differed in all reproductive traits, except for lactation duration, which varied within a very narrow range of 115.7-115.9 days (Table 6).

Table 6*. LSM estimates (± SE) of reproductive traits in sows depending on the year of farrowing*

Trait (unit of measurement)	Year of farrowing				P
	2010 (*n* = 713)	2011 (*n* = 778)	2012 (*n* = 848)	2013 (*n* = 478)	
GL (days)	115.7 ± 0.06a	115.8 ± 0.06a	115.7 ± 0.06a	115.9 ± 0.08a	ns
TNB (heads)	9.77 ± 0.10a	10.44 ± 0.09b	9.97 ± 0.09a	10.02 ± 0.12ab	< 0.001
NBA (heads)	8.34 ± 0.09b	8.83 ± 0.09a	8.78 ± 0.08a	8.80 ± 0.11a	< 0.001
NSB (heads)	1.44 ± 0.07bc	1.62 ± 0.07c	1.19 ± 0.06a	1.22 ± 0.08ab	< 0.001
SBR (%)	13.7 ± 0.56bc	14.4 ± 0.54c	10.9 ± 0.50a	11.6 ± 0.69ab	< 0.001
LWB (kg)	14.9 ± 0.15a	16.5 ± 0.15c	15.6 ± 0.14b	15.1 ± 0.19ab	< 0.001
MBW (kg)	1.79 ± 0.005a	1.87 ± 0.004c	1.78 ± 0.004a	1.72 ± 0.006b	< 0.001

Note: *trait designations as in Table 1. P – significance level. ns – P > 0.05. Significant differences between means of individual subgroups (P < 0.05) based on Tukey's multiple comparison test are indicated by different letters*
Source: *developed by the authors*

The best performance for various reproductive traits was observed in different years. For instance, the highest total number of piglets at birth was recorded in 2011 (10.44 piglets), while the highest *LSM* estimates for the number of live piglets at birth were observed during 2011-2013. The season of farrowing also significantly affected the duration of gestation and other litter characteristics, except the number and proportion of stillborn piglets in the litter (Table 7).

Table 7*. LSM estimates (± SE) of reproductive traits in pigs depending on the season of farrowing*

Trait (unit of measurement)	Season of farrowing				P
	Winter (*n* = 613)	Spring (*n* = 848)	Summer (*n* = 819)	Autumn (*n* = 537)	
GL (days)	116.2 ± 0.07b	115.8 ± 0.06a	115.6 ± 0.06a	115.5 ± 0.08a	< 0.001
TNB (heads)	10.09 ± 0.10ab	10.31 ± 0.09b	9.88 ± 0.09a	9.93 ± 0.11ab	0.003
NBA (heads)	8.60 ± 0.09a	8.94 ± 0.08b	8.58 ± 0.08a	8.62 ± 0.10a	0.005
NSB (heads)	1.48 ± 0.07a	1.37 ± 0.06a	1.30 ± 0.06a	1.31 ± 0.08a	ns
SBR (%)	13.5 ± 0.59a	12.8 ± 0.51a	12.1 ± 0.52a	12.3 ± 0.66a	ns
LWB (kg)	15.4 ± 0.16a	16.1 ± 0.14b	15.3 ± 0.14a	15.2 ± 0.18a	< 0.001
MBW (kg)	1.80 ± 0.005a	1.81 ± 0.004b	1.79 ± 0.004a	1.77 ± 0.005ab	< 0.001

Note: *P – significance level. ns – P > 0.05. Significant differences between means of individual subgroups (P < 0.05) based on Tukey's multiple comparison test are indicated by different letters.*
Source: *developed by the authors*

The highest ratings for both litter size and the total litter weight and the weight of individual piglets were obtained for sows that farrowed during the spring season (i.e., from March to May), while the poorest performance was most often observed in animals that farrowed during the summer season. T.J. Zindove *et al*. (2021) previously noted significant differences between the individual years of the study regarding the reproductive traits of crossbred sows (Landrace × Large White) under conditions in Zimbabwe. A highly significant ($P < 0.001$) effect of the year and season of farrowing on litter size and the weight of individual piglets at birth was also established for Yorkshire sows, whereas no such pattern was observed among Duroc sows.

The significant influence of the farrowing season on reproductive traits has also been demonstrated for Large White sows and their crosses with Duroc, housed in Ghana (Hagan & Etim, 2019). Better results were obtained for farrowings that occurred during the cooler rainy season of the year, compared to those during the hot dry season. These differences applied to both litter size and piglet birth weight. Furthermore, the combined effects of second- and third-order factors, such as "season of the year" × "breed of sow" and "season of the year" × "parity" × "breed of sow", were noted for both litter size at birth and weaning, as well as for piglet birth weight. This may be linked to a reduction in the quality and quantity of sire boar semen production, as well as a decline in the milk production of sows under heat-stress conditions. In crossbred sows (Landrace × Large White), it was shown that the average weight of live piglets at birth was significantly lower for farrowings that occurred in July.

In contrast to the findings of the current study, which showed no effect of the farrowing season on the number and proportion of stillborn piglets in the litter, S. Schild *et al.* (2019) indicated that the risk of stillbirth among crossbred sows (Landrace × Yorkshire) significantly increased during the warmer months, particularly when the air temperature exceeded 27°C. On the other hand, for crossbred pigs (Hampshire × Desi) in India, the farrowing season did not affect either the duration of gestation or the size and weight of the litter at birth (Aeir *et al.*, 2020).

Relationship between gestation length and reproductive traits in sows. Eight publications (i.e., 7.9% of the total number of articles analysed) from the period 2019-2023 were selected, containing estimates of the phenotypic correlation coefficient (Pearson's) between gestation length and reproductive traits in sows. The sows represented widely distributed cross-border breeds (Duroc, Landrace, Large White, and Yorkshire) or their crosses (Landrace × Large White, Landrace × Yorkshire). Additionally, data obtained by the authors for the experimental group of sows were included in the meta-analysis (Table 8). As a result, the initial database for the meta-analysis, containing estimates of the phenotypic correlation coefficient, included 49 entries.

***Table 8**. Correlation coefficients between gestation length and reproductive traits by sow breed*

Trait (unit of measurement)	Sow breed	
	DR ($n = 1,333$)	LN ($n = 1,529$)
TNB (heads)	-0.167 ($P < 0.001$)	-0.123 ($P < 0.001$)
NBA (heads)	-0.076 ($P = 0.006$)	-0.049 (ns)
NSB (heads)	-0.133 ($P < 0.001$)	-0.121 ($P < 0.001$)
SBR (%)	-0.059 ($P = 0.032$)	-0.088 ($P = 0.001$)
LWB (kg)	-0.072 ($P = 0.009$)	-0.057 ($P = 0.026$)
MBW (kg)	0.015 (ns)	-0.015 (ns)

***Note:** P – significance level. ns – $P > 0.05$*
***Source:** developed by the authors*

Due to the very high estimates of the heterogeneity index (I^2) for all the included data (97.0100.0%), a random-effects model was used in all cases for the meta-analysis (Table 9).

***Table 9**. Results of the meta-analysis of the correlation coefficient between gestation length and reproductive traits in sows*

Trait (unit of measurement)	K	I^2, %	χ^2	P	r_{gen}	95% CI
TNB (heads)	12	98.0	475.65	< 0.01	-0.12	-0.16...-0.08
NBA (heads)	11	98.0	472.22	< 0.01	-0.11	-0.15...-0.06
NSB (heads)	13	100.0	161.51	< 0.01	-0.02	-0.06...+0.01
SBR (%)	6	97.0	199.72	< 0.01	-0.12	-0.18...-0.06
LWB (kg)	7	100.0	99.04	< 0.01	+0.06	+0.01...+0.11

***Note:** K – number of studies included in the meta-analysis. P – significance level. I^2 – heterogeneity index estimate. r_{gen} – "general" estimate of the phenotypic correlation coefficient. 95% CI – 95% confidence interval for the "general" estimate*
***Source:** developed by the authors*

For the correlation coefficient between gestation length and the total number of piglets in the litter, as well as the number of live piglets at birth, the "general" estimates were -0.12 and -0.11, respectively. In both cases, the 95% confidence interval for the "general" estimates did not include zero, therefore, a significant (negative) relationship between these two traits and gestation length can be considered established. Regarding the number of stillborn piglets in the litter, the "general" estimate was very low (-0.02), and it fell within the 95% confidence interval (-0.06 to +0.01). Hence, in this case, it cannot be considered that a significant relationship between gestation length and the number of stillborn piglets in the litter has been established.

In the analysis of the relationship between gestation length and the total litter weight at birth, the "general" estimate of the phenotypic correlation coefficient was -0.12 (with a 95% confidence interval from -0.18 to -0.06). In this case, zero does not fall within the confidence interval, so it can be considered that a significant (negative) relationship between gestation length and total litter weight at birth has been established. Finally, for the relationship between gestation length and the average birth weight of live piglets, the "general" estimate of the phenotypic correlation coefficient was +0.06 (with a 95% confidence interval from +0.01 to +0.11). As in the previous case, since zero does not fall within the confidence interval, a significant (positive) relationship between these traits can be considered established. Based on the results of the meta-analysis, the following conclusions can be drawn regarding the relationships between the gestation length of sows and the traits of their litters at birth (Fig. 1).

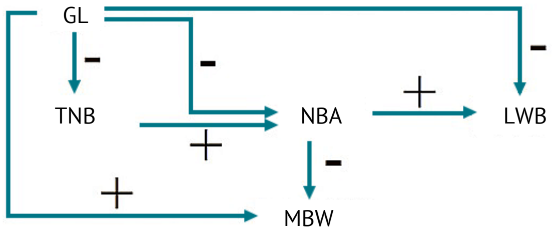

***Figure 1**. Schematic of the relationships between gestation length and reproductive traits of sows based on the results of the meta-analysis*

***Note:** the symbol "+" indicates a significant positive relationship, while the symbol "–" indicates a significant negative relationship between the corresponding traits*

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

There is a negative relationship between gestation length and the total number of piglets in the litter at birth. However, since the number of live piglets in the litter at birth (i.e., the realised litter size) is largely determined by the potential litter size, which includes both live and stillborn piglets, the relationship between gestation length and the number of live piglets in the litter at birth will also be negative. The number of live piglets in the litter at birth significantly influences the total litter weight at birth. Therefore, the relationship between this trait and gestation length will also be negative. Finally, as both the total number of piglets and the number of live piglets at birth increase, the average birth weight of live piglets will decrease, and consequently, the relationship between this trait and gestation length will be positive. Notably, the relationship between gestation length and the total number of piglets, as well as the number of live piglets in the litter at birth, often follows a nonlinear pattern (Pietruszka *et al.*, 2020). In this case, the descending right-hand portion of this curve is more pronounced, which explains why the correlation coefficient between gestation length and litter traits at birth is negative.

On the other hand, a gestation length that is no shorter than the average (usually 114 days) promotes better piglet development at birth and, accordingly, a lower level of postnatal mortality. Furthermore, the number of stillborn piglets in the litter increased with a decrease in gestation length, while the average weight of a piglet at birth tended to decrease as litter size increased (Ogawa *et al.*, 2019). In the study by N.H. Nam and P. Sukon (2020b), it was shown that a gestation length shorter than 114 days is a significant risk factor for stillbirth among Landrace × Yorkshire sows in Vietnam. Sows with a gestation length of less than 114 days had 1.80 times higher ($P < 0.001$) chances of having at least one stillborn piglet in the litter. This may be related to underdeveloped lungs in piglets born during early farrowing (before 114 days of gestation). Although the current study found a significant (negative) correlation between gestation length and the number (and proportion) of stillborn piglets in the litter (Table 8), the generalised results from the meta-analysis for different breeds and/or herds did not confirm the widespread nature of this pattern. Thus, gestation length in sows is a complex trait, shaped by both genotypic (sow and sire boar breed) and environmental (year and season of farrowing) factors, which, in turn, influence the variability in litter size at birth.

CONCLUSIONS

The average gestation length for the animals in the experimental herd was 115.9 ± 0.04 days (ranging from 110 to 121 days) and was characterised by very low inter-individual variability (the coefficient of variation was only 1.65%). A significant effect of sow breed on gestation length and other litter traits at birth was confirmed (in all cases: $P < 0.001$), except the number and proportion of stillborn piglets in the litter. Furthermore, no significant effect of the sire boar breed on gestation length or total litter size was found for sows inseminated with their semen. Overall, the best reproductive performance (maximum number of piglets born in the litter with the minimum level of stillbirths) was observed in Landrace sows inseminated with the semen of Large White or Landrace sire boars. The year of farrowing significantly affected all reproductive traits of the sows (in all cases: $P < 0.001$), except for gestation length. The highest gestation lengths were recorded for sows that were farrowed in winter, while for the remaining reproductive traits, the best results were observed in spring farrowings. The meta-analysis results indicate that the "general" phenotypic correlation coefficients between gestation length, on the one hand,

and total litter size, number of live piglets in the litter, and total litter weight at birth, on the other hand, were significant and negative (-0.12 to -0.11). The correlation between gestation length and the average weight of live piglets at birth was significant and positive (+0.06). The meta-analysis results did not support the presence of a significant relationship between gestation length and the number of stillborn piglets in the litter. Future research perspectives include analysing the impact of sow gestation length on the growth and survival of suckling piglets until weaning.

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CONFLICT OF INTEREST

None.

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Аналіз мінливості тривалості поросності свиноматок та її зв'язок із ознаками гнізда при народженні

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Анотація. Тривалість поросності є важливою комплексною полігенною ознакою свиноматки, що значною мірою формує її продуктивні якості та впливає на формування плоду протягом ембріонального періоду. Головною метою даного дослідження став аналіз впливу генотипових (порода свиноматки та кнура-плідника) та паратипових (рік та сезон опоросу) факторів на мінливість тривалості поросності свиноматок та визначення характеру зв'язку тривалості поросності з ознаками гнізда при народженні (із використанням алгоритму мета-аналізу).Для аналізу було використано первинні матеріали щодо відтворювальних ознак свиноматок основного стада приватне акціонерне товариство «Племзавод «Степной» Запорізької області, отримані протягом 2010-2013 рр. Для тварин дослідного стада оцінка середньої тривалості поросності складала 115,9 ± 0,04 днів (із розмахом від 110 до 121 дня). При цьому, тривалість поросності характеризувалася дуже низьким рівнем міжіндивідуальної мінливості (оцінка коефіцієнта варіації складала лише 1,65 %). Свиноматки породи дюрок поступалися тваринами породи ландрас за тривалістю поросності, загальною кількістю поросят та кількістю живих поросят у гнізді при народженні (у всіх випадках: $P < 0{,}001$). Встановлено вірогідний вплив породи кнура-плідника на відтворювальні ознаки свиноматок, за виключенням тривалості поросності та загальної кількості поросят у гнізді. Найвищі оцінки тривалості поросності було отримано протягом зимових місяців року, у той час як для решти репродуктивних ознак свиноматок найкращі оцінки було отримано для весняного періоду. В результаті мета-аналізу встановлено, що «генеральні» оцінки коефіцієнту фенотипової кореляції між тривалістю поросності та загальною кількістю поросят у гнізді, кількістю живих поросят у гнізді і загальною масою гнізда при народженні були вірогідні та від'ємні, у той час як оцінка між тривалістю поросності та середньою масою живого поросяти при народженні була вірогідна та додатна

Ключові слова: ознаки відтворення; генотипові та паратипові фактори; мета-аналіз; свині

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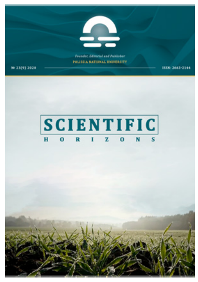

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Technologies of suspension cultivation in bioreactor of the *Chlamydophila abortus* strain on McCoy cell culture

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Abstract. The purpose of the study was to investigate the cultural method of the diagnosis of *Chlamydophila abortus*. For this purpose, laboratory diagnosis of pathological material from the farm was carried out at the LLP Research and Production Enterprise "Antigen", where, based on the data of anamnesis, data of occurrence of similar epizootic picture for the last two years, examination and diagnostic manipulations (clinical symptoms, autopsy data, epizootological anamnesis), the preliminary diagnosis "Enzootic

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abortion of ewes caused by *Chlamydophila abortus*" was made. Samples from the organs of aborted foetuses and swabs with vaginal contents were taken to confirm this diagnosis. Complement fixation tests with chlamydia antigen were found to be positive in 7 (23%) of the 30 animals that were examined. To isolate the pathogen, the technology of suspension cultivation in a bioreactor of the *Chlamydophila abortus* strain on McCoy cell culture was used. Isolated pathological material was grown in McCoy cell cultures that were suspended in a bioreactor in Dulbecco's Modified Eagle's Medium (DMEM) nutrient medium with 10% foetal bovine serum and antibiotics at a concentration of 2×105 cells/mL. Enzyme immunoassay was a confirmation of the successful result of cultivation. Enzyme immunoassay confirmed the presence of the pathogen in 60.9% of cases. 25 samples were received, which were positive. Thus, the accuracy of the cultural diagnostic method turned out to be almost 3 times higher than the serological diagnostic method. Serological examination revealed 23% presence of *Chlamydophila abortus* in the samples, and the cultural diagnostic method revealed 60.9%. Unfortunately, in practice, the use of the cultural diagnostic method is associated with a time-delayed result, which is a disadvantage of this diagnostic method compared to the use of polymerase chain reaction

Keywords: laboratory diagnostics; small cattle; enzootic abortion of ewes; intracellular parasitism; cultural diagnostic method; enzyme immunoassay

INTRODUCTION

The relevance of the study lies in the fact that the problems of loss of animal offspring as a result of abortions are a serious objective modern problem and the study of pathogens that provoke them is extremely important, because the pathogen *Chlamydophila abortus* is not the main cause of mass abortions of farm animals, but is a widespread relatively recently discovered pathogen that causes zoonotic diseases. The prevalence figures of infection caused by this pathogen underline the relevance of its study. Thus, R. Akter *et al*. (2021) note that this pathogen causes periodic abortions of horses, although according to his data, 53-80% of all abortions of horses occur due to bacterial infections in the last months of pregnancy. In the study by T.A. Al-Ahmed and S.S. Salman (2020) a direct serological study revealed 17% positive tests for *Chlamydophila abortus* in cows in Iraq, whereas statistics vary greatly from country to country. In Belgium it is 1.69%, Ireland – 4.44%, India – 4.65%, China – 17.83%, Poland – 26.4%, Turkey – 26.92%, Australia – 45%, Iran – 48.4%, Taiwan – 51.35%. Evidently, these completely different figures indicate that there are various factors that can affect the inaccuracy of these data, both related to growing technologies and laboratory errors and different conditions of statistical calculations. D. Longbottom *et al*. (2021), note the ever-increasing occurrence of *Chlamydophila abortus* in chickens, and J.A. Origlia *et al*. (2019) in parrots, as birds act as a reservoir for the transmission of the pathogen to cattle and other farm animals.

Chlamydia is a family of obligate intracellular gram-negative bacteria, consisting of 16 species. These are zoonotic pathogens of infectious diseases. This genus has a two-phase development cycle, preferring to settle inside the epithelial cells of animals and humans, mainly selectively affecting the reproductive system (Kirimbayeva *et al*., 2023). This pathogen causes the greatest harm to sheep breeding by causing the enzootic abortion of ewes. This infectious disease provokes diseases of the reproductive system of small cattle of both sexes, abortions, and the birth of weak, non-viable offspring, causing losses of GBP 20 million per year in the UK alone. As a rule, abortion occurs in the last 2-3 weeks of lambing during that period and on farms where ewes are densely spaced (Tyrunskiy *et al*., 2023). In addition to the loss of lambs, which, in addition to abortions, is manifested by the birth of full-term dead foetuses, non-viable lambs that do not live for more than two days, the economic costs associated with culling sheep and the cost of treating them are recorded. Enzootic pattern: at the beginning a small number of infected animals, in the second year the so-called "abortion storm" with up to a third of the herd affected (Nyzhnyk *et al*., 2024).

As a rule, it takes some time to find out the reason for the abortion of sheep. For research, whole blood samples and stillborn foetuses from small cattle that have had an abortion are sent to the laboratory. Cultivation of *Chlamydophila abortus* is a method of taxonomic identification, which is based on the isolation of this pathogen. This is a difficult job that requires the involvement of an experienced C3 laboratory professional for this purpose. This method compares favourably with serological tests and polymerase chain reaction, which suffer from inaccuracy due to the carelessness of specialists processing or selecting the material. Total nucleic acid extraction provides an opportunity for differential diagnosis from other pathogens that could cause abortion. According to A.A. Adesiyun *et al*. (2020), M. Şevik (2023), in veterinary practice, coinfection has often been detected in modern research. This complicates the diagnosis.

For the detection of *Chlamydophila abortus*, its nucleic acid amplification tests are most commonly used, hence in practice culturing is usually not performed to separate *Chlamydophila abortus*. These actions are difficult to assess antibiotic sensitivity of isolated

Chlamydophila abortus cultures. This microorganism is formed in a non-acidic intracellular vacuole, which is called inclusion. The development of this unusual chlamydial niche occurs as soon as contact of the microorganism with the host cell occurs, evolving throughout the period of infection. According to J. Cingolani *et al.* (2019) and O. Alzuguren *et al.* (2023), one set of proteins that are necessary for the modification of vacuoles is called membrane inclusion proteins. However, the intracellular development of *Chlamydophila abortus* is a poorly understood process.

The purpose of the study was to identify the practical benefits for the diagnosis of *Chlamydophila abortus* infection when using suspension cultivation on McCoy cell culture in a bioreactor. The objectives for achieving this purpose were to consider the methods of diagnosis of *Chlamydophila abortus*, to carry out cultural diagnostics of *Chlamydophila abortus*, and to investigate all the positive and negative aspects of cultural diagnostics.

LITERATURE REVIEW

In the field of livestock development, there is a list of problems affecting its advancement. The problems of herd renewability and herd reproduction are a pressing issue. There are a lot of factors that can affect these problems, but the infectious aspect is at the heart of most problems. *Chlamydophila abortus* is one of the infectious pathogens that cause disease in humans and animals.

As noted by S. Bommana and A. Polkinghorne (2019), F. Büyük *et al.* (2020), L.A. Campbell and D. Hahn (2020), abortions of farm animals that are caused by infectious aetiological causes are a serious problem in animal husbandry. Y.Y. Cheok *et al.* (2020), A.R. Cross *et al.* (2019), H.K. Cheong *et al.* (2019) note that in practice, those pathogens that are widely known, most often relate to zoonotic infections and that are easily cultured, are most easily diagnosed. These are *Brucella spp., Salmonella spp., Campylobacter spp., Listeria monocytogenes*. The pathogen that is more difficult to diagnose as a result of their properties – obligateness and intracellular infection – *Chlamydophila abortus* – is relatively new to veterinary practice and insufficiently studied.

The European Commission (2019) notes that this bacterium has some properties that complicate the diagnosis and differential diagnosis of infectious diseases in the practice of veterinary medicine, namely, mandatory intracellular host-dependent parasitism, conservation of morphological structure throughout the entire life cycle, division of vegetative forms, the fact that the microbe has a cell wall, sensitivity to a number of broad-spectrum antibiotics, and the existence of a single genus-specific antigen. All these properties are important in the analysis of infectious abortions, and diagnostic actions in case of suspected enzootic abortion of ewes. These scientific facts were the basis for determining this pathogen in an independent position among other prokaryotes.

Anamnesis does not give a complete picture and conclusions that the disease is caused by this particular pathogen. And there is no predisposition by age, breed, or seasonality. The study by T.A. Al-Ahmed and S.S. Salman (2020) noted, however, that 31.71% of diseased cattle belong to the group of animals under three years of age. The researchers explained this by the fact that a mild course of the disease was observed in seropositive cattle older than three years, practically insensitive to the pathogen, but being its carrier. The intracellular development cycle of *Chlamydophila abortus* slowed down in the body of these animals, and during this time immunity to it was developed.

N. Esmaeili *et al.* (2021), M. Fayez *et al.* (2021) and S. Filardo *et al.* (2022) note that the zoonotic potential, the death of embryos in early and late stages, and other economic losses should be the reason for the study of this pathogen. Initially, the veterinarian visualised a picture of suspected abortion caused by *Chlamydophila abortus* upon detection of diffuse placentitis. A. Gojam and D. Tulu (2020), F. Imkamp *et al.* (2022), K. Özgür (2022) highlighted the specificity of this pathogen in that in the form of elementary bodies that are not the cause of infection, *Chlamydophila abortus* does not reproduce, but spreads with abortive tissues, which are amniotic fluid and epithelial tissues of the birth canal, and with vaginal secretions that contain chlamydial agents. T.A. Al-Ahmed and S.S. Salman (2020) also considered the transmission factor with subclinical mastitis. There is a so-called "abortion storm", a phenomenon in which the involuntary birth of dead, non-viable offspring is observed simultaneously in several ewes. Animals become infected again (or the infection spreads to healthy animals) in an alimentary way. But it is also dangerous for people in contact with these infectious biomaterials.

The studies by A. Komar *et al.* (2019) and X. Zhang *et al.* (2020) on the prevalence of *Chlamydophila abortus* serovars and the presence of such a relatively new diagnostic feature of this pathogen as the possibility of coinfection note the reason for the complexity of abortive infections both at the individual and at the herd level. To diagnose this disease and the infection that caused it, clinical symptoms and epizootic analysis are non-specific. Diagnosis of *Chlamydophila abortus*, according to S. Nogarol *et al.* (2024), solves this problem in various ways, including the search for antibodies. Even almost a month after a pathological abortion, the antibody titre remains, which is suitable for such reactions as complement binding reaction and enzyme immunoassay. Direct diagnosis involves polymerase chain reaction (PCR), pathogen isolation, and direct microscopic examination. This is the effect when elementary corpuscles are detected on direct smears that are specific to this infectious agent. However, the final confirmation of this diagnosis is *in vivo* isolation or the already named PCR.

D.L. Hahn (2021), J.J. Rennick *et al.* (2021) and W. Gu *et al.* (2021) suggest that immunohistochemical analysis of aborted embryo tissue samples also provide diagnostic arguments. C. Braun *et al.* (2019) noted that isolation of chlamydia in cell culture is a laborious process that takes a fairly long-time process, but is a serious diagnostic argument in the long term. The method is highly specific, based on the identification of this pathogen directly from biological material. Another method – the Complement Fixation Test – can cross-react with other bacteria.

Real-time PCR for diagnosis has become more often used on samples obtained directly from animals that have been diagnosed with chlamydia. This is a direct search for nucleic acids interacting with the material provided to the laboratory. It is based on the search for those elements of the pathogen that remain unchanged regardless of mutations or phylogenetic features: primers. Polymerase and revertase enzymes. This method is really fast and is considered reliable, but in the field and in the presence of coinfection, there is a possibility of an incorrect diagnosis. However, as noted by R. Kvapil *et al.* (2021), there are confirmed cases of transmission of infection caused by *Chlamydophila abortus* from laboratory materials to humans, which is especially dangerous for female staff.

MATERIALS AND METHODS

Research area and sample collection. The study was conducted at the LLP Research and Production Enterprise "Antigen". The management of the herds met all standards of sheep rearing, the animals received complete feed in the form of grain, hay, and silage, succulent fodder from pastures was added in the spring and autumn period. The breed affiliation was not recorded during the research, but the Romanov breed established the basis of most herds. Abortions were recorded during the most productive breeding season in the period from March to May 2024. Samples were taken from pregnant sheep (n = 12), in which abortions were recorded 14-21 days before lambing for serological testing of *Chlamydophila abortus* (for this purpose, the Complement Fixation Test was used). In addition, to control the spread of infection, samples were taken from clinically healthy 8 rams and 12 lambs aged 2-3 months. Paired serums were taken from 10 pregnant ewes up to 48 hours after abortion and 21 days later. 12 specimens of aborted foetuses from 12 unvaccinated sheep in five herds were also selected. Isolation of *Chlamydophila abortus* was carried out using tissue samples (n = 41). These were the placental membranes of aborted sheep, the organs of the aborted foetus (liver, spleen, and lungs), and tampons with vaginal secretions. The obtained samples were isolated, labelled, and stored in portable cooler bags. Tampons with vaginal secretions were necessary for the extraction of nucleic acid. The liver, spleen, and lungs of the foetuses were frozen at a temperature of -80°C until further use.

Collection and preparation of samples for extraction of *Chlamydophila abortus* isolates. Samples for research: pieces of placenta (n = 12), vaginal swabs (n = 5), foetal lungs (n = 12), foetal liver (n = 5), and foetal spleen (n = 7). The samples were subjected to crushing, suspension in Dulbecco's Modified Eagle's Medium (DMEM) nutrient medium, which contains L-glutamic acid (4.9 mM), foetal bovine serum (10%), streptomycin (100 μg/mL), gentamicin (50 μg/mL), and nystatin (50 μg/mL) to obtain a 10% suspension. The suspension was centrifuged at 2,000 rpm for 10-15 minutes. Next, the supernatants were selected and portioned in small volumes. A separate part of the supernatant was used directly for *Chlamydophila abortus* on McCoy cell culture, and the other part was used for storage at -80°C. Tampons with vaginal secretions, which were collected for further cell culture inoculation, were placed in 1 mL of sucrose phosphate-glutamate buffer and 0.1% bovine serum albumin and contained at -80°C.

Isolation from chlamydia abortions. Subsequent preparation of the isolates was carried out using sustained passage devoid of intermediates on McCoy cell culture that were suspended in a bioreactor in a DMEM nutrient medium with 10% foetal bovine serum and antibiotics at a concentration of $2\times^{10.5}$ cells/mL. Aliquots of 2 mL of cellular suspension were distributed on mattresses with a flat bottom containing cover glasses. Next – daily incubation at 37°C and obtaining a single-layer culture. The somatotropic medium for the cells was removed and duplicated with a material that is being tested for the introduction of cells. After the introduction of the material being tested, the flasks were incubated for 120 minutes. Next, the liquid that was inoculated was reduced and duplicated with a DMEM substrate that contained antibiotics. After that, the cells were kept in an incubator for up to a day, then the substrate was refreshed again and incubated for 7 days. Three to five days after passage, one cover glass was fixed in methanol and enzyme-linked immunoassay (ELISA) was performed directly to prove the presence of *Chlamydophila abortus* in cell culture. The grown cells, which turned out to be negative within 7 days after passage, were inoculated again. This was done up to three passages. Single-layer substrates of McCoy cells were coated with a colouring reagent, which is part of a set of fluorescent globulins for the diagnosis of *Chlamydophila abortus*. The single-layer culture was fixed, washed, incubated, and studied under a CKX53 microscope (Olympus, Japan). The control was uninfected cells.

RESULTS AND DISCUSSION

In the period from March to May 2024, the information provided by LLP Research and Production Enterprise "Antigen" was analysed, where the following information was recorded for anamnesis. Spring seasonality in the farm was noted with recorded abortions, which manifested itself over the past three years. This does not match the data of A. Gojam and D. Tulu (2020), for which the highest seasonal prevalence, namely 18.11%, was recorded in the autumn period, and the lowest was recorded in the summer period (2.22%). The clinical pattern is similar: abortion on the last 21 days of lambing, stillbirth, prolonged placentitis, vaginitis, mastitis, rare cases of the birth of ordinary clinically healthy but weak lambs that died within two days. There have also been cases of normal but dead lambs being born on time, cases of simultaneous births from one sheep of a dead, weak, and/or completely healthy lamb. Abortion cases became more widespread in those technological periods when the farmer kept sheep more crowded due to lack of space.

The grounds for taking samples to identify isolates of *Chlamydophila abortus* and recognising that this particular pathogen is the cause of abortions were clinical symptoms and autopsy data: fresh abortions in sheep in the last two to three weeks of pregnancy, placental necrosis, characteristic lesions of the lungs, liver, and spleen in aborted foetuses. The liver tissue had infiltration zones in the area of the vascular bed, the lungs had a thickened interalveolar wall. Placental lesions: qualitative and obvious thickening of the placental wall, hyperaemia of internodes as a result of inflammation, swelling of cotyledons, cream-coloured exudate that covered the surface of the membranes. But all these signs do not have a pronounced evidence material and only laboratory tests give grounds to make a diagnosis.

To identify the causal chain of the relationship between *Chlamydophila abortus* and sheep abortions, a systematic laboratory research analysis was conducted. It consisted of testing the serum for specific antibodies, then, in order to have a confirmed diagnostic conclusion, an ELISA was made on the cultural material. Positive tests for complement fixation with chlamydia antigen were obtained in 7 (23%) of the 30 animals that were examined, 12 received positive results (Table 1).

Table 1. *Animals seropositive to Chlamydophila abortus*

Age and sex group	Animal units	Positive results (Two-Fold)
Rams	8	1
Ewes	12	4
Lambs (2-3 months old)	10	2
Total, animal units, %	30	7 (23%)

Source: *compiled by the authors*

This testing was confirmed by the detection of *Chlamydophila abortus* from McCoy cell culture samples, which were given a preliminary analysis of "Enzootic abortion of ewes caused by *Chlamydophila abortus*". ELISA confirmed the presence of the pathogen in 60.9% of cases. 25 samples were obtained, which received a positive ELISA result. To detect *Chlamydophila abortus* using ELISA, the obtained smears were stained with Fluorescein isothiocyanate-labelled chlamydia antibodies and examined under a fluorescent microscope. The kit allowed to isolate specific fluorescent antibodies of sheep, to recognise the external lipopolysaccharides of any known chlamydia. The specimen was considered positive if inclusions of a known chlamydial structure were revealed in the form of bright apple-green spots after two passages. Circular formations on a positive-coloured specimen are chlamydia cells (Table 2).

Table 2. *Results of cultivation of Chlamydophila abortus*

Sample	Number of passages per McCoy cell culture
Foetal lungs	16
Tampons with vaginal secretions	14
Foetal liver	13
Placenta	13
Foetal spleen	20

Source: *compiled by the authors*

The property of five isolates of sheep foetuses for *Chlamydophila abortus* has been confirmed. Using all diagnostic methods, namely clinical symptoms, pathological autopsy, laboratory examination: serological, cell culture cultivation, it can be concluded that 23% of the examined animals were infected with *Chlamydophila abortus*. *Chlamydophila abortus* is a causative agent of an infectious disease of livestock, which has great negative economic results, since it provokes enzootic abortions of sheep, but is also a causative agent of human disease (Mussayeva *et al.*, 2023). This pathogen can also provoke an endemic disease not only in small cattle, but also in cattle, pigs, deer, horses, and domestic and agricultural poultry can be a reservoir of the pathogen. Despite such activity of this pathogen, there have been practically no studies of it in Kazakhstan over the past five years.

The pathogen is quite common, as evidenced by the figure of 23% seropositivity obtained during the study, which, given the possible errors in the study, is close to 17% of those obtained by T.A. Al-Ahmed and S.S. Salman (2020), and data from other countries: China – 17.83%, Poland – 26.4%, Turkey – 26.92%. This is significantly more than in Belgium – 1.69%, Ireland – 4.44%, India – 4.65% and significantly less than in Australia – 45%, in Iran – 48.4%, in Taiwan – 51.35%. Perhaps this figure also directly depended on the number of sheep (the main type of farm animal that is susceptible to *Chlamydophila abortus* infection) in the country. In addition, the reasons for the difference in the data on the prevalence of *Chlamydophila abortus* infection could be different breeds in different countries, although the study did not find scientific research on the topic of pedigree predisposition to enzootic abortion. Farm management, control over the biosafety of the farm, specifics of laboratory diagnostic (for example, sampling time, serological tests used, cross-reactivity of the *Chlamydophila abortus* and *Chlamydophila pecorum* antigens, etc.) were also of great importance (Mussayeva *et al.*, 2021). In addition, these data could be influenced by the virulence of chlamydia strains, inherited immunity among animals, constant influence on animals under study, animals that are infected or animals and birds that are reservoirs of the pathogen, an unregulated ban on the transportation of sick livestock from the infected area, organisation, quantity and quality of feed, grazing tactics, parameters of samples that are being studied, the type of serological test and its effectiveness (manufacturer, test quality, compliance with shelf life and storage of the test), the geography of the study.

The diagnosis of *Chlamydophila abortus* has become more accurate with the addition of immunofluorescence assays and PCR methods, this is a direct recognition and determination of the pathogen, which relies on clinical samples obtained from a source that has already been previously diagnosed with chlamydia. This stage of diagnosis detected *Chlamydophila abortus* already in 60.9% of cases with the help of ELISA. In addition, the use of PCR, according to F. Imkamp *et al.* (2022), helped to detect *Chlamydophila abortus* even in milk samples. This was confirmed by the data that the pathogen was present in sheep's milk more often and more abundantly than in goat's milk. The advantage of PCR is its speed and relative reliability, while complying with all strict requirements for taking material for research. X. Zhang *et al.* (2020) noted that in practice, it was necessary to take PCR samples more than three times and only on the fourth a positive result for *Chlamydophila abortus* was received. This means a negative experience with PCR.

But this is not enough for a definitive diagnosis and, nevertheless, suspension cultivation on McCoy cells remains the gold standard of diagnosis, although it is a long and time-consuming process. First of all, the correctness of the selection and storage of samples for research was observed. All materials that were used to isolate the pathogen for laboratory studies in case of a forced delay between sampling and the first stage of isolation were stored in a transport substrate (sucrose, phosphate. glutamic acid, streptomycin) and at a temperature of -80°C. This technology of using the McCoy cell line enabled the application of the blind passage. Accuracy was achieved by reducing the possibility of missing positive samples by inoculating all samples in cell cultures and using at least three blind passages for all negative samples. In addition, the use of bioreactor technology allows growing monocultures of only one pathogen, ensuring the accuracy of the study while avoiding the coinfection factor. If the required parameters do not match, it is possible to eliminate any problems using biotechnological engineering. The stability of the process and confidence in the results of the study were facilitated by the working conditions with the bioreactor, adjusted for the cultivation of a certain pathogen: homogeneous temperature settings, a modular biosynthesis pathway, distribution among artificial joint culture, maintenance of metabolic subunits with the same physicochemical requirements. It also helps to harmonise the development of cell culture composition and implement an all-encompassing biological concept with the extraordinary technological and diagnostic requirements of the strains used. A user-friendly biological system has been obtained, showing a synthetically induced result without the use of a living organism and without risk to the health of laboratory staff. The flexibility of the study implies the cultivation of crops from strains of *Chlamydophila abortus* from samples collected from different farms or, if necessary, from one with a long-lasting, but 100% result. This is absolutely in line with the needs of the unified development of *Chlamydophila abortus*.

Parasitism is caused by an identified metabolic interaction with the cell in which the microbe is parasitising (Verzhykhovsky & Nedosekov, 2024). In this regard, conventional bacteriological diagnostic methods cannot be used for this infection. Isolation of the pathogen in in vitro cell culture is the "gold standard" for the diagnosis of chlamydophila. The main element of this diagnostic method is the infection of a monolayer cell culture with a material that contains chlamydophylla. There are nuances of using this system, which are that most bacteria of the family *Chlamydiaceae* also have difficulties in the ability to reproduce in cell cultures. To do this, several methodological techniques are used that improve adsorption, trigger a process that promotes its absorption by the cell, and inhibits the usual metabolism of *Chlamydiaceae* on the surface of the McCoy cell culture. These techniques are used individually or together. It is centrifugation of material that is examined on the surface of cells with diethylaminoethanol dextran-polycation, which activates the adsorption of macromolecules by cells (chlamydia or chlamydophilus), preparation of cells with 5-iodo-2-deoxyuridine or cycloheximide – antagonists that have a cytotoxic effect, reducing the metabolic rate of host cells and in parallel increasing the reproduction of chlamydophilus. These elements were used in the process of growing cell culture (DMEM substrate was used, which contained antibiotics). There are outdated methods for fixing monolayers of cover glasses in methanol and staining using Gimza or Gimenez techniques, modern methods that often use immunofluorescence with species- or genus-specific antibodies, the modern ELISA method was used in this study. But there is an element of growing *Chlamydophila abortus* on McCoy cells that has not been used. This is an increase in the activity of chlamydia due to the chemical treatment of McCoy cells before or during infection. This is a treatment with substances such as cycloheximide (0.5 μg/mL), emetine (1 μg/mL), 5-iodine-2-deoxyuridine (80 μg/mL). Practice has shown that this was not necessary. O. Alzuguren *et al.* (2023) investigated the growth of *Chlamydophila abortus* on McCoy cell culture, which was not recorded in this study. The researchers noted the blocks of infection formation that arose during the last hours of the day after infection and grew, while the form of inclusion was very different in different infected cells: multiple inclusions were found in a fifth or almost half of those cell populations that were infected during laboratory testing. This feature of *Chlamydophila abortus* (separation of inclusions and their fusion) is a characteristic feature for it and distinguishes it from the features of other chlamydophiles grown on McCoy cell culture.

Unfortunately, in the practice of developing enzootic abortion of ewes, time plays against the decision to use the cultural method of diagnosis of *Chlamydophila abortus* with the cultivation on McCoy cell culture. Indeed, this method is convenient for studying *Chlamydophila abortus* and confirms the presence of these viable pathogens in the pathological material provided by the laboratory, but it is extremely time- and labour-intensive and cannot be used on a permanent basis as an absolute diagnostic tool. This diagnostic tool is perfectly applicable for prolonged abortion of sheep on a farm, when the evidence for the diagnosis of *Chlamydophila abortus* is questioned, when there is an opinion to believe the presence of other pathogens that could cause an "abortion storm". These are dangerous diseases such as brucellosis.

Cultural studies of *Chlamydophila abortus* can be useful for the genomic study of this pathogen, the study of modern strains, and the development of modern safe and effective vaccines based on this information. F. Büyük *et al.* (2020) noted that studies using ELISA help to classify positive infections in relation to their optical density and provides an important basis for future studies of possible effects even at the level limited by the conditions of keeping and feeding the herd. This may cause a difference in the serological correspondence of antibodies to *Chlamydophila abortus* from animals from the same farm. The ELISA diagnosticum was not used in this study. Thus, in a study based on a suspension culture of *Chlamydophila abortus* on a McCoy cell culture, M. Şevik (2023) identified seven DNA sequences that made up the genome, and also confirmed that *Chlamydophila abortus* is a highly monomorphic group that does not have a conservative plasmid associated with virulence. S. Bommana and A. Polkinghorne (2019), in their genome-wide sequencing, stated that although the clinical symptoms of infections associated with chlamydia are different, their genomes are conservative and have practically no species specificity. In addition, the largest part of the isolates of *Chlamydophila abortus*, which are marked internationally, show a low level of variability of nucleotide sequences in their genes. J.A. Origlia *et al.* (2019) noted that there was no recombination among sequenced isolates, but a small level of variation could interfere with the recognition of recombination. In addition, an interesting question was raised that calves can become infected with *Chlamydophila abortus* after birth, that is, not by the vertical transmission factor, but by an alimentary route. This requires verification and additional research.

In addition to the diagnosis on the farm from which samples were taken to diagnose enzootic abortion of ewes, no action was taken to stop the outbreak of this disease. The availability of a sufficient number of samples helped to verify the practical benefits for the diagnosis of *Chlamydophila abortus* using suspension culture technology in a bioreactor of this pathogen on McCoy cell culture, but did not imply curation and rehabilitation of the farm for the diagnosed disease. The company implemented standard procedures for the prevention of this disease in compliance with biosafety. But at the same time, the company has no history of vaccination for enzootic abortions, there were no changes in the conditions of maintenance and feeding, the provision of preventive and medicinal products at the time of the first cases of abortion in sheep in the second or third week before lambing. There was evidence that sheep were exposed to a two-hour outdoor trip with a temperature of 5°C from one area to another grazing area during a 60-minute movement. This could give rise to an outbreak of the disease due to stress. After the "abortion storm", sheep were identified and isolated to prevent the spread of infection through faeces, vaginal secretions, remnants of foetal membranes, etc. The sheep were carefully monitored, cared for, constantly fed and monitored by the owner and the veterinary service of the farm for a month. It was from these animals that samples were taken for research.

The study conducted a diagnostic analysis after the fact, when abortion had already occurred and tissue samples were taken from females and the aborted foetus. An interesting area of research may be the study of males for the transfer of the pathogen, for seropositivity, and the study of the course of infection separately in them. There will also be factors of maintenance, feeding, and management that differ from females.

CONCLUSIONS

There are various ways to diagnose *Chlamydophila abortus*. Clinical symptoms and autopsy give reason to suspect enzootic abortion caused by *Chlamydophila abortus*. This has been tested in practice. The epizootological pattern (abortions of sheep in the last two to three weeks of lambing, the birth of dead lambs, the birth of weak lambs dying during the first two days of life, the "storm of abortions") only allow assuming that the cause of abortion was the pathogen *Chlamydophila abortus*. But only laboratory diagnostic methods provide a basis for making a definitive diagnosis. The cultural method used in this study is the most reliable diagnostic method and is considered the "gold standard" of diagnosis for *Chlamydophila abortus*. Only the molecular genetic diagnostic method is more accurate, but immunological, serological, and morphological methods are considered less reliable. Moreover, the disadvantage of this diagnostic method is the length of time to obtain the results.

In the study, using the suspension culture technique of the *Chlamydophila abortus* strain on McCoy cell culture in a bioreactor, 60.9% of cases of positive results confirmed by enzyme-linked immunosorbent assay were obtained. The advantages of using a monolayer grown in a bioreactor are noted: reliability of results, absence of coinfection, the possibility of visual control of growth and development in McCoy cell culture. All stages and materials necessary for cultivation in a bioreactor have been tested in practice: preparation and sampling, suspension in a DMEM nutrient medium, passivation on McCoy cell cultures that were suspended in a bioreactor in a DMEM nutrient medium with 10% foetal bovine serum and antibiotics, fixation of the results of suspension cultivation of the *Chlamydophila abortus* strain on McCoy cell cultures in a bioreactor using the enzyme immunoassay method. This technology can be used in practice to confirm the previously made preliminary diagnosis of Enzootic abortion of ewes caused by the pathogen *Chlamydophila abortus*.

Thus, 23% of samples from different age and sex groups revealed infection with *Chlamydophila abortus*. An ambiguous conclusion can be drawn that the cause of abortions is infection with *Chlamydophila abortus*. It has also been confirmed that sheep and lambs are reservoirs of this infection. To improve the health of the herd, it is necessary to prescribe treatment in the form of antibiotic therapy to sick animals, separating animals with a confirmed diagnosis in separate premises.

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CONFLICT OF INTEREST

None.

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Технології суспензійного культивування в біореакторі штаму *Chlamydophila abortus* на культурі клітин McCoy

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Анотація. Метою дослідження було вивчення культурального методу діагностики *Chlamydophila abortus*. Для цього на базі ТОО Науково-виробничого підприємства «Антиген» проводилася лабораторна діагностика патологічного матеріалу з ферми, де, ґрунтуючись на даних анамнезу, даних виникнення подібної епізоотичної картини за останні два роки, огляду та діагностичних маніпуляцій (клінічні симптоми, дані розтину, епізоотологічний анамнез), було поставлено попередній діагноз «Ензоотичний аборт овець, спричинений *Chlamydophila abortus*». Для підтвердження цього діагнозу було відібрано проби з органів плодів, що абортувалися,тампони з вагінальним вмістом. Тести на фіксацію комплементу хламідійним антигеном виявилися позитивними у 7 (23 %) із 30 тварин, які були обстежені. Для виділення патогена використовувалася технологія суспензійного культивування в біореакторі штаму *Chlamydophila abortus* на культурі клітин McCoy. Ізольований патологічний матеріал вирощували в культурі клітин Маккоя, які суспендували в біореакторі в поживному середовище Ігла в модифікації Дульбекко (DMEM) з 10 % фетальною бичачою сироваткою та антибіотиками в концентрації 2×105 клітини/мл. Підтвердженням успішного результату культивування був імуноферментний аналіз. Імуноферментний аналіз підтвердив наявність патогена в 60,9 % випадків. Було отримано 25 зразків, які отримали позитивний результат. Таким чином точність культурального методу діагностики виявилася вищою майже в 3 рази порівняно із серологічним методом діагностики. Серологічне дослідження виявило 23 % наявності *Chlamydophila abortus* у пробах, а культуральний метод діагностики виявив 60,9%. На жаль, на практиці використання культурального методу діагностики пов›язане з розтягнутим у часі результатом, що є недоліком цього способу діагностики порівняно з використанням полімеразної ланцюгової реакції

Ключові слова: лабораторна діагностика; дрібна рогата худоба; ензоотичний аборт овець; внутрішньоклітинний паразитизм; культуральний метод діагностики; імуноферментний аналіз

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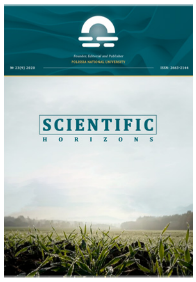

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Reaction of potato varieties to treatment with nitrogen-fixing bacteria and mycorrhizal biopreparations

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Abstract. The commercial value of potato plants for tuber production is substantial enough to explore ways to reduce the cost of the final product by optimising large-scale cultivation systems. Treating tubers with biological products makes it possible to reduce the use of phosphorus fertilisers and shorten the growing season. Furthermore, high-quality and commercially viable plant material can be produced by introducing beneficial microbiota. The objectives of this study were to determine the level of genetic

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potential realisation in early potato varieties when biologically active substances are used in tuber treatment, to identify the maximum achievable potential of the varieties examined, and to diagnose early potato forms. Regarding plant mineral nutrition, mycorrhizal fungi biological preparations represent one of the most important groups of soil microflora and could be applied in agricultural inoculation practices. The results obtained for starch content in the examined potato varieties indicated that treatment with biological preparations had no significant influence on its levels in tubers. However, a positive trend was observed in the dry matter content in almost all tuber treatment variants using biopreparations. The reaction of varieties to the average weight of marketable and individual tubers demonstrated the effectiveness of the preparations in enhancing key marketability indicators across all experimental variants. Treatment with biological preparations does not address the issue of providing all microelements during the potato vegetation period. Therefore, elements like boron should be incorporated into planning an optimal nutrition system

Keywords: starch; soil microflora; biochemical composition of tubers; microelements; productivity

INTRODUCTION

In response to steadily rising costs, a transformative shift in the potato industry can be achieved by developing an adaptive farming system that employs energy-efficient, environmentally friendly, and biologically based technologies. One promising aspect of these technologies is the use of biological products. According to research by N. Fumia *et al.* (2022) and N. Pysarenko *et al.* (2022), biological products can enhance plant resistance to phytopathogens, boost productivity, and improve product quality while simultaneously mitigating the harmful effects of pesticides on agrocenoses. Biological products offer an eco-friendly alternative for plant protection by reducing the prevalence of phytopathogens. Specific agricultural measures, such as pre-planting seed tuber treatments and spraying plants during the growing season with biological products, help reduce the density of pathogen populations in the soil and on new tubers, thereby enhancing plant resistance against these threats.

In addition to achieving high productivity levels, it is equally crucial to ensure consistent expression of desirable traits under specific growing conditions. Therefore, a key challenge in increasing potato tuber production is to determine the adaptive potential of different potato varieties in specific environments, which will help stabilise productivity and other desired traits. Studies by O. Tsyuk *et al.* (2022), J. Goffart *et al.* (2022), and P. von Gehren *et al.* (2023) indicate that earlymaturing potato varieties (with a growing season of 55-60 days) exhibit varietal differences, economically valuable traits, and varied biochemical compositions of tubers. The biological characteristics of these varieties vary in terms of tuber formation, leaf assimilation surface size and activity, photosynthetic efficiency, and the rate of growth and vegetative mass development (Eid *et al.,* 2021; Taktaiev *et al.,* 2023). Currently, and likely in the near future, the primary objective will be to increase the productivity potential and maximise the genetic resources of early-maturing potato varieties, even those with moderate agronomic performance, as highlighted by S. Kokovikhin *et al.* (2020) and S. Tanchyk *et al.* (2021).

The development of adaptive potato varieties remains challenging due to the absence of a unified approach to defining the norm of a genotype's response. Recent research by Y. Kang *et al.* (2020) and O. Karpenko *et al.* (2022) suggests that this concept should be considered through the lens of the ecological-genetic organisation of quantitative traits. This perspective considers the role of heredity during ontogenesis, which interacts with limiting factors in the external environment.

The study aimed to determine the extent of genetic resource utilisation in early potato varieties when biologically active substances are used in tuber processing, to identify the maximum achievable potential of the varieties involved in the research, and to diagnose early-maturing forms of potatoes.

MATERIALS AND METHODS

The research was conducted at the educational, scientific, and industrial complex of Sumy National Agrarian University during 2022-2023. The experimental field is located in the Sumy district of the Sumy region, Ukraine, with geographic coordinates of 50°52.742 N latitude and 34°46.159 E longitude, at an altitude of 137.7 m above sea level (50°52'46.6"N 34°46'07.8"E, map data ©2023 Google). The research area is characterised by long-term average indicators, with an annual mean daily air temperature of +7.4°C and annual precipitation of 593 mm. Average daily temperatures cross the +10°C threshold in the third decade of September (as they decrease) and in the second decade of April (as they increase). The cumulative active temperatures (> +10°C) for the April-September period reach 2,768°C.

The overall climatic characterisation of the study period (2021-2023) indicated lower temperatures and increased spring precipitation compared to the long-term average. The soil at the experimental field is classified as typical chernozem, with the arable layer featuring the following main characteristics: humus content of 4.1%, pH of 6.3, an absorbed base quantity of 31 mg-eq., mobile phosphorus content of 11.3 mg/100 g of soil, exchangeable potassium content of 9.2 mg/100 g of soil, and easily hydrolyzed nitrogen content of 11.2 mg/100 g of soil (measured by the Kornfield method). Field and laboratory research followed the methodological recommendations provided by V. Kononuchenko (2002). Starch determination was conducted using the Parow method, which measures the density difference between the tubers and water (Kononuchenko, 2002; Podgaetskyi *et al.*, 2002; Abby, 2016). The analysis was performed using the "Field Kit for Dry Matter" device manufactured by Martin Lishman. Additionally, the response of different varieties to the average weight of marketable and individual tubers was analysed to evaluate their impact on marketability. To characterise crop structure, tuber samples collected from the plots were classified into fractions: small (less than 25 g), medium-small (26 to 50 g), medium (51 to 80 g), and large (over 80 g). The number and mass of tubers in each fraction were recorded. Crop marketability was determined by weighing all tubers exceeding 25 g, expressed as a percentage of the total harvest (Bondarchuk *et al.,* 2019).

The study involved early-maturing potato varieties from different breeding institutions, including Arizona, Tornado, and Riviera (Netherlands), as well as Bellarosa (Germany), Slauta, and Tiras (Ukraine). The following biological preparations were used for pre-planting tuber treatment: Binoc TK, a complex dry inoculant produced by Enzim Agro (Ukraine); Kartoplex, a complex biotechnological preparation also produced by Enzim Agro (Ukraine); and Mycofriend, a mycorrhizal bio-preparation. Experimental plots were established by planting 33 tubers per row for each variety, with four replicates. Tubers within the same row were spaced 35 cm apart, with a row spacing of 70 cm. After harvest, productivity indicators for the dietary potato varieties were determined, including marketability (%), the number of tubers (pcs./plant), yield (g/plant), dry matter content (%), and starch content (%).

The experimental scheme involved the following methods of tuber treatment:

1. Control (no treatment).
2. Binoc TK treatment using the dry method, applied directly to the tubers in a bag immediately before planting, at a rate of 100 g per 50 kg.
3. Kartoplex treatment using the spraying method, evenly applied to the spread-out tubers with a backpack sprayer at a rate of 100 g per 50 kg.
4. Mycofriend treatment using the dry method, applied similarly to Binoc TK, at a rate of 150 g per 50 kg.

Kartoplex is a long-acting, complex biotechnological formulation that stimulates growth, increases potato yields, and has insecticidal properties. The use of this agent reduces the spread of diseases caused by phytopathogenic microorganisms. Active colony formation in the root system by fungal producers of this agent aids in plant protection against root rot and fungal and bacterial complexes. Colony formation and synthesis of bioactive substances in plant tissues enhance immunity and reduce susceptibility to phloem-complex diseases. The composition of Kartoplex includes mycelia and spores of soil-endophytic fungi *Beauveria bassiana* and *Metarhizium robertsii*, along with bacteria such as *Bacillus megaterium* and *Bacillus azotofixans*, as well as their metabolites (plant hormones and organic substance complexes).

Binoc TK is a complex inoculant formulated as a graphite-talc mixture for seed treatment before planting. Its composition includes microbial cultures that are antagonists of root rot pathogens, nitrogen fixers, phosphorus-solubilising cultures, potassium mobilisers, phytohormones, antibiotics, vitamins, amino acids, growth regulators, and trace elements.

Mycofriend is a bioproduct based on the mycorrhizal fungi *Glomus* and *Trichoderma harzianum*. Its active components include agriculturally valuable microorganisms such as mycorrhizal fungi *Glomus sp.*, rhizosphere microorganisms (e.g., *Trichoderma harzianum*, *Pseudomonas fluorescens*, and *Streptomyces sp.*), phosphate-fixing bacteria, and fungicidal and bactericidal bacteria (e.g., *Bacillus subtilis*, *Bacillus megaterium* var. *phosphaticum*, *Bacillus mucilaginosus*, and *Enterobacter sp.*).

Experimental studies of plants (both cultivated and wild), including the collection of plant material, followed institutional, national, or international guidelines. The authors adhered to the standards of the Convention on the Conservation of Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

Mycorrhiza offers numerous benefits to various plants: mycorrhizal seeds exhibit improved germination rates and greater resistance to root rot. Seedlings of fruit plants establish more successfully in new locations and develop more vigorously (Chifetete & Dames, 2020). During the growing season, mycorrhizal plants develop more extensive root systems, enabling them to absorb greater amounts of nutrients and moisture than non-mycorrhizal plants. Mycorrhiza supplies plants with essential vitamins, minerals, enzymes, and hormones. Through the mycelium, plant root systems expand their absorption area for key elements such as phosphorus, potassium, and other growthstimulating substances (Adavi *et al.,* 2020). Fungi forming mycorrhizal associations with plant roots also act as protective agents against certain diseases, such as late blight.

The analysis of tuber treatment effects with biological preparations on early potato variety performance indicators is presented in Table 1. From the data provided, it can be concluded that the response of potato varieties to the application of bio-preparations differed significantly in terms of productivity. The maximum productivity was observed in four varieties – Tiras, Bellarosa, Slauta, and Riviera – when treated with the

Kartoplex preparation. Meanwhile, two varieties, Tornado and Arizona, exhibited the highest productivity when treated with Binoc TK. The average productivity of the six potato varieties showed the following results: Kartoplex ranked first with a yield of 710.9 g/plant, followed by Binoc TK with 697.9 g/plant, Mycofriend with 547.5 g/plant, and the control group in last place with 540.9 g/plant.

***Table 1**. Influence of tuber treatment with bio-preparations on productivity indicators of early potato varieties (average 2022-2023)*

Variety	Yield (g/plant)			
	Control	Binoc TK	Kartoplex	Mycofriend
Tiras	495.5	695.0	800.0	695.5
Bellarosa	595.5	713.6	718.2	600.0
Slauta	700.0	768.2	827.3	685.0
Tornado	604.5	675.0	620.0	520.0
Arizona	318.2	745.5	686.4	338.9
Riviera	531.8	590.0	613.6	445.5
Average	540.9	697.9	710.9	547.5

***Source:** field studies conducted at the experimental field of Sumy National Agrarian University*

The results of laboratory analyses on the response of potato varieties to the content of 14 microelements during tuber formation are shown in Figure 1. These results offer insights into the yield indicators of the studied varieties. The findings indicate that potato varieties responded variably to tuber treatments with bio-preparations. Figure 1 highlights significant deficiencies in nitrogen, boron, and cobalt content, which corresponded to reduced productivity in the experimental variants. One critical indicator of potato nutritional value is starch, which constitutes 70-80% of the dry matter in tubers. However, its content primarily depends on the potato variety, with higher starch levels typically observed in mid- to late-maturing varieties. This study focused on early-maturing potato varieties (Navarre *et al.,* 2016; Bondarchuk *et al.,* 2021; Radchenko *et al.,* 2023). The research aimed to establish correlations between tuber treatments with biological preparations and starch and dry matter content in the studied varieties.

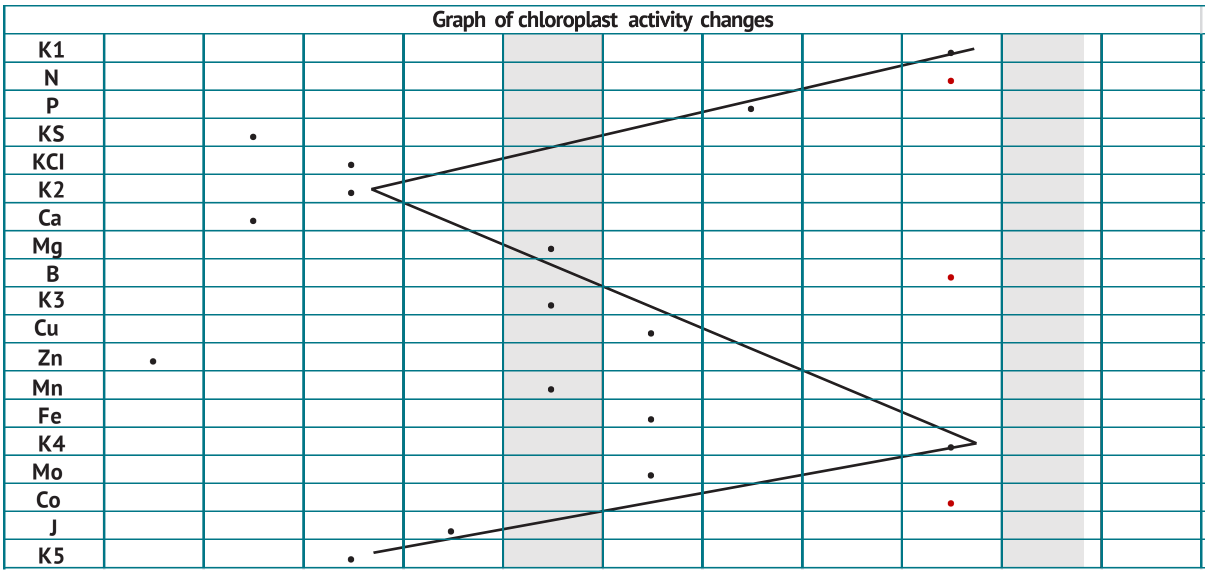

***Figure 1**. Trace element content in potato varieties during tuber formation*
***Source:** laboratory studies conducted at the Centre for Collective Use of Scientific Equipment, Sumy National Agrarian University*

The research results demonstrated that all potato varieties exhibited acceptable starch levels. The starch and dry matter content values for the different experimental conditions are presented in Table 2. The data suggest a minimal but noticeable response of the varieties to tuber treatments. Differences between the control and treatment methods were observed in most varieties.

Table 2. *Starch and dry matter content values depending on experimental conditions (average 2022-2023)*

Variety/Treatment	Starch	Dry matter
Tiras/Control	12.1	16.05
Tiras/Binoc TK	10.7	19.80
Tiras/Kartoplex	12.2	19.80
Tiras/Mycofriend	13.5	22.30
Bellarosa/Control	12.0	15.30
Bellarosa/Binoc TK	10.3	16.05
Bellarosa/Kartoplex	10.1	16.55
Bellarosa/Mycofriend	10.1	14.55
Slauta/Control	10.0	14.05
Slauta/Binoc TK	12.3	16.55
Slauta/Kartoplex	11.2	16.05
Slauta/Mycofriend	10.7	15.30
Tornado/Control	10.6	14.05
Tornado/Binoc TK	10.0	14.55
Tornado/Kartoplex	10.0	15.30
Tornado/Mycofriend	10.0	14.55
Arizona/Control	10.0	13.80
Arizona/Binoc TK	10.0	14.05
Arizona/Kartoplex	10.9	14.05
Arizona/Mycofriend	10.0	14.55
Riviera/Control	10.0	16.55
Riviera/Binoc TK	9.9	18.80
Riviera/Kartoplex	9.9	18.05
Riviera/Mycofriend	9.9	15.30

Source: *laboratory studies conducted at the Centre for Collective Use of Scientific Equipment, Sumy National Agrarian University*

As practical experience indicates, the dry matter content of a specific variety may also vary across growing seasons in the same field. The effectiveness of tuber treatments was assessed based on dry matter content. Compared to the control group, the highest dry matter content was observed when treating tubers with the Mycofriend preparation in the Tiras variety (22.30%) and Arizona (14.55%), while Binoc TK treatment resulted in the highest values for Riviera (18.80%) and Slauta (16.55%). The Kartoplex preparation produced the best results in Bellarosa (16.55%) and Tornado (15.30%). Conversely, lower values were recorded for most varieties in the control group. Thus, it can be concluded that tuber treatments with specific bio-preparations have a positive and measurable impact on dry matter content. The favourable response of early-maturing potato varieties to tuber treatments underscores the practicality of employing such methods to improve dry matter content.

The best marketability indicators were achieved with Kartoplex-treated varieties: Bellarosa (166 g), Tiras (111 g), and Arizona (108 g). Additionally, Mycofriend-treated Slauta (128 g) and Binoc TK-treated Arizona (110 g) displayed promising outcomes (Table 3). Conversely, the highest average marketable tuber weight was observed in the control group for Riviera (120 g). No significant differences were observed among treatment variants for the Tornado variety. The observed trends in the average marketable tuber weight directly impacted the size of individual tubers per plant.

Table 3. *Influence of bio-preparations on marketability indicators (average 2022-2023)*

Variety/Treatment	Average tuber weight, g		Marketability, %
	Product	One	
Tiras/Control	95	75	95
Tiras/Binoc TK	100	83	95
Tiras/Kartoplex	111	97	95
Tiras/Mycofriend	97	85	97
Bellarosa/Control	118	81	90
Bellarosa/Binoc TK	127	86	94
Bellarosa/Kartoplex	166	136	97
Bellarosa/Mycofriend	116	80	95

Table 3. Continued

Variety/Treatment	Average tuber weight, g		Marketability, %
	Product	One	
Slauta/Control	117	93	91
Slauta/Binoc TK	113	97	96
Slauta/Kartoplex	111	88	94
Slauta/Mycofriend	128	112	97
Tornado/Control	81	67	92
Tornado/Binoc TK	89	68	92
Tornado/Kartoplex	83	71	94
Tornado/Mycofriend	83	68	92
Arizona/Control	79	64	81
Arizona/Binoc TK	110	94	96
Arizona/Kartoplex	108	80	91
Arizona/Mycofriend	82	62	92
Riviera/Control	120	90	92
Riviera/Binoc TK	97	79	97
Riviera/Kartoplex	113	95	96
Riviera/Mycofriend	76	65	93

Source: *laboratory studies conducted at the Centre for Collective Use of Scientific Equipment, Sumy National Agrarian University*

An analysis of the data regarding tuber marketability indicates differences among the varieties depending on the experimental conditions, with the lowest marketability index recorded in the Arizona variety under control conditions at 81%. Research has demonstrated that organic crops tend to be richer in phenolics and other antioxidants compared to conventional crops, while also containing lower levels of undesirable pesticide residues and nitrates. Conventional tubers exhibited higher concentrations of nitrates and lutein, whereas organic potatoes generally contained greater amounts of phenolic compounds (Kazimierczak *et al.,* 2019). These compounds are notable for their physiological and ecological roles, which arise from interactions between the plant and its environment.

Therefore, trait improvement, including quality traits, may be achieved by cultivating existing varieties under conditions that enhance or positively influence their expression. Organic cultivation, in particular, is anticipated to have a favourable effect on the antioxidant quality of potato tubers. Micronutrients play essential roles in both plants and humans, and their deficiencies can lead to significant health issues in humans or result in yield and quality losses in plants. The bioactive compounds often found in higher concentrations in organically grown crops not only provide nutritional and health benefits but also contribute to their distinctive taste and flavour profiles. As a result, variations in the concentrations of these compounds may influence the sensory characteristics of plant products (Wijesinha-Bettoni & Mouillé, 2019; Hussain *et al.,* 2021). More than half of the global potato production originates from developing countries, where micronutrient malnutrition is a widespread issue. This underscores the critical importance of micronutrient biofortification in potatoes for human health, as potatoes are widely consumed by a large proportion of the global population (Pysarenko *et al.,* 2022; Hryhoriv *et al.,* 2022). The dietary potato varieties examined in this study are distinguished by varietal differences, economic value, and the biochemical composition of their tubers. Assessing the potential of these varieties under organic farming conditions, without the use of chemicals, enables researchers to evaluate their maximum productivity potential and the extent to which key agronomic traits are expressed.

CONCLUSIONS

An analysis of the obtained results reveals substantial differences in productivity indicators compared to the control. Most varieties exhibited a positive response to tuber treatments with the biopreparations included in the study. A significant increase in productivity was observed in the Slauta variety with the application of the Kartoplex preparation, where productivity was 1.2 times higher compared to the control. In the Tiras variety, productivity was 1.6 times higher. Similar positive responses were recorded in some varieties following the application of the Binoc TK biopreparation. The highest values were recorded in the Arizona and Tornado varieties, with productivity differences of 427.3 g/plant and 70.5 g/plant, respectively, compared to the control. Therefore, the use of the biopreparations Binoc TK and Kartoplex during tuber treatment is recommended as an effective method for enhancing key economic traits in the cultivation of earlymaturing potato varieties. This approach allows for a substantial yield increase of 20-30%.

Global trends in healthy nutrition encourage the development of dietary products rich in antioxidants, contributing to disease prevention. The cultivation of specialised potato varieties in Ukraine and globally represents a critical area for enhancing food security. Future research will focus on increasing the yield of dietary potato varieties by producing *in vitro* potato seed material and evaluating the biochemical composition of their tubers.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Реакція сортів картоплі на обробку азотфіксуючими бактеріями та біопрепаратами з мікоризою

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Анотація. Комерційна цінність рослин картоплі для виробництва бульб є досить значною, щоб дослідити шляхи зниження собівартості кінцевого продукту шляхом оптимізації великомасштабних систем вирощування. Обробка бульб біопрепаратами дозволяє зменшити використання фосфорних добрив і скоротити вегетаційний період. Крім того, за допомогою інтродукції корисної мікробіоти можна отримати високоякісний та комерційно життєздатний рослинний матеріал. Метою даного дослідження було визначення рівня реалізації генетичного потенціалу ранніх сортів картоплі при застосуванні біологічно активних речовин для обробки бульб, виявлення максимально досяжного потенціалу досліджуваних сортів, а також діагностика ранніх форм картоплі. Що стосується мінерального живлення рослин, то біопрепарати мікоризних грибів є однією з найважливіших груп ґрунтової мікрофлори і можуть бути застосовані в практиці сільськогосподарської інокуляції. Отримані результати щодо вмісту крохмалю в досліджуваних сортах картоплі свідчать про те, що обробка біопрепаратами не мала суттєвого впливу на його рівень у бульбах. Проте за вмістом сухої речовини спостерігалася позитивна тенденція майже у всіх варіантах обробки бульб біопрепаратами. Реакція сортів на середню масу товарних та індивідуальних бульб продемонструвала ефективність препаратів у підвищенні основних товарних показників на всіх варіантах досліду. Обробка біопрепаратами не вирішує питання забезпечення всіма мікроелементами протягом вегетації картоплі. Тому такі елементи, як бор, слід враховувати при плануванні оптимальної системи живлення

Ключові слова: крохмаль; мікрофлора ґрунту; біохімічний склад бульб; мікроелементи; продуктивність

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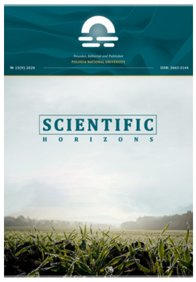

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Innovative approaches to growing grain crops in the Southern Steppe of Ukraine

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Abstract. The aim of the study was to analyse the impact of innovative approaches to cereal cultivation in the Southern Steppe of Ukraine. The study used the latest plant varieties, efficient irrigation systems and biological products to increase crop yields and resilience. The wheat varieties used were Stepova 1 and Dniprovska 1, as well as Pivdennyi 1 barley, which are highly resistant to drought and high temperatures. Drip and sub-surface irrigation systems were used, as well as bio-fertilisers and organic composts to improve soil structure and increase soil fertility. The main results of the study showed that wheat yields in the experimental groups reached 5.2-5.7 tonnes/ha, which is 1.8-1.9 tonnes/ha more than in the control groups. Water consumption in the experimental groups was reduced by 35-40%, and the cost of plant protection products by 45-50%. The protein content of wheat in the experimental groups was 14-15% and the fibre content was 30-32%, while in the control groups it was 11-12% and 25-27%, respectively. Soil analysis in the experimental groups showed higher levels of nitrogen,

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phosphorus and potassium, which indicates the effectiveness of biofertilisers. In addition, the use of biological products helped to reduce the chemical load on the environment. The results obtained indicate a significant increase in productivity, reduced resource use and improved environmental sustainability with the introduction of innovative methods of growing crops in this region, which is important for ensuring food security and economic development in Ukraine

Keywords: wheat; barley; biofertilisers; drip irrigation; biological products; fertility

INTRODUCTION

The Southern Steppe of Ukraine is one of the most important regions for growing grain crops. This region provides a significant portion of the country's grain harvest, which is a key factor for Ukraine's food security and economic development. The Southern Steppe of Ukraine faces significant climatic challenges that negatively affect grain yields. The hot and dry climate, frequent droughts and high temperatures reduce plant productivity and can lead to crop losses. Water scarcity exacerbates the situation, as traditional irrigation methods are water-intensive, leading to depletion of water reserves. Soil depletion due to intensive agriculture and the use of chemical fertilizers and crop protection products is reducing soil fertility. In addition, chemical crop protection products pollute soil and water resources, reduce biodiversity and contribute to the development of pest resistance. The high cost of traditional production reduces the economic efficiency of agricultural enterprises, which affects their competitiveness. In this regard, it is necessary to introduce innovative approaches that will ensure sustainable production, improve the environment and increase the economic efficiency of grain growing in the region.

The integration of modern technologies into agriculture requires a systematic approach to training and professional development of farmers. The introduction of innovative methods involves not only technical equipment, but also knowledge and skills to use the latest technologies. In this regard, an important aspect is the organization of educational programmes and trainings for farmers, which allows them to effectively use new techniques and increase the productivity of their farms. V. Pichura *et al.* (2024) also note that the use of biological products and biofertilisers requires careful adherence to technological standards and recommendations for their use. Failure to comply with the dosages and application periods can lead to a decrease in the effectiveness of these products and negative consequences for plants (Tonkha *et al.*, 2024). Therefore, it is important to ensure constant monitoring of plant and soil conditions to adjust agronomic measures in a timely manner.

M. Korkhova *et al.* (2023) add that in order to ensure global food security, it is necessary not only to increase grain yields, but also to improve the overall efficiency of agricultural resource use. This requires the implementation of integrated, multifaceted and sustainable strategies aimed at increasing the productivity of each unit of land. In Ukraine, smallholder farmers often grow traditional crop varieties that, while having low yields, are also vulnerable to water shortages, high temperatures, diseases, and other stressors, as shown in the study by A. Panfilova *et al.* (2021). In contrast, modern improved varieties can offer significantly better product quality, more stable yields and much higher yields.

V. Gamayunova and A. Panfilova (2019) indicate that more than 880 new varieties have been made available to farmers, generating annual economic benefits of approximately $850 million. To optimize the potential of these varieties, technology "packages" have been developed that include crop management, irrigation, and pest control strategies. With regard to the selection of new varieties, data provided by S. Shahini *et al.* (2023) show that focusing on developing perennial plants with improved traits – such as larger seed size, stronger stems, better palatability and higher productivity – is an important area of development. Developing varieties with deeper and denser root systems can improve soil structure, carbon sequestration, water and nutrient conservation, and yields.

Previous studies have shown the significant potential of innovative methods to increase grain yields in the Southern Steppe of Ukraine, but several aspects remain unexplored. In particular, many studies do not take into account the long-term effects of biological products and biofertilisers, their adaptation to specific local conditions, and their cost-effectiveness in the long term. Most studies focus on individual aspects of innovative technologies, leaving gaps in a comprehensive approach to integrating these technologies into practice. Thus, the aim of this study was to conduct a comprehensive analysis of innovative approaches to grain crops in the Southern Steppe of Ukraine. The objectives of the study included assessing the impact of the latest varieties, biofertilisers and biological products on crop yields and analysing the efficiency of drip and subsurface irrigation systems.

MATERIALS AND METHODS

The research was conducted on the territory of the Educational and Research Centre of Mykolaiv National Agrarian University on a total area of 50 hectares. The area was divided into four fields: two control fields for wheat and barley and two experimental fields for new grain varieties. The fields were located on ordinary low-humus deep micellar carbonate black soil, approximately 10 km south of the city of Mykolaiv. For the control group, the traditional wheat varieties Odeska 267 and Myronivska 808, as well as the barley variety Lutskyi 96 were used. Traditional cultivation methods included ploughing in autumn to a depth of 25-30 cm, spring harrowing and cultivation. Sowing was carried out in the second decade of October using mechanical seeders SZ-3.6 to a depth of 4-5 cm. Mineral fertilizers (ammophos and urea) were applied at a dose of 200 kg/ha during sowing. Irrigation was carried out using traditional irrigation systems (sprinklers) at a rate of 600-700 m^3/ha during the period of active growth (June-July). Herbicides (Glyphosate at a dose of 2 l/ha), insecticides (Chlorpyrifos at a dose of 1.5 l/ha) and fungicides (Tebuconazole at a dose of 1 l/ha) were used for plant protection.

New wheat varieties Stepova 1 and Dniprovska 1, as well as barley Pivdennyi 1, were used in the experimental group. Soil preparation included deep ploughing in autumn to a depth of 30-35 cm, followed by harrowing to preserve moisture, and spring cultivation using machinery to minimize soil disturbance. Sowing was carried out in the third decade of October using modern John Deere 1775NT precision seeders with precise control of depth and seeding rate. We used biofertilizers based on mycorrhizal fungi and nitrogen-fixing bacteria at a dose of 150 kg/ha during sowing. Additionally, organic composts were applied at a dose of 100 kg/ha in the phase of active plant growth (April). Irrigation was carried out using drip irrigation and sub-surface irrigation systems with automated control based on moisture sensors. The irrigation rate was 400-450 m^3/ha during the period of active growth. For plant protection, biological products based on natural entomopathogenic fungi (*Beauveria bassiana)* at a dose of 1.5 l/ha and bacteria (*Bacillus thuringiensis)* at a dose of 1 l/ha were used, as well as integrated pest management, which included biological, cultural and mechanical methods.

The experimental group used high-resolution satellite imagery and DJI Agras T20 drones to monitor the condition of the fields, which provided rapid detection of areas with insufficient or excessive moisture. The data was analysed using Trimble Ag Software to make irrigation and fertilization decisions. The drip and subsurface irrigation systems were controlled by automated systems that used data from soil moisture sensors (Sentek Drill & Drop). Irrigation was carried out in accordance with the soil moisture regime, which reduced water consumption by 35-40%. Precision agrochemical analyses were used to determine the nutrient requirements of the plants. Fertilization was carried out on a spot basis using precision seeding and fertilization systems (*Väderstad Tempo L)*. In the experimental group, biofertilizers based on mycorrhizal fungi (*MycoApply)* and nitrogen-fixing bacteria (*Azospirillum brasilense*) were used, which were applied during sowing and in the phase of active plant growth. Biological products based on natural entomopathogenic fungi (*Beauveria bassiana)* and bacteria (*Bacillus thuringiensis)* were used to control pests and diseases. The treatments were carried out according to a schedule designed to prevent and control major pests and diseases.

Drip irrigation systems provided precise water delivery directly to the root system of plants using Netafim drip lines. The irrigation was based on data from moisture sensors, which ensured optimal moisture conditions. Subsurface irrigation systems were also used to deliver water to a depth of 20-30 cm, preventing evaporation. Irrigation was carried out at intervals of 7-10 days during the period of active growth. Integrated pest management included biological methods, such as the use of natural enemies of pests such as predatory insects (*Coccinellidae)* and entomopathogenic fungi (*Metarhizium anisopliae), as* well as the application of biological products during the active growth phase and at the time of maximum pest risk. Cultural practices included crop rotation and intercropping to reduce the spread of pests, as well as mulching and cover crops to improve soil structure and reduce erosion. Mechanical methods included the use of traps (pheromone traps) and physical barriers to prevent pests from accessing plants, as well as regular manual inspections and mechanical removal of affected plants.

Monitoring of plant growth and development included regular measurements of plant height, developmental stage, leaf condition and photosynthetic rate every two weeks. Hand-held instruments (ruler, photometer) and modern digital tools (PlantEye F500) were used to estimate biomass and photosynthetic activity. Soil and plant samples were analysed in the laboratory to determine nutrient content, moisture, pH and microbiological composition. After harvesting, the weight, moisture, protein, and fibre content of the crops were determined in the laboratory. Yields were estimated as the weight of harvested grain per unit area (t/ha), and grain quality was assessed using standard methods, including the DSTU methodology (DSTU 3768:2019, 2019). The economic analysis of production costs included accounting for the costs of seeds, fertilizers, plant protection products, irrigation, maintenance, and labour. The economic efficiency was assessed based on the calculation of production costs, gross margin and profit from crop sales. 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

The results of the study showed a significant increase in the efficiency of grain growing when using innovative methods compared to traditional approaches. Wheat yields in the experimental groups were 1.8-1.9 tonnes/ha higher than in the control groups. This yield increase was achieved through a set of innovative measures, including the use of the latest varieties, biofertilizers, biological products and improved irrigation systems. The control groups showed stable yields, ranging from 3.4-3.9 tonnes/ha, which is in line with the average for traditional cultivation methods in the region. These results confirm that traditional methods have a certain efficiency, providing stable yields within the established standards. However, in today's agricultural production environment, there is a need to increase productivity and optimize resource use, which stimulates the search for and implementation of new methods and technologies.

The experimental groups using innovative varieties and techniques achieved yields of 5.2-5.7 tonnes/ha. This is a significant increase compared to the control groups, which demonstrates the effectiveness of the new agronomic approaches. A yield increase of 1.8-1.9 tonnes/ha is a significant indicator that demonstrates the potential of the innovations implemented. Such results can be achieved through the use of new varieties with improved genetic characteristics, better resistance to diseases and pests, as well as through the application of more efficient tillage and plant care methods. This increase in yields has several important implications. It allows farmers to increase production without expanding their acreage, which is particularly important in regions with limited land resources. The increase in yields also helps to reduce production costs, which can have a positive impact on the competitiveness of grain crops in domestic and foreign markets.

The increase in yields in the experimental groups was achieved due to several factors. The use of new varieties resistant to drought and high temperatures has reduced yield losses under stressful conditions. This is especially important in the Southern Steppe, where frequent droughts can significantly reduce yields, and the introduction of biofertilizers and organic composts provided better plant nutrition, which contributed to their more intensive growth and development. The experimental group used new wheat varieties such as Stepova 1 and Dniprovska 1, as well as barley Pivdennyi 1. These varieties showed high resistance to drought and high temperatures, as well as excellent yield characteristics (Table 1).

***Table 1**. Characteristics of wheat and barley varieties*

Variety	Resistance to drought	Plant height (cm)	Yield (tonnes/ha)	Protein content (%)	Fibre content (%)
Stepova 1	High	90-95	5.2-5.4	14-15	30-32
Dniprovska 1	High	90-95	5.3-5.5	14-15	30-32
Pivdennyi 1	High	85-90	5.5-5.7	14-15	30-32

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

Innovative irrigation methods used in the experimental groups significantly reduced water consumption, which is an important factor in the context of limited water resources and growing demand for food. In the control groups, water consumption for wheat cultivation was 6,000-6,050 m^3/ha, while in the experimental groups this figure was much lower – only 3,900-4,000 m^3/ha. This indicates that innovative irrigation systems provide more rational use of water, which allows conserving its resources and reducing irrigation costs.

For barley, the situation is similar: water consumption in the control groups was 6,200-6,250 m^3/ha, while in the experimental groups it dropped to 4,000-4,050 m^3/ha. This reduction in water consumption is the result of the use of technologies such as drip and subsurface irrigation, which allow water to be delivered directly to the root zone of plants, minimizing losses due to evaporation and run-off. Reducing water consumption by 35-40% has significant environmental and economic benefits. Lower water consumption contributes to the conservation of water resources, which is especially important in the context of climate change and frequent droughts in the Southern Steppe of Ukraine. In addition, lower irrigation costs reduce production costs, which has a positive impact on the profitability of agricultural enterprises. The efficient use of water resources was made possible by the introduction of drip and subsurface irrigation systems that provided precise water supply directly to the root system of plants. This reduced water losses through evaporation and ensured stable soil moisture. The use of moisture sensors and automated irrigation control systems allowed optimising irrigation regimes and reducing overall water consumption.

The use of integrated pest management and biological products in the experimental groups significantly reduced the cost of plant protection products, which is a significant economic indicator. In particular, the cost of plant protection products for wheat in the control groups was 1,500-1,550 UAH/ha, while in the experimental groups these costs were reduced to 800-820 UAH/ha (Table 2). This represents an almost two-fold reduction in costs, which allows farmers to save money and increase profitability. A similar situation was observed for barley: in the control groups, the cost of protection products was 1,600-1,650 UAH/ha, while in the experimental groups it fell to 850-860 UAH/ha.

***Table 2**. Costs of plant protection products (UAH/ha) in control and experimental groups*			
Year	**Culture**	**Control group**	**Experimental group**
2021	Wheat	1,500	800
	Barley	1,600	850
2022	Wheat	1,550	810
	Barley	1,650	860
2023	Wheat	1,520	820
	Barley	1,620	830

Source: *compiled by the authors*

Reducing the cost of crop protection products by 45-50% has several important aspects. It helps reduce the chemical burden on the environment, which contributes to the preservation of biodiversity and improves the ecological condition of soil and water resources. In addition, the use of biological products can reduce the risk of pests developing resistance to chemical protection products, which is a pressing issue in modern agriculture. Integrated pest management included the use of biological, cultural and mechanical methods, which ensured effective pest control without excessive chemical load. The use of natural enemies of pests, such as predatory insects and entomopathogenic fungi, helped reduce pest numbers to an economically unviable level. Cultural practices, such as crop rotation and intercropping, have helped to reduce the spread of pests and improve soil structure. Mechanical methods, such as traps and physical barriers, prevented pests from accessing plants.

Regular measurements of plant height, developmental stage, leaf condition and photosynthetic intensity were carried out every two weeks, which allowed monitoring the dynamics of crop growth and development in detail. The use of modern digital tools, such as PlantEye F500, provided accurate data on plant biomass and photosynthetic activity. These data became the basis for analysing the effectiveness of the implemented agrotechnical methods. In the control groups, the average height of wheat was 80-85 cm, while in the experimental groups this figure was higher and reached 90-95 cm. This indicates a positive impact of innovative methods on wheat growth, which can be attributed to improved nutrition and water supply conditions, as well as the use of more productive varieties. Similar results were obtained for barley: in the control groups, the average plant height was 75-80 cm, while in the experimental groups it was 85-90 cm. The increase in plant height in the experimental groups may indicate more intensive growth and development due to the use of innovative irrigation and fertilization methods. In addition, measurements of leaf condition and photosynthetic intensity showed that plants in the experimental groups were in better health and had higher photosynthetic activity compared to the control groups. This is important because photosynthesis is the main process that determines plant productivity. Higher photosynthetic activity indicates better conditions for growth and development, which ultimately translates into higher yields. Digital tools such as PlantEye F500 provide accurate and objective data, which is essential for scientific analysis and decision-making in agriculture. These tools help not only to identify differences between control and experimental groups, but also to evaluate the effectiveness of various agricultural practices, which ultimately contribute to the productivity and sustainability of agroecosystems.

The increase in plant height and biomass indicates an improvement in the physiological state of plants due to the use of innovative methods. This, in turn, contributes to higher yields and product quality. The improvement in photosynthetic activity of plants in the experimental groups also indicates the effectiveness of the applied methods. A higher level of photosynthesis means that plants are able to use sunlight more efficiently to synthesize organic matter, which directly affects their growth and development. The analysis of the selected soil and plant samples showed that the experimental groups had better nutrient uptake, which is an important indicator of the effectiveness of integrated pest management and biological products. The content of the main macronutrients such as nitrogen, phosphorus, and potassium in the soil and plants was higher compared to the control groups. In particular, the nitrogen content in the soil of the experimental groups was 120-130 mg/kg, while in the control groups this figure was 90-100 mg/kg. A similar trend was observed for other nutrients: the phosphorus content in the experimental groups was 45-50 mg/kg, while in the control groups this figure did not exceed 30-35 mg/kg. The potassium content in the soil of the experimental groups reached 200-210 mg/kg, compared to 150-160 mg/kg in the control groups. The increased content of nutrients in the soil and plants of the experimental groups indicates improved assimilation and efficiency of fertilizers in combination with biological products. This may be due to improved biological activity of the soil, stimulation of root growth and increased ability of plants to absorb nutrients. This confirms the effectiveness of using biofertilisers and organic composts, which help to improve soil fertility and provide plants with the necessary nutrients. Improved plant nutrition has a positive impact on plant growth, development, and yield. Higher concentrations of nutrients in the soil ensure more robust plant growth, allowing them to better withstand stressful conditions such as droughts or low temperatures.

After harvesting, the weight, moisture, protein, and fibre content of the grain was analysed (Table 3). In the experimental groups, wheat had a higher protein content (14-15%) compared to the control groups (11-12%). The fibre content in the experimental groups was also significantly higher – 30-32% compared to 25-27% in the control groups. This indicates the improved quality of the grain, which makes it more attractive to consumers and processors. High-quality grain has a higher market value, which contributes to higher farmers' incomes. Higher protein content ensures better nutritional and feed value of the products, which is an important factor for food security.

***Table 3**. Indicators of wheat grain quality in control and experimental groups*

Year	Indicator	Control group	Experimental group
2021	Protein content (%)	11	14
2021	Fibre (%)	25	30
2022	Protein content (%)	12	15
2022	Fibre (%)	27	32
2023	Protein content (%)	11.5	14.5
2023	Fibre (%)	26	31

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

The economic analysis showed that the introduction of innovative methods of growing grain crops significantly reduced production costs and increased gross income and profit from the sale of the crop. The increase in yields by 1.8-1.9 tonnes/ha provided additional profit due to the increase in production volumes. Reducing the cost of water and plant protection products helped to reduce production costs, which also had a positive impact on the economic performance of the companies. The profitability of production in the experimental groups increased by 25-30% compared to the control groups, and the gross profit per hectare exceeded the control groups' figures by 15-20%. A comparison of the effectiveness of different methods showed that the use of innovative varieties and biofertilisers had the greatest impact on increasing yields. Innovative irrigation methods have contributed to a significant reduction in water consumption, which is critical in a region with limited water resources. The use of biological products has reduced the cost of plant protection products and improved the environment. The relative impact of each method was assessed by calculating indices of impact on yield, water consumption and crop protection costs, which provided a holistic picture of the effectiveness of different agricultural practices.

The use of innovative plant varieties has proved to be one of the most effective methods, leading to a 20-25% increase in yields (Fig. 1). These varieties have improved genetic characteristics that provide them with greater resistance to diseases and pests, as well as increased productivity compared to control varieties.

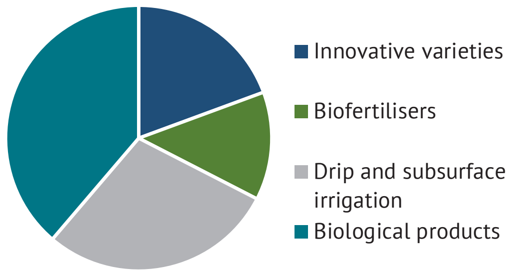

***Figure 1**. Relative impact of different innovative methods in the cultivation of grain crops*
***Source:** compiled by the authors*

The introduction of biofertilisers also had a significant impact on yields, increasing them by 15-20%. Biofertilisers help to improve soil structure, increase its fertility and stimulate plant growth due to the content of beneficial microorganisms and organic matter. Drip and sub-surface irrigation systems have demonstrated high efficiency in reducing water consumption by 35-40%. These systems provide targeted moisture to the root zone of plants, which significantly reduces water loss through evaporation and surface run-off, while ensuring optimal conditions for plant growth. The use of biological products to protect plants from pests and diseases has reduced the cost of plant protection products by 45-50%. Biological products are more environmentally friendly and less toxic to the environment than traditional chemicals, making them an attractive choice for sustainable agriculture (Ivanova *et al.*, 2022).

One of the important benefits of implementing innovative methods is the positive impact on the environment. The use of biological products and bio-fertilisers has significantly reduced the chemical load on soil and water resources. Reducing the use of chemical plant protection products helps to preserve biodiversity and improve water quality. Drip and sub-surface irrigation systems have reduced water losses through evaporation and infiltration, which helps to conserve water resources in the region. This is especially important in the context of climate change, when frequent droughts can negatively affect yields. The use of innovative varieties that are resistant to drought and high temperatures has significantly increased the plants' resistance to stressful conditions. This is critical in the context of climate change, when extreme weather conditions can significantly reduce the yield of traditional varieties. Innovative varieties ensure stable yields even in conditions of low rainfall and high temperatures.

The introduction of innovative grain growing methods also has an important socio-economic impact. Increased yields and product quality contribute to the growth of agricultural revenues, which has a positive impact on the economic development of the region. Increasing the profitability of agriculture helps to create new jobs and improve the living standards of the local population. Reducing the chemical burden on the environment improves people's quality of life by reducing the risk of diseases associated with soil and water pollution. The introduction of environmentally friendly farming methods contributes to the development of organic farming, which is in high demand on the domestic and foreign markets.

Thus, the introduction of innovative methods of growing grain crops has led to a significant increase in yields, product quality and economic efficiency. The use of innovative varieties, bio-fertilisers, biological products and improved irrigation systems has led to a significant reduction in water and plant protection products costs, improved environmental conditions and increased plant resilience to climate change. These results confirm the feasibility of introducing innovative technologies in agriculture that ensure sustainable production of high-quality products and conservation of natural resources.

DISCUSSION

The results of the study show a significant potential for innovative approaches to growing grain crops in the Southern Steppe of Ukraine. The use of the latest varieties, efficient irrigation systems and biological products has significantly increased yields, reduced inputs and improved product quality. This research is an important step towards ensuring food security and economic development in the region, especially in the face of climate change, which is increasing the challenges for traditional agriculture. The results obtained in the Mykolaiv region showed that the yields of the innovative varieties Stepova 1 and Dniprovska 1 are 5.2-5.7 tonnes/ha, which is 1.8-1.9 tonnes/ha higher than the control groups. The high protein (14-15%) and fibre (30-32%) content in the grain also indicates an improvement in product quality, which is important for domestic and foreign markets. Research by S.K. Singh *et al.* (2022) confirms that the use of drought-resistant varieties can significantly increase yields in regions prone to climate change, and a study by E.A. Chapman *et al.* (2022) shows that the introduction of the latest drought-resistant wheat varieties can increase yields by 20-25% in similar climatic conditions, which confirms the findings.

The results of the study of the introduction of new cereal varieties of the Southern Steppe of Ukraine are also consistent with the work of Y.Q. Fu *et al.* (2021), who investigated the impact of drought-tolerant maize varieties under similar climatic conditions in the Mexican Central Plain. He found that yields increased by 18-22% compared to traditional varieties. In a similar context, B. Basso *et al.* (2021) conducted a study in north-western India, where drought is also a problem. The results showed that the newest wheat varieties specially developed for arid conditions showed a 15-18% increase in yield, which confirms the conclusions about the effectiveness of the newest wheat varieties Stepova 1 and Dniprovska 1. Increased yields under conditions of limited water supply demonstrate the importance of crop adaptation to climate change.

The data of the above study also indicate a 45-50% reduction in the cost of crop protection products when using integrated pest management and biological products, which is confirmed by G. Albahri *et al.* (2023) and N. Pérez-Méndez *et al.* (2021). They note that biological methods can significantly reduce the cost of chemical plant protection products and reduce the chemical burden on the environment. The study by E. Elahi *et al.* (2022), P. Langridge and M. Reynolds (2021) also highlight the effectiveness of modern irrigation systems. They have shown that drip irrigation can reduce water consumption by up to 30-40%, which is consistent with the results in the Mykolaiv region (35-40% reduction). According to studies by H.J. Smith *et al.* (2022) and A. Périnelle *et al.* (2021), the use of drip irrigation in combination with moisture sensors can optimize water resources, reducing water consumption by 30-40%, which is fully consistent with the findings of the above study.

The above study also showed that the use of bio-fertilisers and organic composts increases the levels of nitrogen, phosphorus, and potassium in the soil. Comparison of the results shows that the experimental groups in the Mykolaiv region had higher nitrogen levels (120-130 mg/kg versus 90-100 mg/kg in the control groups), which contributes to more sustainable plant growth. This is consistent with the findings of A. Saini *et al.* (2022) and C. Bihari *et al.* (2023), who note that organic fertilizers can improve soil structure and increase soil fertility. The study by N. Carton *et al.* (2022) in Argentina and Y.I. Atta *et al.* (2021) in Brazil, which studied the impact of organic fertilizers on soil fertility and soybean yields, also confirm the results of our study. They showed that the use of organic fertilizers increased soil nitrogen levels to 135 mg/kg and 128 mg/kg, respectively, which is similar to the results in the Mykolaiv region, where nitrogen levels increased to 120-130 mg/kg. This demonstrates the effectiveness of organic fertilizers in improving soil fertility and increasing grain yields.

The economic analysis also confirmed that the introduction of innovative methods can reduce production costs and increase the profitability of agricultural enterprises (Mamchur & Studinska, 2024). In the Mykolaiv region, yields are 1.8-1.9 tonnes/ha higher than in the control groups, which generates additional profit through increased production volumes. Reduced water and crop protection costs also contribute to economic growth. X. Zhu and L. Marcelis (2023) also note that the use of the latest varieties and biofertilisers increases the economic efficiency of agricultural production. Comparison with the study by M. Dimitrijević *et al.* (2022) in Canada, who studied the economic efficiency of the latest technologies in grain production, shows similar results in terms of increased profitability. The use of innovative methods in India, described by M.A.S. Raza *et al.* (2023), increased profitability by 20-30%, which is consistent with the findings on the cost-effectiveness of introducing new varieties and irrigation systems in the Southern Steppe of Ukraine. Reducing the cost of water and plant protection products contributes to an increase in farm profits, which is an important factor for sustainable agricultural development (Bobos *et al.*, 2019).

Optimisation of water resources through the use of moisture sensors and automated irrigation control systems in the Mykolaiv region has reduced water consumption and ensured stable soil moisture, which is critical in times of water shortage. The results are consistent with international research. For example, the study by N. Sarwar *et al.* (2021) in the United States showed that the use of drought-tolerant wheat varieties can increase yields by 20-25% in regions with similar climatic conditions. Data on yield increases of 1.8-1.9 tonnes/ha in the Mykolaiv region confirm these findings. Z. Zhang *et al.* (2021) and M. Kumaresan *et al.* (2023) in China, who studied the effectiveness of drip irrigation in rice cultivation, also confirm the effectiveness of modern irrigation systems. They showed that drip irrigation reduces water consumption by 30-40%, which is consistent with the results obtained in the Mykolaiv region.

The study also showed that innovative methods can have a positive impact on the environmental sustainability of agroecosystems. The use of organic fertilizers increases the level of nitrogen, phosphorus, and potassium in the soil, which helps to improve yields and plant resistance to stress factors (Zaiets *et al.*, 2022). Compared to the control groups, which used conventional methods, the experimental groups showed significantly better results in all indicators. The nitrogen content in the soil increased to 120-130 mg/kg, which is important for healthy plant growth and increased productivity. The study by S. El-Hendawy *et al.* (2022) in the United States showed that the use of organic fertilizers reduces greenhouse gas emissions by 30% compared to traditional chemical fertilizers. The implementation of such methods not only reduces the negative impact on the environment, but also improves soil quality by improving its structure and increasing the level of organic matter. This is also consistent with the results of the study by R. Kumar *et al.* (2023), which noted a significant increase in soil nutrient levels when using organic fertilizers. This is an important aspect for reducing the impact of agriculture on climate change and confirms the need to introduce environmentally friendly methods in the Southern Steppe of Ukraine.

Thus, the comparison of the results of this study with the works of other authors confirms the effectiveness of innovative approaches to growing grain crops in the Southern Steppe of Ukraine. The use of the latest varieties, irrigation systems and biological products can increase yields, reduce inputs and improve product quality, which is important for food security and economic development in the region.

CONCLUSIONS

The study found that the application of innovative approaches to growing grain crops in the Southern Steppe of Ukraine significantly increases their yield, economic efficiency and environmental sustainability. The use of the latest varieties of wheat and barley, such as Stepova 1, Dniprovska 1 and Pivdennyi 1, has resulted in yields of 5.2-5.7 tonnes/ha, which is 1.8-1.9 tonnes/ha more than in the control groups. The high protein (14-15%) and fibre (30-32%) content in the grain confirms the improvement in product quality. The use of drip and sub-surface irrigation systems has contributed to a significant reduction in water consumption by 35-40%, which is critical given the water shortage in the region. The use of bio-fertilisers and organic composts has increased the levels of nitrogen, phosphorus, and potassium in the soil, demonstrating the effectiveness of these methods in improving soil fertility. Integrated pest management and the use of biological products have reduced the cost of crop protection products by 45-50%, which reduces the chemical burden on the environment and improves the ecological situation. These results were of great importance for increasing the productivity and sustainability of agriculture in the face of climate change. Innovative methods can reduce the use of resources, lower production costs and increase the economic efficiency of agricultural enterprises. The introduction of such methods contributes to food security and economic development in Ukraine.

The limitation of the study is that it covered only a certain period of time and a specific region, which may affect the universality of the results. In addition, some aspects of the impact of innovative methods on long-term environmental sustainability require more detailed study. Nevertheless, the results clearly demonstrate the benefits of innovative approaches to grain growing and can serve as a basis for further research and implementation in agricultural practice. To further improve the results obtained, it is recommended to conduct additional research on the adaptation of innovative methods to different local conditions, as well as to investigate the long-term effects of the use of biological products and biofertilisers. It is also important to develop educational programmes and trainings for farmers to enable them to effectively use the latest technologies and increase the productivity of their farms.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Інноваційні підходи до вирощування зернових культур у Південному Степу України

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Анотація. Метою дослідження був аналіз впливу інноваційних підходів до вирощування зернових у Південному Степу України. Під час дослідження використовувалися новітні сорти рослин, ефективні системи зрошення та біопрепарати для підвищення врожайності та стійкості культур. Було застосовано сорти пшениці «Степова 1» та «Дніпровська 1», а також ячмінь «Південний 1», які відзначаються високою стійкістю до посухи та високих температур. Використовувалися системи крапельного та підповерхневого зрошення, а також біодобрива та органічні компости для покращення структури ґрунту та підвищення його родючості. Основні результати дослідження показали, що врожайність пшениці в експериментальних групах досягала 5,2-5,7 тонн/га, що на 1,8-1,9 тонн/га більше, ніж у контрольних групах. Витрати води в експериментальних групах знизилися на 35-40%, а витрати на засоби захисту рослин – на 45-50 %. Вміст білка у пшениці експериментальних груп становив 14-15 %, а клітковини – 30-32 %, тоді як у контрольних групах – відповідно 11-12 % та 25-27 %. Аналіз ґрунту в експериментальних групах показав вищий рівень азоту, фосфору та калію, що свідчить про ефективність застосування біодобрив. Крім того, використання біопрепаратів сприяло зниженню хімічного навантаження на навколишнє середовище. Отримані результати свідчать про значне підвищення продуктивності, зменшення використання ресурсів та покращення екологічної стійкості при впровадженні інноваційних методів вирощування зернових культур у цьому регіоні, що є важливим для забезпечення продовольчої безпеки та економічного розвитку України

Ключові слова: пшениця; ячмінь; біодобрива; крапельне зрошенння; біопрепарати; родючість

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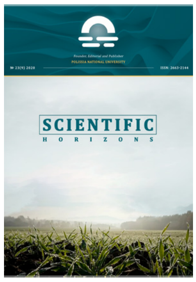

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Forecasting and modelling the rye market, as a niche grain crop, under conditions of increasing mineral fertiliser costs

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Abstract. The cultivation of rye as a niche crop is gaining increasing importance in Ukraine. However, the rising cost of mineral fertilisers necessitates forecasting and market modelling to mitigate risks and enhance the economic efficiency of production. This study aimed to assess the current state of supply and demand in the rye market, which is considered a niche grain crop, and to forecast the effects of changes in mineral fertiliser costs on key market parameters under probable scenarios. The research employed comparative analysis, tabular representation, statistical economic approaches, abstract-logical reasoning, and econometric modelling. In particular, the econometric partial equilibrium model AGMEMOD has been utilised. The potential of rye as a niche crop has been revealed, the current state of its production has been analysed, and the key factors influencing the formation of supply and demand in the Ukrainian rye market have been identified; the dynamics of the supply and demand balance in the rye market, taking into account various economic and other factors, have been analysed; a forecast has been made of the consequences of changes in the cost of mineral fertilisers on the main parameters of the development of the rye market in Ukraine under several probable scenarios. The forecast extended to 2026 and evaluated the effects of different changes on yields, sown areas, gross production, and the economic efficiency of rye cultivation. The research provided a foundation for improving the efficiency of decision-making and implementation of management strategies, contributing to the achievement of national agricultural policy objectives, including ensuring food security. The proposed methodological approaches and research findings may be valuable for public and sectoral authorities in developing priority measures aimed at enhancing the performance of the domestic grain sector

Keywords: agricultural policy; rye; niche crops; grain market; diversification; food security; mineral fertilisers; AGMEMOD

INTRODUCTION

In the context of escalating global food security challenges, new demands are emerging for the formulation of agricultural policy, alongside a growing emphasis on the diversification of agricultural production. Diversification is facilitated through the expansion of niche crop cultivation, both within traditional farming systems and under the principles of organic production. The potential of niche crops lies in their ability to enhance global food security and deliver a range of additional benefits across economic, agrotechnological, environmental, and social dimensions. Economically, niche crops help mitigate market risks, serve as raw materials for high-value-added products, and provide additional income streams for farmers, particularly for small and medium-sized enterprises. Agrotechnologically and environmentally, niche crops offer advantages such as diversifying crop rotations, increasing agricultural biodiversity, improving soil health, and contributing to climate change mitigation. From a social perspective, cultivating niche crops supports the development of small-scale agricultural enterprises, generates additional employment opportunities in rural areas, and fosters rural community development. Given these considerations, focused research on the development of agricultural markets – particularly using the example of a specific niche crop under conditions of rising mineral fertiliser costs – is increasingly relevant and warrants detailed investigation.

Research indicates that diversified farming systems provide greater employment opportunities for rural populations without reducing profitability for agricultural producers. For instance, A. Sánchez *et al.* (2022) emphasised that promoting diversification, particularly through the expansion of niche crops, is a promising strategy for ensuring sustainable livelihoods for farmers and adequate nutrition for households and society. A. Mavroeidis *et al.* (2022) highlighted that niche crops hold significant potential for the future of agriculture and align with the UN's Sustainable Development Goals. Similarly, A. Pradhan *et al.* (2021) noted that many niche crops – also referred to as alternative, speciality, indigenous, or underutilised crops – are resilient to abiotic stresses, well-suited to marginal environments, and represent a rich pool of genetic resources for enhancing future yields. Integrating such crops into existing farming systems can help establish sustainable, nutritious, healthy, and diverse food systems, particularly in marginalised agroecological contexts. Furthermore, S. Padulosi *et al.* (2021) and I. Kakabouki *et al.* (2021) demonstrated that several niche crops exhibit high acclimatisation and adaptive potential to conditions such as salinity, drought, waterlogging, and lowfertility soils. Hirich *et al.* (2020) noted in their study that utilising marginal lands, which constitute a significant portion of available arable land, through the introduction of stress-resistant niche crops has the potential to enhance their agricultural productivity. This, in turn, could improve food security by increasing the availability of food resources.

L. Clinton *et al.* (2020) highlighted that niche crops are high-value agricultural products but are associated with relatively higher risks and increased production costs, necessitating a cautious approach to their integration into cropping systems. In the absence of adequate information on production technology, management, and marketing, agricultural producers may face the risk of low economic profitability. Conversely, with a well-planned and professional approach to cultivating niche crops, producers can unlock new market opportunities. This observation is particularly relevant for Ukraine. For instance, O. Drebot and M. Vysochanska (2024) noted that the strategic production and export of niche products are viewed as effective pathways to addressing economic challenges both in the agricultural sector at large and for individual producers. Furthermore, in the current environment, the growing trend of healthy eating is increasing consumer willingness to pay for novel and unique products, providing farmers with opportunities to access regional, domestic, and global markets with innovative offerings (Cherevko & Cherevko, 2020). This statement is especially pertinent given the wide variety of niche (speciality or alternative) crops available globally and in specific regions or countries. It is important to note that a crop may simultaneously be considered a primary, secondary, or niche crop depending on the region or country. For example, rye, which is classified globally as a secondary cereal, is considered a niche crop in Ukraine due to its relatively small cultivation area compared to traditional commercial crops.

This study aimed to assess the current state of supply and demand in Ukraine's rye market and to forecast the impact of changes in mineral fertiliser costs on key development parameters under probable scenarios through to 2026, using the AGMEMOD econometric partial equilibrium model.

MATERIALS AND METHODS

This article was prepared as part of the research project titled "Forecasting the Development of the Market of Grain Niche Crops in the Conditions of Challenges and Threats to Food Security of Ukraine (Using the AGMEMOD Partial Equilibrium Econometric Model)", with the state registration number 0123U102156. The study employed the following methods: comparative analysis was utilised to evaluate the current state of rye production, identify trends, and compare indicators such as yield, gross harvest, and cultivated area across various groups of producers in Ukraine. This method was also used to determine Ukraine's position among the leading rye-producing countries globally; tabular method facilitated the organisation and visual representation of analytical data and research findings; the statistical-economic method was applied for collecting and analysing data to identify the status, trends, and patterns in the development of key parameters of Ukraine's rye market; factor analysis to identify and evaluate the impact of key factors on the efficiency of rye production; abstract-logical method supported the formulation of conclusions, generalisation of research results, and development of theoretical propositions; econometric modelling was used to assess the impact of mineral fertiliser costs on key parameters of rye market development in Ukraine, forecast future trends, and justify optimal strategies to reduce costs and enhance production efficiency in the country.

The data used for this study were collected from various sources, including the Ministry of Economy of Ukraine (2024), the Ministry of Finance of Ukraine (2024), the Ministry of Agrarian Policy and Food of Ukraine (2024), the State Statistics Service of Ukraine (2024), the World Bank (2024), the International Monetary Fund (2024), the US Department of Agriculture (2024), Statistics. FAOSTAT (2024), the International Trade Centre (2024), and the OECD (2024). Additionally, the research incorporated information from Ukrainian and international scientific publications, as well as the authors' own studies and practical observations.

To evaluate the impact of changes in mineral fertiliser costs on key parameters of the rye market in Ukraine, the econometric dynamic partial equilibrium model AGMEMOD (Agricultural Member State Modelling) was employed. This model is designed for detailed analysis and forecasting of the effects of agricultural policy decisions on agricultural production, markets, and the economies of both European Union member states and neighbouring countries. The equations describing the key parameters of the Ukrainian rye market were estimated using time series data covering the period from 1992 to 2021. The equations were assessed as linear regressions using the ordinary least squares method in the statistical software R. Prior to estimation, the data underwent rigorous processing, including the identification and correction of inconsistencies and missing values, to ensure high accuracy and reliability in the analysis. This approach accounted for all key factors influencing the rye market and allowed the development of a detailed model suitable for forecasting market trends under changing economic and political conditions.

This study involved a four-step regression selection process:

1) *Hypothesis formation*. Based on microeconomic theory and specific industry characteristics, hypotheses were formulated regarding potential relationships between dependent and explanatory variables. This stage involved identifying key factors that could potentially influence the outcomes and constructing a theoretical model to represent these relationships;

2) *Graphical analysis of relationships*. After formulating hypotheses, the potential relationships between variables were analysed graphically. This allowed for a visual assessment of the nature and strength of the relationships, as well as the identification of potential anomalies or non-linearities that could affect the results of the regression analysis;

3) *Autocorrelation testing*. Variables were tested for autocorrelation. This involved using statistical tests to detect dependencies between consecutive values of

variables, ensuring the accuracy and reliability of the regression estimates;

4) *Analysis of estimation results*. The results of the regression estimation were analysed in detail to assess the overall fit of the model, statistical significance, and consistency with the hypotheses. This stage involved checking the adequacy of the model using various criteria, such as the coefficient of determination (R^2), significance of regression coefficients, and analysis of model residuals.

This comprehensive systematic approach to regression selection ensured a high level of accuracy and reliability in the obtained results, allowing for a deep understanding of the relationships between variables and informed conclusions about the development of the Ukrainian rye market. The coefficient of determination (R^2) which indicates the proportion of the variance in the dependent variable that is predictable from the independent variable(s), 1 was 0.269. This means that the regression equation explains only 26.9% of the variation in the dependent variable due to the variation in the independent variable. However, for complex models with limited datasets, this value of the coefficient of determination can be considered acceptable and sufficient for assessing its reliability. Furthermore, the p-value of the regression equation is 0.00000000000000358, indicating the high statistical significance of all variables in the model, as the value is much smaller than the threshold value of 0.05. This confirms that the variables in the model have a significant impact on the dependent variable. All other regression estimation results obtained using R software are presented in Figure 1, allowing for a detailed analysis of the model parameters and drawing well-founded conclusions about its adequacy and reliability.

Based on the analysis conducted, equations that demonstrated higher statistical reliability and better reflected the current trends of the dependent variables were added to the AGMEMOD model. These equations were carefully selected to ensure a more accurate and reliable estimation of key market parameters. The introduction of such equations enabled the model to more effectively account for interactions between different variables and provide more precise forecasts of agricultural market development. This, in turn, increases the utility of the AGMEMOD model for analysing policy decisions and developing strategies for agricultural sector development, providing a deeper understanding of economic processes and market responses to external influences.

```
l1:
plm(formula = yld_ry_t ~ 0 + trend08 + price1_ry_real_uah_hkg,
    data = pdata_subs_no_Ukr, model = "random")

Unbalanced Panel: n = 24, T = 5-8, N = 183

Effects:
                var std.dev share
idiosyncratic 0.204   0.451  0.51
individual    0.197   0.444  0.49
theta:
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
   0.59    0.66    0.66    0.66    0.66    0.66

Residuals:
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
 -1.222  -0.262  -0.018   0.001   0.211   1.569

Coefficients:
                       Estimate Std. Error z-value             Pr(>|z|)
trend08                 0.94842    0.08118   11.68 < 0.0000000000000002 ***
price1_ry_real_uah_hkg  0.02736    0.00667    4.11              0.00004 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Total Sum of Squares:    49.8
Residual Sum of Squares: 36.4
R-Squared:      0.269
Adj. R-Squared: 0.265
Chisq: 66.5287 on 2 DF, p-value: 0.00000000000000358
```

***Figure 1**. Regression estimation using R packages*

***Source:** authors' calculations based on (Nykolyuk et al., 2023)*

The primary equations for modelling and forecasting the main demand and supply parameters of the rye market in Ukraine include:

1. Area harvested with rye, thousand hectares (Equation (1)):

$$RYAHAUA = RYASHUA \times RYAHAUA. \tag{1}$$

2. Rye yield, tonnes per hectare (Equation (2)):

$$RYYHAUA = 0.94842 \times TREND08 + + 0.02736 \times RYPFNUA(-1)/GDPDUA(-1). \tag{2}$$

3. Gross rye production, thousand tonnes (Equation (3)):

$$RYSPRUA = RYYHAUA \times RYAHAUA. \quad (3)$$

4. Domestic consumption, thousand tonnes (Equation (4)):

$$RYUDCUA = RYUFOUA + RYUFEUA + RYUDLUA. \quad (4)$$

5. Feed use, thousand tonnes (Equation (5)):

$$RYUFEUA = \max(50 - 520.471 - 0.4555181 \times \times \frac{RYPFNUA}{GDPDUA} + 0.0570071 \times CMSPRUA. \quad (5)$$

6. Food use, thousand tonnes (Equation (6)):

$$RYUFDUA = RYUPCUA \times POPUA. \quad (6)$$

7. Food and seed use, thousand tonnes (Equation (7)):

$$RYUFOUA = RYUFDUA + RYUFSUA. \quad (7)$$

8. Rye price on the domestic market, UAH per centner (Equation (8)):

$$RYPFNUA = \max(0.0001)$$
$$RYPFNUA = 4.5278 + 0.8383^{*}BAPFNUA. \quad (8)$$

9. Profitability of rye production in real prices from the previous period, thousand UAH (Equation (9)):

$$RYEGUUA = \frac{RYPFNUA(-1)}{GDPDUA(-1)} - \frac{RYCGUUA}{GDPDUA}. \quad (9)$$

10. Rye imports, thousand tonnes (Equation (10)):

$$RYSMTUA = 0.02 + \max(0.RYUDCUA - RYSPRUA). \quad (10)$$

11. Rye exports, thousand tonnes (Equation (11)):

$$RYUXTUA = 0.02 + \max(0.RYSPRUA - RYUDCUA). \quad (11)$$

Notation:
RYAHAUA – area harvested with rye;
GRAHAUA – total grain area;
RYYHAUA – rye yield;
RYSPRUA – gross rye production;
RYUDCUA – domestic consumption volume;
RYCCTUA – ending stocks;
RYUFEUA – feed use;
RYUDLUA – losses;
RYUFDUA – food use;
RYUFSUA – seed use;
RYUFOUA – food and seed use;
RYPFNUA – domestic market price of rye per centner;
RYUOTUA – processing;
RYCGUUA – production costs per hectare of rye area;
RYEGUUA – rye profitability;
BAPFNUA – price of barley (as a rye substitute) from the previous period;
GDPDUA – GDP deflator;
GDPDUA (-1) – GDP deflator from the previous period;
TREND08 – logarithmic trend;
POPUA – population of Ukraine;
EXRDUA – USD to UAH exchange rate;
RYSMTUA – rye imports;
RYUXTUA – rye exports.

The database for the Ukrainian model country begins in 1992. For the current study, it has been updated to 2021, and where possible, to 2022. These data series encompass a wide range of indicators reflecting the state of the agricultural sector. These include observations on crop production in terms of yields and harvested areas, livestock numbers and productivity, slaughter weights, and production of oilseeds and oilcakes. Domestic data use covers aspects such as feed use, human consumption, processing, and product losses. Additionally, the database includes information on agricultural product prices, stock changes, imports, and exports. This comprehensive dataset enables detailed analysis and modelling of agricultural markets, ensuring accurate and comprehensive forecasts and aiding in informed decision-making for the development of Ukraine's agricultural sector.

Data on most domestic market prices and supply components were obtained from the State Statistics Service of Ukraine (2023). For information on export and import volumes, components of domestic consumption, and domestic prices for oils and oilseed meal, data from Statistics. FAOSTAT (2024) and the International Trade Centre (2024) were used. Data for 2022 was collected from publicly available commodity price databases and reports from the Ministry of Agrarian Policy and Food of Ukraine (2024). This provided a comprehensive and accurate dataset for analysis and modelling, which in turn contributed to a deeper understanding of market dynamics.

Forecasts of agricultural commodity balances in the AGMEMOD model are based on several factors, such as agricultural and trade policy, production costs, world market prices for agricultural products, and macroeconomic indicators including national GDP, GDP deflator, exchange rate, and population. These factors are exogenous variables, meaning they are not calculated or forecasted by the model itself. Their observed and forecasted values are collected from various external sources such as national and international statistical services, analytical reports, and economic forecasts. These data are then input into the model as a separate component representing the modelling assumptions. This allows for the consideration of external influences on the agricultural sector and provides more accurate and reliable forecasts, supporting effective decision-making in agricultural policy and management.

While the model allows for simulations with various global market price values, the current study was conducted within the general parameters defined by the

OECD-FAO Agricultural Outlook (OECD-FAO…, 2023). Therefore, the historical and projected values of global market prices for the analysed commodities correspond to the data presented in the EU Agricultural Outlook. This ensured consistency and comparability of the research results with international standards and forecasts, increasing the reliability and robustness of the conclusions. The use of these authoritative sources allowed for the consideration of a wide range of global economic and political factors affecting agricultural markets, providing a more comprehensive approach to analysing and forecasting the development of the agricultural sector.

However, the full-scale Russian armed aggression against Ukraine significantly hindered the process of updating and expanding the information for modelling due to limited access to statistical data. At the time of writing this article, the authors were unable to obtain complete official statistical data for 2022-2023 to construct the model. Additionally, 2022-2023, characterised by a state of war, exhibited a trend of decline in all indicators, and data from these years could have affected the reliability of the modelling. Moreover, the economic shocks caused by the war significantly impacted the trends in the rye market, which is important to consider when interpreting the results. Given these limitations, the authors of the study used the most up-to-date data available until 2021, which allowed them to build a model based on the most recent complete data, considering the need to obtain a reliable modelling result. However, changes in the market caused by economic fluctuations and an unstable situation may affect the reliability of future forecasts, therefore the results should be considered in light of these limitations.

RESULTS

A review of the global rye market in 2023 reveals that EU countries were the leading producers in terms of harvested area and production volume (Table 1), with Ukraine ranking among the top ten. Notably, the group of leading countries in terms of harvested rye area and production volume was not identical, indicating the significance of intensive production methods. This is confirmed by the top ten countries with the highest rye yields, which included only three countries from those leading in harvested area in 2023 (belarus, Canada, and Turkey) (Table 1). In terms of initial rye stocks, domestic consumption, and ending stocks in 2023, EU countries were also the leaders (Table 2). Countries consuming more rye than they produced in 2023 included the USA, Turkey, Norway, and Kazakhstan, indicating an existing demand for this grain.

***Table 1**. Rye production worldwide, 2023*

Leading countries by harvested rye area	Harvested area, thousand hectares	Leading countries by rye production volumes	Production volume, thousand tonnes	Leading countries by rye yield	Yield, tonnes/hectare
EU	1,830	EU	7,750	Switzerland	6
rf	875	rf	1,900	Norway	6
belarus	310	belarus	780	EU	4
USA	121	Canada	375	UK	4
Canada	115	Turkey	320	Albania	3
Turkey	110	USA	266	Bosnia and Herzegovina	3
Argentina	90	Ukraine	230	Serbia	3
Ukraine	80	Argentina	165	belarus	3
Australia	45	Norway	50	Canada	3
Kazakhstan	30	Kazakhstan	40	Turkey	3

***Source:** Indexmundi (2023)*

As the research revealed, ending stocks of rye worldwide in 2023 were quite low, and in some countries, they were completely absent (Table 2). Meanwhile, Ukraine in 2023 was among the top ten in terms of initial stocks, domestic consumption, and ending stocks.

***Table 2**. Initial stocks, domestic consumption, and ending stocks of rye by leading countries worldwide, 2023*

Initial stocks, thousand tonnes	Country	Domestic consumption, thousand tonnes	Country	Ending stocks, thousand tonnes	Country
362	EU	7,700	EU	387	EU
179	rf	1,850	rf	149	rf
106	Canada	750	belarus	72	Canada
42	Ukraine	518	USA	65	belarus
37	belarus	334	Turkey	60	Ukraine
19	USA	230	Canada	16	USA

Table 2. Continued

Initial stocks, thousand tonnes	Country	Domestic consumption, thousand tonnes	Country	Ending stocks, thousand tonnes	Country
14	Turkey	202	Ukraine	5	Kazakhstan
5	Kazakhstan	165	Argentina	1	Japan
1	Japan	55	Norway	0	Republic of Korea
0	Republic of Korea	45	Kazakhstan	0	Turkey

Source: *Indexmundi (2023)*

In 2023, the global rye market was valued at USD 3.76 billion and is projected to grow by 2.23.3% over the next decade (Rye Market Share..., 2024). In terms of application, the current global rye market is classified into segments such as bakery products, alcoholic beverages, animal feed, and other uses.

The main advantages of multifunctional rye and the diverse opportunities it offers include: high nutritional content; cover crop properties; and adaptability to climatic conditions – rye can grow in harsher climates and poorer soils than other cereals, making it valuable for regions with less fertile soils and more extreme weather conditions; potential for sustainable cultivation, as it contributes to lower CO_2 emissions, consumes less nitrogen and water compared to other cereals, and exhibits erosion resistance – rye's root system effectively holds the soil, reducing the risk of erosion and thus contributing to soil fertility and ecological sustainability; the ability to produce a range of high-value products, including those with high nutritional value and aligned with the popular trend of healthy eating; niche market potential – as a niche crop, rye can have stable market demand, especially in the health food and organic product sectors. This allows farmers to obtain a higher price for their products; opportunities for agricultural diversification – growing rye contributes to crop rotation diversification, reducing risks associated with monocultures and instability in markets for other cereals; opportunities for livestock development – rye is also used as animal feed, making it an important component in livestock farms; potential for biomass production in the context of bioenergy development.

Despite rye's multifunctionality and significant economic potential, Ukraine has witnessed a steady decline in its cultivation and production for several decades. Traditionally, rye is grown in the Polissia region of Ukraine, specifically in the northern parts of Sumy, Zhytomyr, Rivne, Chernihiv, and Volyn regions. On the sandy soils of Polissia, rye outperforms wheat in terms of yield. Since 1990, the peak of gross rye harvest in Ukraine occurred in 1995 at 1,208 thousand tonnes, followed by a decline. Compared to 1995, the gross harvest in 2023 decreased by 19 times to 230 thousand tonnes (Table 3). However, over this period, the gross harvest of rye in Ukraine fluctuated significantly. Until 2021, when the Ukrainian rye market began to activate, the state was not a major rye exporter. In 2020, Ukraine exported only 17 thousand tonnes of rye, while in 2021, this figure increased to 162 thousand tonnes. This can be explained by Ukrainian companies developing new profitable markets. However, 2022-2023 was characterised by a decline in rye exports from Ukraine due to the full-scale Russian invasion.

***Table 3**. Rye market in Ukraine*

Years	Gross harvest, thousand tonnes	Initial stocks, thousand tonnes	Domestic consumption, thousand tonnes	Ending stocks, thousand tonnes	Export, thousand tonnes	Import, thousand tonnes
1990	919	203	1,426	287	0	250
1995	1,208	250	1,188	250	29	9
2000	968	104	1,000	88	1	17
2005	1,054	339	1,050	274	69	0
2010	464	411	650	189	38	2
2015	394	106	420	75	21	16
2020	459	48	402	90	17	2
2021	600	90	415	114	162	1
2022	285	114	337	42	20	0
2023	230	42	202	60	10	0

Source: *Indexmundi (2023)*

In the 2021/22 marketing year, Spain, Turkey, and Poland were among the most active buyers of Ukrainian rye. Ukraine's share in global rye exports during this period increased not only due to the growth of its own production but also due to a decrease in supply from other exporters. For a long time, the Netherlands (which purchased USD 41.9 million worth of rye in 2020), Spain (USD 60.8 million in 2020), and Germany (USD

189 million) were traditional destinations for Ukrainian rye exports. In 2022, despite the war, South Korea and Japan surpassed Spain and Germany in export volumes. As a result, in recent years, the geographical scope of Ukrainian rye exports has expanded to East Asian countries. Rye was exported to these regions for the production of alcoholic beverages, animal feed, fertilisers, and rye straw. In 2023, the top three exporters of Ukrainian rye were Poland (39%), Germany (33%), and Slovakia (24%) (State Customs Service..., 2023). Overall, this segment is highly profitable for Ukrainian agricultural producers as they face virtually no competition in this niche crop market.

Despite the existing demand, Ukraine witnessed a trend of increasing sown areas under rye in 2020-2021. In 2021, the area under cultivation reached 175 thousand hectares, which is 59.5 thousand hectares (51.5%) more than in 2019 (Table 4). However, in 2022-2023, sown areas of rye decreased significantly by 11.7% and 30.7%, respectively, compared to 2019. Consequently, rye grain production also decreased. This is primarily attributed to the full-scale russian invasion. Meanwhile, the crop yield in 2019-2023 was quite stable and fluctuated within the range of 27-35 centners per hectare across different categories of farms. Lower rye yields were typical for household farms, while higher yields were characteristic of agricultural enterprises. Although, overall, rye yields in Ukraine are currently quite low compared to other leading rye-producing countries.

***Table 4**. Level and dynamics of rye production in Ukraine by main producers*

	2019	2020	2021	2022	2023	2023 to 2019, %
Sown area, thousand hectares						
All types of farms	115.5	140.0	175.0	102.0	80.0	69.3
Including agricultural enterprises	57.9	82.6	116.3	57.6	38.9	67.2
Of which: farms	10.6	16.4	21.5	n/a	n/a	
households	57.6	55.9	55.7	44.4	40.4	70.1
Production, thousand centners						
All types of farms	3,346.8	4,567.8	5,931.5	3,140.3	2,311.8	69.1
Including agricultural enterprises	1,792.9	3,047.2	4,440.2	1,959.1	1,175.6	65.6
Of which: farms	329.9	636.6	779.6	n/a	n/a	
households	1,553.9	1,520.6	1,491.3	1,181.2	1136.2	73.1
Yield, centners/hectare						
All types of farms	28.9	33.2	34.5	30.9	29.4	101.7
Including agricultural enterprises	31.0	37.2	38.1	34.2	30.9	99.7
Of which: farms	31.2	39.5	36.6	n/a	n/a	
households	26.8	27.3	26.9	26.7	27.9	102.2

***Note:** n/a – data not available*
***Source:** Plant Growing in Ukraine (2022)*

It should be noted that modern rye varieties and hybrids have a yield potential of 10-12 tonnes per hectare, which is one of the key arguments supporting the high economic potential of rye. In recent years, there has been a growth in the share of hybrids in the Ukrainian rye market – almost half of rye areas are sown with hybrids. This is due to their higher yield, greater resistance to pests, lower seeding rate, and consequently, higher profitability compared to varieties. An argument in favour of hybrid rye is that it is a cheaper raw material with a high content of crude protein, the use of which provides a noticeable economic effect for livestock farms.

As of 2023, rye production in Ukraine was almost evenly distributed between agricultural enterprises (50.9%) and household farms (49.1%). However, as recently as 2021, the majority of rye in Ukraine was grown by agricultural enterprises. In 2021, they produced 4,440.2 thousand centners of rye, accounting for 74.6% of the gross harvest. Significantly, during 2019-2021 (before the full-scale russian invasion), households (by 136%) and agricultural enterprises (by 147.7%) significantly increased their rye production. This was facilitated by both an increase in sown areas under rye and a growth in yields. This trend can be seen as one of the indicators that niche crops are increasingly attracting the attention of farmers, particularly small agricultural businesses, which may not be able to compete with large enterprises in the production of so-called "cash crops". For these businesses, focusing on a specific niche and diversifying their crops is a viable strategy for effective development.

While exploring the advantages of rye that contribute to its economic value and potential, it is essential to focus on the primary factors hindering its production. First and foremost, rye exhibits different storage characteristics compared to wheat: even under favourable conditions, rye's seed viability declines, whereas wheat can retain its viability for a year or more. Overcoming this obstacle, i.e., preserving the quality of rye seed, can be achieved by selecting optimal varieties. Another reason for the relatively small scale of rye cultivation, particularly in Ukraine, is its comparatively lower yield. However, as the experience of leading rye-producing countries demonstrates, yield primarily depends on cultivation technology rather than the crop itself. Niche crops like rye have significant potential. Breeders have already developed rye varieties with yields comparable to other cereal crops. Ukrainian agricultural market experts assert that in 9 out of 10 years, winter rye produces a high yield (⩾ 5 tonnes/hectare), although there is a risk of crop failure once every 26 years, primarily due to weather conditions (Opara, 2020). The concentration of Ukrainian farmers on traditional, widely cultivated commercial crops, for which well-established domestic and international markets exist, also negatively impacts the development of rye production and its market. These crops have established distribution channels, making it more challenging for rye to gain a significant market share.

Furthermore, one of the most significant factors currently hindering the development of rye production in Ukraine is the steady increase in the cost of mineral fertilisers. The sharp rise in global natural gas prices in 2021 led to a substantial increase in the cost of mineral fertilisers. This is because up to 80% of the production cost of mineral fertilisers depends on the use of natural gas as a primary raw material. As a result of this increase in gas prices, production costs for fertiliser companies have risen significantly, which, in turn, has affected the final product price. This situation has created an additional financial burden on farmers, which could have influenced their decisions regarding production volumes and the use of agrochemicals.

According to the World Bank, global mineral fertiliser prices increased by an average of 80% in 2021. In the first quarter of 2022, they rose by almost another 30% (World Bank Group, 2022). As shown in Table 5, for the period from January 2020 to January 2024, global prices for diammonium phosphate, urea, and potassium chloride increased by 2.25, 1.56, and 1.06 times, respectively (World Bank, 2024). The highest global prices for mineral fertilisers were recorded in April 2022, which was due to the imposition of economic sanctions on russia and belarus following russia's full-scale invasion of Ukraine, as well as export restrictions on fertiliser exports imposed by China (World Bank Group, 2022, The World Bank..., 2024). Similar trends are observed when analysing the Fertiliser Affordability Index (FAI), which is used to assess the economic affordability of fertilisers for farmers. This index is calculated as the ratio of fertiliser costs to agricultural product prices. A higher index indicates that fertilisers are less affordable for farmers, as their cost is relatively high compared to the income from agricultural sales.

Table 5. *Dynamics of global mineral fertiliser prices, USD per tonne*

Period	Diammonium phosphate	Urea	Potassium chloride	Fertiliser Affordability Index (FAI)
January 2020	264.9	215.4	268.7	0.77
January 2021	421.3	265.0	255.5	0.75
January 2022	699.4	846.4	785.6	1.82
April 2022	954.0	925.0	1,202.0	1.92
January 2023	631.0	443.8	508.8	1.34
January 2024	596.3	335.4	284.0	0.98
April 2022 to January 2020, times	3.60	4.29	4.47	2.49
January 2024 to January 2020, times	2.25	1.56	1.06	1.27

Source: *compiled by the authors based on data from the World Bank (2024)*

Conversely, a lower index indicates that fertilisers are more affordable, as their cost is relatively low compared to the income from product sales. The highest global FAI was recorded in April 2022, reaching 1.92. Overall, after high FAI values in the period from 2022 to 2023, the index decreased to 0.98 only in January 2024. This change indicates an improvement in the economic affordability of fertilisers for farmers, which may contribute to increased fertiliser use and higher crop yields.

As previously noted, one of the main drivers of rising mineral fertiliser prices, both globally and in the Ukrainian market, remains high natural gas prices, which continue to increase. For example, at the TTF (Title Transfer Facility) gas hub in the Netherlands, the price of natural gas increased from USD 263.5 to USD 412.2 per 1,000 m^2 between June 1, 2023, and June 3, 2024, or by 56.4% (Ministry of Finance of Ukraine, Gas prices..., 2024). In addition, the increased cost of electricity and logistics services in Ukraine indicates that the trend of rising mineral fertiliser prices will continue. High energy and logistics costs affect the overall cost of fertiliser production, which ultimately is reflected in their market price. Thus, farmers and agricultural producers, particularly in Ukraine, may face further increases in the cost of purchasing mineral fertilisers, which could affect their production decisions and economic efficiency.

The high prices of mineral fertilisers, coupled with the adherence to modern agricultural technologies, significantly increase the production costs of grain crops. According to estimates, the production cost of agricultural products may increase by 10-12% due to the rising cost of fertilisers (Ministry of agrarian policy...). Small and medium-sized family farms, which cultivate small areas of land (up to 400-500 hectares) and have limited working capital for fertiliser purchases, are particularly vulnerable to these changes. As a result, many farmers will be forced to reduce their fertiliser use, as the additional benefit of their application does not compensate for the purchase costs. This can lead to a decrease in yields and overall production efficiency, negatively impacting farmers' financial situation and the stability of the agricultural sector as a whole (Gromov, 2022).

From a scientific and practical standpoint, it is crucial to assess the economic consequences of changing mineral fertiliser prices on key parameters of the rye market in Ukraine. Such assessments can only be preliminary, as there is insufficient data for a detailed analysis. For example, some agricultural producers managed to purchase mineral fertilisers in advance, while others are doing so under the current challenging conditions, and some plan to make purchases in the spring, hoping for a decrease in market prices or government compensation. Due to the different procurement strategies and uncertainty in the fertiliser market, accurate calculations of the impact of changing fertiliser prices on the rye market require a comprehensive approach and additional data. These factors complicate the analysis but make it critically important for understanding and forecasting the development of the agricultural sector in the face of fluctuating fertiliser prices.

To assess the impact of changing mineral fertiliser prices on key parameters of supply and demand in the Ukrainian rye market, an econometric dynamic partial equilibrium model – AGMEMOD – was used. According to the fundamentals of economic theory, agricultural product and factor markets are closely interconnected and influence each other. For example, an increase in gross grain harvests leads to a rise in demand for mineral fertilisers. This increased demand stimulates a growth in domestic fertiliser prices, which, in turn, affects market prices for grain crops. The interdependence between these markets means that changes in one segment can have significant consequences for others. Therefore, analysis using the AGMEMOD model allows for a more accurate prediction of the impact of changing mineral fertiliser prices on the overall situation in the rye market, including production costs, product prices, and producer incomes. This approach provides a deeper understanding of economic processes and supports the adoption of effective decisions in the field of agricultural policy and management.

To assess the impact of production factors on the development of the rye market, various production costs were included in the AGMEMOD model. These costs encompass rent for agricultural land and property, wages, fuel and lubricant costs, seeds, and mineral fertilisers. These costs were calculated per hectare of harvested area for the period from 1992 to 2021. The inclusion of these costs in the AGMEMOD model allows for a more detailed analysis of their impact on key parameters of the rye market, including yield, gross harvest, and profitability. This approach contributes to a better understanding of the economic conditions in which farmers operate and aids in the development of policies aimed at supporting and developing the agricultural sector:

$$RYCGUUA = R + RP + S + SPM + FL + MF \times K_n, \qquad (12)$$

where *RYCGUUA* is the production costs of rye per hectare of the sown area; *R* is the land rent per hectare of agricultural land, UAH; *RP* is the rent for the property per hectare, UAH; *S* is the labour costs per hectare, UAH; *SPM* are the costs for seeds and planting material per hectare, UAH; *FL* is the fuel and lubricant costs per hectare, UAH; *MF* are the costs for mineral fertilisers per hectare, UAH; K_n is the coefficient for changes in mineral fertiliser costs.

In this study, the authors hypothesise that changes in the cost of mineral fertilisers influence key parameters of the rye market by altering the costs per hectare of cultivated land. To assess this impact, three different scenarios were developed and modelled. These scenarios were designed to analyse various possible situations and their consequences for the Ukrainian rye market, taking into account changes in the cost of mineral fertilisers. Each scenario reflects a certain level of change in fertiliser costs and its impact on yield, production costs, gross harvest, and other key market parameters. This approach allows for a detailed examination of potential economic consequences and provides well-founded recommendations for producers and policymakers on managing risks associated with changes in fertiliser costs. The baseline scenario assumes that the cost of mineral fertilisers per hectare remains at the 2022 price level. Other scenarios model an increase in fertiliser costs by 50%, 100%, and 150% compared to the baseline level. To introduce these scenarios into the model, the coefficient of change in mineral fertiliser costs (Kn) was used according to formula 12. Thus, for the "+50%", "+100%", and "+150%" scenarios, Kn is 1.5, 2.0, and 2.5, respectively.

As evidenced by Table 6, the results of the modelling scenarios confirm that, with an increase in the cost of mineral fertilisers compared to the baseline scenario, the average rye yield exhibits a steady downward trend. This is likely because small and medium-sized farms, which primarily grow rye as a niche crop, will be forced to reduce fertiliser application rates due to their high cost. A decrease in fertiliser use can lead to a decline in soil fertility and, consequently, a decrease in yield. This is particularly relevant for small farmers who have limited financial resources and cannot afford additional expenses for expensive fertilisers. Such changes can have a significant impact on the overall productivity of the agricultural sector and the economic stability of farms. According to the modelling results, an increase in the cost of mineral fertilisers will also lead to a reduction in sown areas and, consequently, to a decrease in gross rye harvests compared to the baseline scenario. If the harvested area of rye remains at around 143.7 thousand hectares, the gross harvest with an increase in the cost of mineral fertilisers will decrease to 462 thousand tonnes, which is 9.2% less compared to the baseline scenario.

***Table 6**. Modelling scenarios of the impact of changes in mineral fertiliser costs on key parameters of the rye market in Ukraine using the AGMEMOD model*

	Baseline scenario, 2022	**Scenarios of mineral fertiliser price changes relative to the baseline scenario, 2022**		
		"+50%"	**"+100%"**	**"+150%"**
Average yield, thousand /hectares	3.24	3.21	3.21	3.21
Harvested area, thousand hectares	157.2	143.7	143.7	143.7
Share of rye in total cereal area, %	1.0%	1.0%	1.0%	1.0%
Gross harvest, thousand tonnes	508.7	462.0	462.0	462.0
Import, thousand tonnes	0.02	0.02	0.02	0.02
Change in stocks at year-end, thousand tonnes	232.8	150.6	150.6	150.6
Total Resources	**508.76**	**462.0**	**462.0**	**462.0**
Export, thousand tonnes	135.54	125.9	125.9	125.9
Feed use, thousand tonnes	50.0	50.0	50.0	50.0
Seed use, thousand tonnes	34.6	31.6	31.6	31.6
Losses, thousand tonnes	19.6	17.8	17.8	17.8
Food use, thousand tonnes	269.1	236.8	236.8	236.8
Total Resources	**508.8**	**462.0**	**462.0**	**462.0**
Consumption fund	373.2	336.2	336.2	336.2
Production/Domestic consumption	1.36	1.37	1.37	1.37
Feed costs/Production	0.10	0.11	0.11	0.11
Export/Production	0.27	0.27	0.27	0.27

***Source:** authors' calculations based on data from Plant Growing in Ukraine (2022), Balances and Consumption..., 2021)*

Furthermore, it was found that an increase in the cost of mineral fertilisers does not have a significant impact on the volumes of rye exports and imports, as this crop is primarily grown to meet domestic market needs, although, as noted above, the potential for exporting the crop from Ukraine exists. The obtained modelling results, according to which an increase in the cost of mineral fertilisers by 50%, 100%, and 150% did not affect the yield, sown areas, and gross harvest of rye, are interpreted as follows. Firstly, due to the low elasticity of costs, the volumes of gross rye harvest may be less sensitive to changes in the cost of fertilisers compared to other factors. This means that farmers can use fertilisers more efficiently or replace them with other agronomic practices, which will allow them to maintain yields at a stable level even with a significant increase in cost.

Secondly, farmers may have stockpiles of fertilisers purchased at lower prices, allowing them to temporarily avoid the impact of rising costs on yields. Such reserves can be used to maintain stability in production. Thirdly, agricultural producers may adapt their agronomic practices in response to rising fertiliser prices. This may include more precise fertiliser application, the use of organic fertilisers, or changes in crop rotation, which helps to maintain productivity. Fourthly, changes in yield and areas may only become noticeable after several years. The impact of rising fertiliser costs may be more pronounced in the long term; in the forecast year, such changes may not yet have had time to manifest. Fifthly, the AGMEMOD model may have taken into account other compensating factors that reduce the impact of rising fertiliser costs on the predicted indicators. For example, an increase in grain prices may offset the increase in production costs.

Therefore, changes may be more noticeable over time as the gradual accumulation of negative effects from high fertiliser costs can influence long-term trends in the industry. However, in the short term, farmers may find ways to maintain production stability through adaptive strategies and agronomic solutions. Using the econometric model AGMEMOD, a forecast was developed for the medium-term consequences of increasing the cost of mineral fertilisers (a scenario of a +100% increase in fertiliser costs compared to the actual data for 2021) on the development of the rye market in Ukraine for the period up to 2026 (Table 7).

***Table 7**. Forecasting the consequences of changes in the cost of mineral fertilisers on key parameters of the development of the rye market in Ukraine using the AGMEMOD model (scenario of a "+100%" increase in fertiliser costs compared to 2021)*

	Actual data for 2021	Forecast data for the period up to:		
		2024	2025	2026
Average yield, thousand /hectares	3.43	3.11	3.16	3.21
Harvested area, thousand hectares	172.90	143.12	143.60	143.71
Gross harvest, thousand tonnes	593.00	445.25	454.30	461.99
Import, thousand tonnes	0.02	0.02	0.02	0.02
Export, thousand tonnes	238.67	94.61	111.06	125.85
Feed costs, thousand tonnes	35.00	50.00	50.00	50.00
Sowing costs, thousand tonnes	33.00	31.49	31.59	31.62
Losses, thousand tonnes	8.00	17.14	17.49	17.78
Food use, thousand tonnes	278.35	252.03	244.19	236.76
Consumption fund	354.35	350.66	343.27	336.16
Production/Domestic consumption	1.67	1.27	1.32	1.37
Feed costs/Production	0.06	0.11	0.11	0.11
Export/Production	0.40	0.21	0.24	0.27

***Source:** authors' calculations based on data from Plant Growing in Ukraine (2022), Balances and Consumption... (2021)*

The results of the forecast indicate that under the scenario of a "+100%" increase in the cost of mineral fertilisers, the key parameters of supply and demand in the Ukrainian rye market, as a niche grain crop, compared to the actual data for 2021, will reach the following indicators in 2026: the average yield will decrease from 3.43 to 3.21 tonnes per hectare; the harvested area will remain at around 144 thousand hectares; the gross harvest will decrease from 593 to 462 thousand tonnes, or by 22.0%; the use of rye for animal feed will remain at a fixed level, which is primarily due to negative trends in the development of the livestock industry in Ukraine; the ratio of production to domestic consumption will decrease from 1.67 to 1.37, but this will be quite sufficient to meet domestic needs; the ratio of exports to production will have a slight upward trend from 0.21 to 0.27. These forecasts indicate a significant impact of rising mineral fertiliser costs on the productivity and economic performance of rye production. Although harvested areas will remain stable, a decrease in yield and gross harvest can create additional challenges for the Ukrainian agricultural sector, primarily for small and medium-sized farms.

DISCUSSION

The results of this research, in the context of the multifunctionality of the niche crop rye, are connected to several other studies that focus on the properties of this crop and the opportunities provided by its production and processing. For example, B. Brockmueller *et al.* (2022) investigated the impact of rye on biodiversity, while W.L. Carrasco-Chilón *et al.* (2023) highlighted the potential for growing rye in arid conditions. However, the difference of this study in the context of the significance of the niche crop rye lies in the generalisation of its characteristics that form its multifunctionality, rather than highlighting a specific one. Similarly, the issue of ensuring food security and shaping effective agricultural policy has been the focus of many researchers in various interpretations, from different perspectives, and using examples from different countries. For instance, R. Byaruhanga *et al.* (2023) substantiated the prerequisites for sustainable food security through the establishment of national food sovereignty. M.A. Djan (2023) investigated the opportunities associated with ensuring food security in cities and in the context of global megatrends that shape the future world. It should be noted that the authors of the current study support the emphasis on global megatrends and in this research also highlighted the fact that the rye market today is largely dependent on the popular trend of healthy eating. In turn, I. Petrunenko *et al.* (2021) studied the issue of ensuring food security in the EU countries in the context of sustainable development and emphasised the need for a systematic improvement of the food security policies of EU member states, which echoes the results of this specific study, in which the authors substantiate the interconnection between the development of rye production and sustainable development.

Food security, agricultural potential, and agricultural productivity are directly linked to the development of production and markets for niche crops, such as rye. In this regard, the results of this study, in the context of the advisability of agricultural production diversification, are similar to the conclusions presented in the scientific publication by T.X. Neik *et al.* (2023), in which the scientists propose diversifying food markets, agricultural production, and technologies to ensure global food supply and build resilience to potential future shocks. In turn, T.X. Neik *et al.* (2023) consider agricultural diversification in the context of producing a crop as popular worldwide as rice, while the authors of this publication, on the contrary, consider the possibilities of diversifying agricultural production through the widespread cultivation of niche crops, particularly rye. Furthermore, the findings of C. Di Bene *et al.* (2022) support the results obtained in this study regarding the economic feasibility of incorporating rye into crop rotations. The authors also prove that combining agricultural diversification, including crop rotation, cover crops, and perennial crops, with low-cost management strategies such as agroecology, conservation agriculture, and organic farming, contributes to increasing crop productivity and the sustainability of the farming system in the long term. At the same time, the difference of this study is an attempt to generalise the advantages of rye as a niche agricultural crop and the opportunities provided by its production and processing in environmental, sociological, agronomic, and economic terms.

It is important to note that the majority of studies on rye production and its market focus on the advantages of this crop, while this study also addresses the barriers that hinder the development of rye production and its market. In particular, a distinctive feature of this study is the identification of a key factor that negatively affects the development of the rye market in Ukraine, such as the rising cost of mineral fertilisers. In this regard, the most significant scientific and practical novelty of this study is the forecasting of the rye market under various probable scenarios using the econometric partial equilibrium model AGMEMOD, within which an assessment was made of the impact of changes in the cost of mineral fertilisers on the main parameters of the formation of supply and demand in the Ukrainian rye market. Forecasting and modelling the market to reduce risks and increase the economic efficiency of production.

CONCLUSIONS

Therefore, rye, as a niche crop, is characterised by its multifunctionality and enjoys stable demand on the market, particularly in the health food and organic product sectors. This allows farmers to obtain a higher price for their produce. Additionally, growing rye contributes to crop rotation diversification, reducing risks associated with monocultures and the instability of other grain markets. Ultimately, this positively impacts food security levels. As of 2023, Ukraine was among the top 10 countries in the world in terms of rye production, consumption, and export. However, the development of rye production and its market under current challenges is hindered by several factors. The most threatening and restraining factor for the development of the rye market, according to the authors, is the rising cost of mineral fertilisers. Based on the conducted research, the impact of changes in the cost of mineral fertilisers on the main parameters of supply and demand in the rye market under probable scenarios has been quantitatively justified using the econometric partial equilibrium model AGMEMOD. Calculations have shown that under the “+100%” scenario (an increase in the cost of mineral fertilisers compared to 2021), the gross harvest of rye in Ukraine will decrease from 593 to 462 thousand tonnes, or by 22.0%, due to a decrease in yield by 6.3% and harvested area by 16.9%.

Regression results indicated that due to the low elasticity of costs, the volumes of gross rye harvests in Ukraine were less sensitive to changes in fertiliser prices compared to other factors. Specifically, modelling a 50%, 100%, and 150% increase in the cost of mineral fertilisers did not affect the average yield, harvested area, or gross harvest of this niche grain crop. This means that farmers can optimise fertiliser use or replace them with other agronomic methods, allowing them to maintain yields at a stable level even with a significant increase in fertiliser costs. In particular, they can implement precision agriculture, which involves using modern technologies to optimally determine the amount of fertiliser required for each field plot. This reduces costs and increases efficiency; they can use organic fertilisers or green manure, which contribute to improving soil structure and increasing its fertility without significant additional costs. Another approach could be the application of integrated nutrient management methods that optimise the use of both organic and mineral fertilisers. Given the above, ensuring that farmers have access to mineral fertilisers and maintaining low food prices will become new global challenges for many countries. Such steps will help strengthen the agricultural sector of Ukraine, making it more resilient to economic and market fluctuations, and will contribute to preserving the country’s food security in the face of current threats and challenges. The prospects for further scientific study in this direction are closely related to the continued application of the AGMEMOD econometric model to forecast markets for niche crops in the context of the need to ensure food security in Ukraine and the world.

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CONFLICT OF INTEREST

None.

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Прогнозування і моделювання ринку жита, як нішевої зернової культури, в умовах зростання вартості мінеральних добрив

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Анотація. Вирощування жита як нішевої культури в Україні набуває дедалі більшого значення, але через зростання вартості мінеральних добрив необхідне прогнозування та моделювання ринку для зниження ризиків і підвищення економічної ефективності виробництва. Метою даного дослідження була оцінка поточного стану попиту і пропозиції на ринку жита, яке розглядається як нішева зернова культура, та прогнозування наслідків зміни вартості мінеральних добрив на ключові параметри його розвитку за ймовірними сценаріями. У рамках дослідження застосовано такі методи, як: порівняльного аналізу, табличний, статистико-економічний, абстрактно-логічний, економетричне моделювання, зокрема використано економетричну модель часткової рівноваги AGMEMOD. Було розкрито потенціал жита як нішевої культури, сучасний стан його виробництва і визначено ключові чинники, що впливають на формування попиту і пропозиції на ринку жита в Україні; проаналізовано динаміку балансу попиту і пропозиції на ринку жита, враховуючи різні економічні та інші фактори; здійснено прогнозування наслідків зміни вартості мінеральних добрив на основні параметри розвитку ринку жита в Україні за кількома ймовірними сценаріями. Прогноз охоплював період до 2026 року та дозволяє оцінити вплив різних змін на врожайність, площі посівів, валові збори та економічну ефективність виробництва жита. Дослідження надає передумови для підвищення ефективності ухвалення та реалізації управлінських рішень, сприяючи досягненню цілей державної аграрної політики, в тому числі стосовно забезпечення продовольчої безпеки. Запропоновані методичні підходи і результати дослідження можуть бути корисними для органів державного та галузевого управління при розробці пріоритетних напрямів, спрямованих на підвищення результативності вітчизняної зернової галузі

Ключові слова: аграрна політика; жито; нішеві культури; ринок зерна; диверсифікація; продовольча безпека; мінеральні добрива; AGMEMOD

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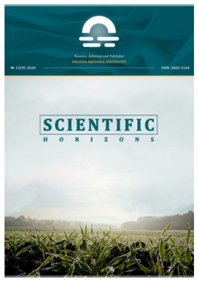

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Study of legume-rhizobia symbiosis in soybean for agroecosystem resilience

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Abstract. Research into innovative methods of regulating legume-rhizobia symbiosis is crucial for enhancing nitrogen fixation, thereby promoting soil health and increasing crop yields. This contributes to sustainable agriculture by reducing the need for chemical fertilisers and enhancing the resilience of agroecosystems. The study aimed to determine the impact of seed inoculation, environmental conditions, and varietal characteristics of soybean varieties on biological nitrogen accumulation. The research

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was conducted under the environmental conditions of Kyiv, Poltava, and Vinnytsia regions from 2010 to 2021. Cultivation practices for the soybean varieties adhered to standard regional agronomic guidelines. The findings detail the effects of seed inoculation on the dynamics of formation and productivity of soybean-rhizobial symbiosis in soils with existing native rhizobial populations. The nitrogen-fixing potential of soybean varieties under inoculation was identified, showing that inoculation enhances the efficiency of the soybean symbiotic system. It has been demonstrated that, across varied environmental conditions, seed inoculation with *Bradyrhizobium japonicum* enhances the formation and functioning of the soybean symbiotic apparatus, even in soils with existing native populations of nodule bacteria. The efficacy of seed inoculation is influenced by the hydrothermal conditions of the year, environmental factors, and soybean variety. Seed inoculation contributes to the development of a greater mass of active nodules on plant roots, positively impacting nitrogen fixation. The highest nitrogen fixation levels were observed in the soybean varieties Ametyst, Artemida, and Hoverla across different environmental conditions. Seed inoculation increased the amount of biologically fixed nitrogen in these varieties by 33.9-36.1 kg/ha. Varieties Ametyst, Artemida, and Hoverla showed a particularly strong response to inoculation with nitrogen-fixing bacteria and are recommended for cultivation in diverse environmental conditions. Innovative approaches to enhancing the efficiency of the soybean legume-rhizobia symbiosis through the use of biological inoculants based on nitrogen-fixing bacteria will enable the development of biologically-oriented cultivation technologies, promoting the resilience of agroecosystems

Keywords: nodule number and mass; nitrogen fixation; symbiotic potential; inoculation; hydrothermal coefficient; rhizobia; biologically fixed nitrogen

INTRODUCTION

Nitrogen is an essential plant nutrient, vital for biomass accumulation, phytohormonal regulation, and enzyme function. Nitrogen fixation, the process of converting atmospheric nitrogen into a plant-available form, plays a crucial role in maintaining soil fertility. The efficiency of nitrogen fixation is influenced by various factors, including the number and development of root nodules, the species of nitrogen-fixing microorganisms, the host plant, and environmental conditions. Soybean (*Glycine hispida* Maxim.) is a strategic crop for implementing the Green Deal in agriculture due to its unique ability to combine two essential processes: photosynthesis and biological nitrogen fixation. Therefore, investigating the efficiency of the legume-rhizobia symbiosis in soybeans, as influenced by varietal characteristics and environmental growing conditions, is highly relevant.

E. Kebede (2021) and S. Langyan *et al.* (2022) noted that the challenges of plant protein supply and soil fertility preservation can be addressed by cultivating optimal areas of legume crops. However, this is contingent upon ensuring effective symbiosis between legumes and rhizobia. Through the fixation of atmospheric nitrogen by symbiotic systems of legumes and rhizobia, as well as associative and free-living nitrogen-fixing microbes, approximately the same amount of biological nitrogen is annually contributed to the arable layer of the soil as is introduced through mineral nitrogen fertilisers.

Host plants are colonised by various rhizobia species differing in their virulence. Indigenous rhizobial populations in the arable layer are more mobile and virulent. However, nitrogen fixation in such legume-rhizobia symbioses is often inefficient, which is linked to the sensitivity of rhizobia to moisture conditions. According to A. Soumare *et al.* (2020), understanding the diversity of nitrogen-fixing microorganisms, their fixation mechanisms, and developing innovative biofertilizers based on this knowledge is an alternative approach to address this issue and optimise nitrogen fixation. Measures such as seed inoculation with biofertilizers before sowing, selecting drought-tolerant cultivars, and adjusting sowing dates can help maximise the potential of the legume-rhizobia symbiosis in soybeans. Optimising symbiotic nitrogen fixation is becoming increasingly important as it is an environmentally friendly and cost-effective method for maintaining soil fertility and increasing crop productivity (Abd-Alla *et al.,* 2023).

Soybeans consume more nutrients to produce a crop compared to other legumes. This legume crop absorbs mineral nutrients unevenly throughout its growth and development stages and has the ability to assimilate nitrogen from the air through symbiosis with rhizobia. Additionally, soybeans can utilise phosphorus and potassium from soil-bound, insoluble compounds and reallocate these reserves from stems to seeds. According to studies by S. Kots (2021) and O. Mazur *et al.* (2024), the absence of beneficial, specific microflora in the root zone of crops encourages colonisation by other, atypical microorganisms, including phytopathogens. Given this, the ecological and economic viability of inoculating soybeans and other crops is undeniable (Panchyshyn *et al.*, 2023).

Inoculation is particularly effective in soils not already populated by active soybean strains of *Rhizobium japonicum*. On fields where soybean has been cultivated long-term, an indigenous population of nodule bacteria develops that can spontaneously infect the roots of young plants; however, these bacteria are often low in activity and efficiency and may inhibit the effectiveness of productive strains. As a result, the use of bacterial inoculants may be ineffective in such cases. Bioinoculants are formulated with specific nodule bacteria for each type of legume crop. When an unsuitable strain is applied, it has no effect, as it cannot form nodules on a non-responsive legume plant. Research by M. Mendoza-Suárez *et al.* (2024) has shown that only competitive, specific strains of nodule bacteria should be used for soybean seed inoculation.

Given the interest in and promotion of technologies aimed at increasing nitrogen availability and legume crop productivity, seed inoculation with nitrogen-fixing bacteria is an effective tool for reducing the environmental impact of mineral fertilisers and enhancing plant nutrition (Sousa *et al.,* 2022). Using effective rhizobial strains with compatible legume varieties can decrease not only the need for nitrogen fertilisers but also the greenhouse gas emissions associated with their production and use. A better understanding of symbiotic relationships will contribute to the development of sustainable agriculture and the preservation of biodiversity.

The symbiotic relationship between legumes and rhizobia is one of the most studied models of nitrogen fixation, demonstrating a complex interaction between plants and microorganisms. Most research, including work by S. McCormick (2018) and J. Hawkins and I. Oresnik (2021), has focused on the mechanisms of nitrogen fixation, which provide benefits to both partners in the symbiosis through nitrogen and carbon exchange. The authors noted that the symbiosis between legumes and rhizobial bacteria is based on a complex sequence of morphophysiological changes in partner cells. Rhizobia interacting with plants experience various stress factors such as decreased pH, osmotic pressure, oxidative stress, and plant antimicrobial peptides. For the symbiotic process to proceed effectively, protection against oxidative stress is required at all stages of legume-rhizobia symbiosis formation (Mamenko, 2021).

However, limited attention has been paid to research on the impact of environmental conditions on the functioning of legume-rhizobia symbiosis and how stress tolerance affects the interaction between legumes and bacteria. Such research, combined with the establishment of parameters for symbiotic apparatus formation in soybeans, will help in the search for effective symbiotic systems that ensure maximum realisation of symbiotic potential and high tolerance to adverse growing conditions. This suggests that research to improve the productivity of nitrogen-fixing symbiotic systems, their adaptability to environmental conditions (including stress), and understanding the mechanisms of interaction between soybean plants and microorganisms under changing climate conditions is relevant and promising. This study aimed to determine the influence of seed inoculation, hydrothermal and edaphic conditions, and varietal characteristics of soybean varieties on the formation of biologically fixed nitrogen.

MATERIALS AND METHODS

The research was conducted under various soil and climatic conditions in Ukraine, specifically in Kyiv, Poltava, and Vinnytsia regions. In the Vinnytsia Region, the soils were represented by grey forest soils, in the Poltava Region by chernozems podzolized, and in the Kyiv Region by chernozems typical during the period 2010-2021, which differed in their hydrothermal conditions (Fig. 1).

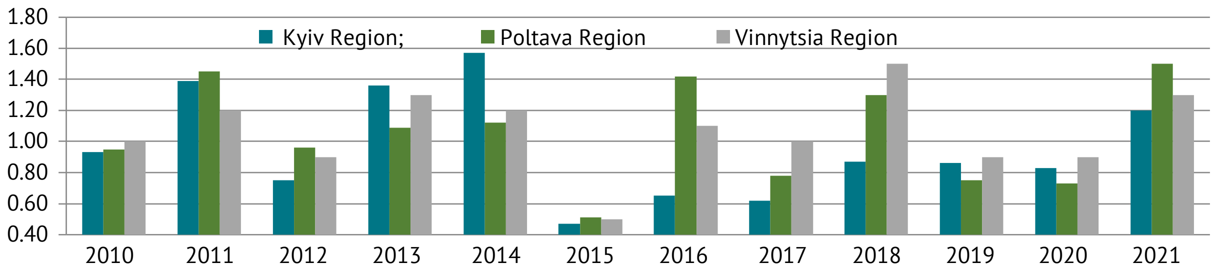

***Figure 1**. Hydrothermal coefficients during the growing season (BBCH 10-99, May-September, 2010-2021)*
***Source:** developed by the authors*

The research material consisted of soybean cultivars bred by the Krasnohrad Research Station of the Institute of Grain Management of the National Academy of Agrarian Sciences of Ukraine, specifically Ametyst (early-maturing); the Prykarpattia State Agricultural Research Station of the Institute of Agriculture of the Carpathian Region of the National Academy of Agricultural Sciences of Ukraine and the Institute of Feed and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine, Hoverla (early-maturing); the Krasnohrad Research Station of the Institute of Grain Management of the National Academy of Agrarian Sciences of Ukraine and the Institute of Feed and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine, Artemida (mid-early); the Institute of Agriculture of the Ukrainian Academy of Agrarian Sciences and the Institute of Feed and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine, Femida (mid-season), and Zolotysta (mid-early), Oriana (mid-early); and the Institute of Feed and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine, Vezha (mid-early).

Seed inoculation was performed one day before sowing using the biopreparation Optimize 200 (2.8 L/t) based on strains of *Bradyrhizobium japonicum*. The titre of the preparation was $2x10^9$ CFU bacteria/g.

The study was conducted under conditions of a dense soybean rhizobia population, which was established in previous years by cultivating soybeans inoculated with various strains of rhizobia and bacterial preparations. To determine the presence of nodules on plant roots at different growth and development stages, soil monoliths with a diameter of 50 cm and a depth of 0-20 cm were sampled. Soybean roots were washed under water on sieves with 1 mm mesh openings. The remaining clay particles were removed with a soft brush under running water over the sieve. After the entire root was completely cleared of soil, the nodules were dried with filter paper, separated from the root, weighed, and the number of nodules with and without leghaemoglobin was determined. The active symbiotic potential (ASP) was calculated using formula 1:

$$ASP = \frac{M_1 \pm M_2}{2 \times T}, \quad (1)$$

where ASP is the active symbiotic potential, thousand kg days/ha; M_1, M_2 is the average mass of nodules with leghaemoglobin over a period of time, kg/ha; T is the period between two successive determinations, days.

The amount of biologically fixed nitrogen was determined as the product of the active symbiotic potential and the specific activity of the symbiosis. The assessment of the symbiotic apparatus was carried out according to well-known methods. Mathematical processing of the research results was performed using dispersion and correlation-regression analysis on a personal computer using specialised application packages such as MS Excel. Experimental studies of plants (both cultivated and wild), including the collection of plant material, complied with institutional, national, or international guidelines. 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

Nodules became visible on soybean roots 7-10 days after emergence, that is, during the formation of the first trifoliate leaf. Approximately 15-25 days after their formation, the nitrogen fixation process began and continued until plant senescence. In the early stages of soybean development, nitrogen fixation was weak, but its activity increased sharply later, reaching its maximum during flowering and pod filling. After that, it decreased as maturity approached. The lowest number of active nodules was observed at the BBCH microstage 51-59 (Table 1).

Table 1*. Number of active nodules (number/plant) on soybean roots depending on the variety, seed inoculation, and environmental conditions at the BBCH microstage 51-59*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	7.7	10.1	7.0	9.7	10.4	3.4	6.3	5.6	8.1	7.9	7.6	9.4
	i	12.7	15.3	12.6	15.1	16.0	7.8	11.7	10.2	13.8	12.6	12.7	14.6
Hoverla	w/i	9.0	10.8	8.0	9.9	11.2	4.0	7.7	6.1	9.0	8.2	7.9	9.7
	i	15.1	16.1	13.1	15.6	17.5	8.8	12.8	10.9	14.2	13.3	13.1	15.0
Artemida	w/i	8.3	10.6	8.2	10.5	10.5	3.7	6.6	5.5	8.6	8.1	7.9	9.8
	i	13.2	15.9	12.9	15.4	16.9	8.1	12.3	10.5	14.0	12.9	12.9	14.8
Femida	w/i	8.2	10.5	7.1	9.9	10.9	3.4	6.4	5.4	7.8	7.7	7.6	9.3
	i	12.2	14.8	12.1	14.6	15.8	7.2	10.8	9.5	12.9	12.2	12.1	14.2
Zolotysta	w/i	9.9	10.5	7.0	9.7	10.4	3.1	6.1	5.3	7.8	7.8	7.3	9.2
	i	12.1	14.4	11.7	14.4	15.3	6.9	10.5	9.4	12.6	12.1	11.8	13.9
Vezha	w/i	7.7	10.6	7.3	10.1	10.8	3.5	6.4	5.6	8.0	7.8	7.4	9.4
	i	12.4	15.1	12.3	14.8	15.8	7.5	11.4	10.1	13.2	12.4	12.4	14.6
Oriana-standart	w/i	7.2	10.4	6.4	9.1	10.4	2.9	6.0	5.0	7.3	7.0	6.9	9.3
	i	11.6	14.2	11.2	14.2	15.6	6.7	10.3	9.1	12.3	11.8	11.5	13.7
Poltava Region													
Ametyst	w/i	7.5	11.1	7.5	8.3	8.9	3.8	10.8	6.4	10.6	6.3	6.2	11.6
	i	12.6	16.5	12.6	13.7	14.1	8.3	16.5	12.4	16.4	11.8	11.3	17.8
Hoverla	w/i	7.9	11.6	8.0	8.6	9.2	4.4	11.4	8.1	11.5	7.0	6.6	12.6
	i	13.2	17.1	13.1	14.1	15.0	8.7	17.2	13.1	17.0	12.2	11.7	18.5
Artemida	w/i	8.3	11.1	8.2	9.1	9.1	3.9	11.0	7.5	11.1	6.4	6.2	11.9
	i	12.9	17.0	12.9	14.0	14.6	8.6	16.4	12.6	16.7	12.1	11.5	18.1
Femida	w/i	7.5	10.9	7.5	8.6	9.4	3.6	10.9	7.4	10.5	6.2	5.9	11.4
	i	12.0	16.1	12.4	13.4	14.1	7.8	15.7	11.9	15.7	11.5	10.8	17.2
Zolotysta	w/i	7.3	10.9	7.3	8.2	9.0	3.5	10.6	4.3	10.4	6.0	5.8	11.2
	i	11.8	15.8	12.1	13.1	13.6	7.5	15.5	10.7	15.6	11.1	10.5	16.7

Table 1. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Vezha	w/i	7.9	11.0	8.1	8.6	9.3	3.7	10.8	7.6	10.5	6.3	6.1	11.4
	i	12.5	16.2	12.5	13.5	14.1	8.0	15.9	12.1	16.1	11.6	11.1	17.4
Oriana-standart	w/i	7.3	10.6	7.0	8.1	9.0	3.2	10.5	7.1	10.0	5.8	5.5	11.3
	i	11.7	15.5	11.4	12.9	13.5	7.2	15.3	10.6	15.2	10.5	10.2	16.4
Vinnytsia Region													
Ametyst	w/i	7.7	8.5	6.5	8.4	9.1	3.6	8.4	7.3	10.9	7.7	7.2	9.3
	i	13.2	13.4	11.5	13.6	14.2	7.8	13.7	13.5	16.9	13.2	12.1	16.2
Hoverla	w/i	8.1	8.9	7.0	8.8	9.5	4.1	8.9	7.9	12.1	8.1	7.5	9.6
	i	13.9	14.1	12.0	14.0	15.1	8.4	14.1	13.8	17.8	13.7	12.6	16.9
Artemida	w/i	8.2	8.6	7.2	9.0	9.3	3.7	8.6	7.2	11.4	8.0	7.5	10.0
	i	13.5	13.7	11.7	13.8	14.5	8.0	14.0	13.8	17.3	13.4	12.3	16.7
Femida	w/i	7.7	8.4	6.4	8.7	9.6	3.4	8.4	7.1	10.6	7.5	6.8	9.2
	i	12.2	13.1	11.0	13.3	13.8	7.3	13.1	12.9	15.9	12.7	11.6	15.3
Zolotysta	w/i	7.5	8.3	6.2	8.5	9.3	3.3	8.2	7.0	10.6	7.6	6.8	9.0
	i	12.1	12.9	10.7	13.1	13.5	7.1	12.8	12.3	15.6	12.4	11.2	14.8
Vezha	w/i	8.0	8.6	7.1	8.7	9.5	3.4	8.4	7.2	10.8	7.6	7.0	9.3
	i	12.7	13.2	11.2	13.4	14.0	7.5	13.3	13.2	16.1	12.8	11.8	15.6
Oriana-standart	w/i	7.5	8.3	5.9	8.2	9.2	3.0	8.0	6.8	10.1	6.9	6.5	9.1
	i	11.9	12.8	10.4	12.8	13.3	6.9	12.5	12.0	15.2	12.1	10.9	14.6

Source: *developed by the authors*

The number of active nodules depended on seed inoculation, ecogradient (hydrothermal and edaphic conditions), and soybean variety characteristics. The highest number of active nodules was observed in Poltava Region in 2021 following seed inoculation in the varieties Hoverla (18.5 nodules), Artemida (18.1 nodules), and Ametyst (17.8 nodules). This was 5.9, 6.2, and 6.2 nodules higher, respectively, compared to untreated seeds. In Vinnytsia Region, the highest number of nodules was observed in 2018 following seed inoculation in the varieties Hoverla (17.8 nodules), Artemida (17.3 nodules), and Ametyst (16.9 nodules). This was 5.7, 5.9, and 6.0 nodules higher, respectively, compared to untreated seeds. In Kyiv Region, the highest number of nodules was observed in 2014 in the varieties Hoverla (17.5 nodules), Artemida (16.9 nodules), and Ametyst (16.0 nodules), which was 6.3, 6.4, and 6.4 nodules higher, respectively, compared to non-inoculated seeds. The lowest number of active nodules was observed in all soybean varieties in different growing zones (Kyiv, Vinnytsia, Poltava) under the most drought-prone year (2015). The number of active nodules in untreated soybean seeds varied across these regions from 2.9-3.2 per plant (variety Oriana) to 4.0-4.4 per plant (variety Hoverla). In inoculated soybean seeds, the number of active nodules ranged from 6.7-7.2 per plant (variety Oriana) to 8.4-8.8 per plant (variety Hoverla). It should be noted that across different growing years, the highest number of active nodules was observed, primarily with seed inoculation in 2021 in the Poltava Region, ranging from 16.4 per plant (variety Oriana) to 18.5 per plant (variety Hoverla). The highest number of active nodules with seed inoculation was observed in Vinnytsia Region in 2018, ranging from 15.2 per plant (variety Oriana) to 17.8 per plant (variety Hoverla). In Kyiv Region, the highest number of active nodules was observed in 2014, ranging from 15.3 per plant (variety Zolotysta) to 17.5 per plant (variety Hoverla). At the BBCH microstage 61-62, a higher number of active nodules on plant roots was established compared to the BBCH microstage 51-59 (Table 2).

Table 2*. Number of active nodules (number/plant) on soybean roots depending on the variety, seed inoculation, and environmental conditions at the BBCH microstage 61-62*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Kyiv Region													
Ametyst	w/i	17.0	22.0	14.5	21.0	22.8	5.0	12.5	10.6	16.8	16.4	15.7	20.2
	i	35.2	37.2	31.8	37.4	38.3	20.8	29.9	27.3	32.1	31.9	30.3	34.7
Hoverla	w/i	19.3	22.6	16.0	21.6	23.8	6.2	15.2	11.9	18.9	17.0	16.3	20.9
	i	37.5	38.9	33.8	39.0	39.9	22.4	31.7	29.1	34.8	33.1	32.3	36.8
Artemida	w/i	18.2	22.1	16.2	21.8	23.0	5.6	12.8	10.3	17.9	16.9	16.5	21.1
	i	36.0	37.8	33.1	38.2	39.1	21.6	30.7	28.4	33.3	32.3	31.0	36.1

Table 2. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Femida	w/i	16.3	21.9	14.5	21.5	23.3	5.0	12.4	10.3	16.5	15.9	14.8	20.1
	i	33.2	36.2	30.2	36.2	36.5	19.3	28.4	25.9	31.0	30.4	29.1	32.5
Zolotysta	w/i	16.6	21.9	14.2	20.9	22.8	4.0	11.9	9.8	16.3	16.0	14.9	19.9
	i	31.9	35.2	29.8	35.4	35.4	18.8	28.1	25.3	30.0	29.8	28.4	31.7
Vezha	w/i	16.7	22.1	14.9	21.5	23.1	5.0	12.5	10.4	16.6	16.3	15.1	20.2
	i	34.4	36.7	31.1	36.5	37.4	20.0	29.2	26.6	32.0	31.1	29.6	33.5
Oriana-standart	w/i	15.4	21.5	13.4	20.2	22.7	3.6	11.5	9.2	15.1	14.6	14.1	19.8
	i	31.6	34.4	29.2	34.5	34.4	18.3	27.4	24.6	29.1	28.9	27.8	30.7
Poltava Region													
Ametyst	w/i	16.4	25.5	16.2	18.2	18.8	6.7	24.9	13.3	24.1	13.1	12.9	26.4
	i	33.6	41.1	32.2	35.6	37.1	23.2	40.3	32.9	41.4	29.3	30.0	43.3
Hoverla	w/i	17.0	26.5	17.3	18.8	19.6	8.2	25.9	17.8	26.5	14.2	13.7	29.1
	i	35.0	44.0	35.5	37.8	38.8	25.2	42.6	35.2	43.5	31.4	31.4	46.6
Artemida	w/i	17.5	25.5	17.9	19.9	19.2	6.9	25.0	16.1	25.3	12.9	13.1	27.5
	i	34.4	42.5	33.6	36.9	38.2	24.4	41.1	33.6	42.5	30.1	30.4	44.8
Femida	w/i	16.7	25.3	16.2	18.6	19.7	6.2	24.8	15.8	23.7	13.0	12.1	26.5
	i	32.5	39.4	30.9	34.1	34.4	22.3	40.9	31.2	39.2	27.7	28.0	40.9
Zolotysta	w/i	15.7	25.4	15.7	18.0	19.1	5.9	24.3	15.6	23.7	12.6	11.9	25.9
	i	31.4	38.7	29.6	34.2	33.4	21.6	39.9	30.4	38.7	28.9	27.1	40.1
Vezha	w/i	16.8	25.3	17.7	18.8	19.7	6.6	24.7	16.2	24.0	13.0	12.6	26.4
	i	32.9	40.3	31.4	35.0	35.6	22.8	39.6	31.7	40.5	28.4	28.8	41.9
Oriana-standart	w/i	16.1	24.9	14.9	17.8	19.2	5.4	24.0	15.2	22.7	11.8	11.1	26.2
	i	31.0	37.8	29.4	33.2	32.9	21.0	39.2	29.9	38.2	27.1	26.4	39.5
Vinnytsia Region													
Ametyst	w/i	16.6	18.7	13.5	18.6	20.3	6.3	18.4	15.6	24.6	16.8	15.2	20.7
	i	33.7	33.6	31.0	35.6	37.0	23.0	34.6	31.2	41.9	33.0	32.0	36.6
Hoverla	w/i	17.5	19.5	14.8	19.4	21.1	7.4	19.6	17.1	26.9	17.4	15.8	21.3
	i	34.5	36.3	32.3	36.7	37.9	24.5	36.2	34.2	43.4	34.9	33.1	39.2
Artemida	w/i	18.0	19.1	15.2	19.9	21.0	6.5	18.9	15.4	26.1	17.3	16.2	21.7
	i	34.0	34.4	31.4	35.9	37.5	23.5	35.4	32.6	42.7	34.2	31.7	37.3
Femida	w/i	16.6	18.6	13.5	19.2	21.3	5.5	18.4	15.1	24.1	16.1	14.1	20.7
	i	32.5	32.8	29.6	34.7	35.9	21.9	33.5	29.7	40.4	31.1	30.4	35.1
Zolotysta	w/i	16.2	18.6	13.2	18.6	20.7	5.1	17.7	14.9	24.1	16.2	14.5	20.3
	i	31.9	32.1	29.2	34.1	35.2	21.4	32.7	29.1	39.6	32.5	29.8	34.2
Vezha	w/i	17.3	18.8	14.7	19.2	21.1	5.6	18.6	15.6	24.6	16.4	15.0	20.7
	i	33.3	33.1	30.4	35.0	36.6	22.2	33.9	30.8	41.1	31.8	31.6	36.1
Oriana-standart	w/i	16.2	18.4	12.0	17.9	20.6	4.6	17.6	14.2	23.3	14.7	13.6	20.3
	i	31.4	31.5	28.4	33.7	34.2	21.0	31.7	27.7	38.8	30.1	28.7	33.6

Source: *developed by the authors*

In the Poltava Kegion, the highest number of active nodules following seed inoculation was observed in the Hoverla variety in 2021 (46.6 nodules), 2011 (44.0 nodules), 2018 (43.5 nodules), and 2016 (42.6 nodules). This was 16.7-17.5 nodules higher compared to non-inoculated seeds. A lower number of active nodules was observed in 2014 (38.8 nodules), 2013 (37.8 nodules), 2012 (35.5 nodules), 2017 (35.2 nodules), and 2010 (35.0 nodules). This was 17.4-19.2 nodules higher compared to non-inoculated seeds. The lowest number of active nodules was observed in 2019 and 2020 (31.4 nodules) and in 2015 (25.2 nodules), which was 17.0-17.7 nodules higher compared to inoculated seeds. The most favourable hydrothermal conditions for all soybean varieties in the Poltava Region were observed in 2021. The number of active nodules following seed inoculation in the soybean varieties Hoverla, Artemida, Ametyst, Vezha, Femida, Zolotysta, and Oriana was 13.3-17.5 nodules higher compared to non-inoculated seeds. In the Kyiv Region, the lowest number of active nodules following seed inoculation was observed in 2015 for the varieties Hoverla (22.4 nodules), Artemida (21.6 nodules), Ametyst (20.8 nodules), Vezha (20.0 nodules), Femida (19.3 nodules), Zolotysta (18.8 nodules), and Oriana (18.3 nodules). This is 14.3-16.2 nodules higher compared to non-inoculated seeds of these varieties. The obtained data correlate with the values of hydrothermal coefficients in the Poltava Region during the most favourable (2021) and least favourable (2015) years. A high number of active nodules was also observed in the Vinnytsia Region. With seed inoculation in 2018, the number of active nodules in soybean varieties Hoverla (43.4 nodules), Artemida (42.7 nodules), Ametyst (41.9 nodules), Vezha (41.1 nodules), Femida (40.4 nodules), Zolotysta (39.6 nodules), and Oriana (38.8 nodules) was 15.5-17.3 nodules higher compared to non-inoculated seeds. In the Kyiv Region, the highest number of active nodules was observed in 2014 in soybean varieties Hoverla (39.9 nodules), Artemida (39.1 nodules), Ametyst (38.3 nodules), Vezha (37.4 nodules), Femida (36.5 nodules), Zolotysta (35.4 nodules), and Oriana (34.4 nodules), which was 11.7-16.1 nodules higher compared to non-inoculated seeds. At the BBCH microstage 68-69, a higher number of active nodules on plant roots was established compared to the BBCH microstage 61-62 (Table 3).

***Table 3**. Number of active nodules (number/plant) on soybean roots depending on the variety, seed inoculation, and environmental conditions at the BBCH microstage 68-69*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	20.3	25.3	17.6	24.2	25.9	8.3	15.9	13.9	20.0	19.7	18.9	23.4
	i	36.3	40.9	34.8	37.9	41.0	24.3	34.5	30.6	38.8	36.3	35.7	40.1
Hoverla	w/i	22.5	26.0	19.2	24.9	26.8	9.6	18.5	15.3	22.2	20.4	19.6	24.2
	i	38.8	43.7	36.4	41.2	43.9	26.2	36.1	32.7	41.2	38.3	37.9	42.5
Artemida	w/i	21.6	25.5	19.6	25.3	26.2	8.8	16.2	13.8	21.3	20.3	19.8	24.5
	i	37.8	41.8	35.7	38.9	41.9	25.2	35.5	31.9	39.5	37.8	36.8	41.3
Femida	w/i	19.8	25.2	17.8	24.8	26.6	8.1	15.9	13.6	19.6	19.2	18.0	23.4
	i	35.4	39.5	33.1	36.5	39.8	22.8	32.2	29.3	36.5	34.6	34.1	38.5
Zolotysta	w/i	19.8	25.1	17.4	24.3	26.0	7.3	15.3	13.2	19.5	19.4	18.2	23.1
	i	35.0	38.5	32.0	35.5	38.9	22.1	31.7	28.5	35.7	33.7	33.6	37.7
Vezha	w/i	20.0	25.4	18.3	24.8	26.5	8.2	15.9	13.9	19.9	19.5	18.5	23.5
	i	35.9	40.2	34.2	36.9	40.9	23.6	33.7	29.8	37.8	35.5	34.7	39.4
Oriana-standart	w/i	18.8	24.9	16.7	23.7	26.1	6.9	15.0	12.8	18.5	17.9	17.4	23.2
	i	34.4	39.4	31.2	34.4	39.5	21.7	31.0	27.9	34.4	32.3	32.8	36.9
Poltava Region													
Ametyst	w/i	19.5	28.7	19.6	21.5	22.2	9.9	28.2	16.6	27.5	16.3	16.1	29.8
	i	36.8	45.1	36.9	39.4	39.3	26.1	45.0	35.7	45.5	33.7	32.7	48.2
Hoverla	w/i	20.3	29.6	20.8	22.2	22.9	11.3	29.3	21.0	29.7	17.5	17.0	32.3
	i	38.5	47.1	38.9	41.4	41.1	27.6	46.7	38.4	47.4	35.7	35.1	50.3
Artemida	w/i	20.7	28.7	21.2	23.2	22.7	10.2	28.5	19.5	28.8	16.3	16.2	30.8
	i	37.6	45.8	37.8	40.7	40.3	26.6	45.4	37.2	46.6	34.7	34.1	49.2
Femida	w/i	19.6	28.4	19.4	22.1	23.1	9.4	28.2	19.3	27.1	16.2	15.4	29.7
	i	35.1	43.7	35.1	37.6	38.5	24.7	43.4	35.0	43.9	32.3	31.1	46.7
Zolotysta	w/i	19.0	28.3	19.0	21.4	22.6	9.1	27.6	18.9	27.0	15.7	15.1	29.4
	i	34.3	43.1	34.3	36.4	37.5	23.7	42.4	34.1	42.8	31.4	31.1	44.6
Vezha	w/i	20.2	28.6	20.9	22.1	23.0	9.7	28.2	19.6	27.4	16.3	15.9	29.8
	i	35.9	44.3	36.6	38.3	38.7	25.3	44.2	35.2	44.9	32.9	31.8	47.4
Oriana-standart	w/i	19.0	28.1	18.3	21.0	22.6	8.4	27.3	18.5	26.0	15.0	14.3	29.5
	i	33.6	41.9	33.3	35.4	37.0	22.8	41.7	33.1	41.8	30.4	30.2	44.1
Vinnytsia Region													
Ametyst	w/i	20.0	22.0	16.8	21.9	23.7	9.4	21.8	18.8	28.0	20.0	18.5	23.9
	i	36.6	38.5	33.5	38.4	40.2	25.5	38.6	35.7	46.0	36.0	34.6	40.3
Hoverla	w/i	20.8	22.7	18.0	22.6	24.4	10.7	22.9	20.2	30.2	20.7	19.2	24.7
	i	38.1	40.3	35.6	39.9	41.9	26.7	40.3	37.9	47.8	37.9	35.6	42.4
Artemida	w/i	21.2	22.2	18.4	23.0	24.2	9.7	22.1	18.7	29.3	20.6	19.4	25.0
	i	37.2	39.5	34.7	39.3	41.3	26.3	39.3	36.5	46.9	36.8	34.8	41.3
Femida	w/i	20.1	21.9	16.6	22.5	24.6	8.8	21.8	18.5	27.6	19.5	17.6	23.9
	i	35.0	37.3	32.1	35.8	38.8	24.1	37.2	33.7	44.1	34.0	33.1	38.4
Zolotysta	w/i	19.5	21.8	16.2	22.0	24.1	8.5	21.2	18.1	27.5	19.7	17.8	23.6
	i	33.8	36.6	31.2	34.7	37.8	23.3	36.5	32.5	43.4	33.4	32.3	37.4
Vezha	w/i	20.7	22.1	18.1	22.5	24.5	8.9	21.8	18.8	27.9	19.8	18.1	24.0
	i	35.8	37.9	32.7	36.9	39.6	24.7	37.8	34.5	44.7	35.0	33.9	39.3
Oriana-standart	w/i	19.5	21.6	15.5	21.4	24.1	7.8	20.9	17.7	26.5	18.2	17.0	23.7
	i	34.3	35.5	30.7	33.7	37.0	22.5	35.3	31.5	42.4	32.5	31.9	36.4

Source: *developed by the authors*

The highest number of active nodules was observed in the Poltava Region in 2021 with seed inoculation of varieties Hoverla (50.3 nodules), Artemida (49.2 nodules), Ametyst (48.2 nodules), Vezha (47.4 nodules), Femida (46.7 nodules), Zolotysta (44.6 nodules), and Oriana (44.1 nodules). This is 14.6-18.4 nodules higher compared to non-inoculated seeds. In the Poltava Region, on the roots of Hoverla, Artemida, and Ametyst varieties, the highest number of active nodules formed in 2021 (48.2-50.3 nodules), 2018 (45.5-47.4 nodules), 2011 (45.1-45.8 nodules), 2016 (45.0-46.7 nodules), 2013 (39.4-41.4 nodules), 2014 (39.3-41.1 nodules), 2012 (36.9-38.9 nodules), 2010 (36.8-38.5 nodules), 2019 (33.7-35.7 nodules), 2020 (32.7-35.1 nodules), and 2015 (26.1-27.6 nodules), compared to other varieties. In the non-inoculated variants, the number of active nodules on these varieties decreased by 16.2-19.2 nodules depending on the year of cultivation.

A high number of active nodules was observed in the Vinnytsia Region in 2018 with seed inoculation of varieties Hoverla (47.8 nodules), Artemida (46.9 nodules), Ametyst (46.0 nodules), Vezha (44.7 nodules), Femida (44.1 nodules), Zolotysta (43.4 nodules), and Oriana (42.4 nodules). This was 15.9-18.0 nodules higher compared to non-inoculated seeds. In the Kyiv Region, the highest number of active nodules was observed in 2014 with seed inoculation of varieties Hoverla (43.9 nodules), Artemida (41.9 nodules), Ametyst (41.0 nodules), Vezha (40.9 nodules), Femida (39.8 nodules), Zolotysta (38.9 nodules), and Oriana (39.5 nodules). This was 13.2-17.1 nodules higher compared to non-inoculated seeds. The lowest number of active nodules in the Kyiv Region was observed in 2015 with seed inoculation of varieties Hoverla (26.2 nodules), Artemida (25.2 nodules), Ametyst (24.3 nodules), Vezha (23.6 nodules), Femida (22.8 nodules), Zolotysta (22.1 nodules), and Oriana (21.7 nodules). This was 14.7-16.6 nodules higher compared to non-inoculated seeds. During soybean maturation, a decrease in nitrogen fixation was observed. At the BBCH microstage 80-90, a lower number of active nodules was observed on soybean roots compared to the BBCH microstage 68-69 (Table 4).

***Table 4**. Number of active nodules (number/plant) on soybean roots depending on the variety, seed inoculation, and environmental conditions at the BBCH microstage 80-90*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	10.2	12.4	9.8	11.7	13.3	6.1	9.0	8.5	11.2	10.7	10.3	12.4
	i	15.6	19.0	14.7	17.5	20.2	8.7	13.4	12.6	17.0	16.3	15.7	19.0
Hoverla	w/i	12.2	14.0	11.1	12.7	14.5	7.2	10.8	9.3	12.3	11.4	11.1	12.9
	i	18.5	21.4	16.9	19.6	22.4	10.6	16.7	14.2	18.7	17.2	16.8	20.9
Artemida	w/i	10.9	13.7	11.5	13.7	13.6	6.8	9.5	8.4	11.7	11.0	10.9	13.2
	i	15.6	22.1	17.4	21.2	20.8	9.9	14.2	12.6	17.8	16.6	16.6	20.4
Femida	w/i	10.8	13.2	9.9	12.6	13.8	6.0	9.2	8.2	10.6	10.3	10.1	12.4
	i	16.3	21.3	14.8	19.4	21.1	8.6	13.6	12.3	16.2	15.7	15.2	19.2
Zolotysta	w/i	12.9	13.1	9.7	12.3	13.1	5.6	8.6	7.9	10.5	10.5	9.6	12.0
	i	18.7	20.1	14.5	19.7	20.3	8.0	13.7	11.8	15.7	15.8	14.6	18.4
Vezha	w/i	10.0	13.2	9.8	13.3	13.7	6.7	9.1	8.6	11.0	10.3	9.8	12.5
	i	15.1	20.3	14.9	20.1	21.1	9.6	13.6	12.7	16.6	15.6	14.7	19.1
Oriana-standart	w/i	9.6	12.9	8.7	11.6	13.2	5.2	8.4	7.5	9.9	9.3	9.1	12.2
	i	14.5	19.8	13.0	17.5	20.4	7.5	12.5	11.2	14.8	14.2	13.6	18.3
Poltava Region													
Ametyst	w/i	10.2	14.3	10.1	10.6	11.5	6.4	13.2	9.4	13.4	9.3	8.8	14.8
	i	15.4	22.0	15.2	16.2	18.4	9.3	20.4	14.0	20.5	14.2	13.4	22.6
Hoverla	w/i	11.3	15.0	10.7	11.6	11.9	7.3	14.4	11.1	14.5	10.0	9.8	16.1
	i	17.2	23.1	16.3	17.9	19.2	10.8	22.0	16.8	22.2	15.9	14.7	24.8
Artemida	w/i	11.5	14.4	10.8	12.3	11.7	6.6	13.8	10.5	14.0	9.4	8.7	15.3
	i	18.4	22.2	17.2	18.7	18.8	10.5	21.1	15.9	21.6	14.9	13.9	23.5
Femida	w/i	10.1	13.6	10.5	11.0	12.3	5.9	13.6	10.4	13.1	9.2	8.1	13.9
	i	15.2	20.8	15.8	16.6	17.9	8.4	20.8	15.6	20.3	13.7	12.1	21.6
Zolotysta	w/i	9.8	13.5	9.9	10.4	11.4	5.7	12.9	7.3	12.9	9.0	7.8	13.1
	i	14.7	20.6	14.8	15.5	17.3	8.2	19.7	12.0	19.7	13.4	11.9	20.5
Vezha	w/i	10.9	14.0	10.6	11.1	12.1	6.2	13.3	10.6	13.2	9.3	8.5	14.0
	i	16.6	21.4	16.2	16.8	18.3	9.0	20.4	16.0	20.2	14.1	12.6	21.4
Oriana-standart	w/i	9.7	13.1	9.4	10.2	11.5	5.3	12.7	10.1	12.4	8.0	7.4	13.1
	i	14.5	20.2	14.0	15.3	17.6	7.6	19.3	15.2	19.1	12.3	11.2	20.3
Vinnytsia Region													
Ametyst	w/i	10.5	11.1	9.2	10.9	11.4	6.2	11.1	10.3	13.9	10.5	10.0	11.9
	i	16.9	16.8	13.7	16.4	17.3	9.0	17.2	15.7	21.3	17.8	15.2	18.2

Table 4. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Hoverla	w/i	11.2	11.9	10.1	12.1	12.7	6.9	12.2	11.1	15.3	11.3	10.7	12.8
	i	18.0	18.2	15.4	18.6	19.6	10.3	18.5	16.8	23.5	17.3	16.6	19.5
Artemida	w/i	11.5	11.3	10.4	12.2	12.1	6.2	11.7	10.1	14.5	10.9	10.4	12.5
	i	17.4	17.3	15.6	18.5	18.4	9.0	17.6	15.4	22.1	16.6	15.6	19.1
Femida	w/i	10.4	10.9	9.0	11.7	12.8	5.7	11.1	9.6	13.4	10.0	9.3	11.6
	i	16.7	16.4	13.6	17.3	19.5	8.1	16.8	14.5	20.8	16.0	14.2	17.5
Zolotysta	w/i	10.1	10.6	8.7	11.1	11.9	5.5	10.7	9.5	13.2	10.2	9.2	11.2
	i	16.3	16.2	13.0	16.6	18.0	7.8	16.5	14.4	20.4	15.6	13.7	17.1
Vezha	w/i	10.9	11.0	9.9	11.4	12.5	5.8	11.0	9.8	13.7	10.3	9.7	11.8
	i	17.5	16.8	14.8	17.3	19.2	8.2	16.6	14.7	21.2	15.6	14.5	18.2
Oriana-standart	w/i	10.0	10.5	8.2	10.6	11.6	5.1	10.4	9.2	12.6	9.2	8.7	11.4
	i	16.1	16.4	12.3	16.2	17.8	7.2	15.8	13.9	19.4	13.7	13.2	17.4

Source: *developed by the authors*

At BBCH microstage 80-90, a general trend of maintaining higher nitrogen fixation rates was observed in the same top-performing treatments as in the previous microstages (BBCH 61-62 and BBCH 68-69). The highest number of active nodules was observed in the Poltava Region in 2021 with seed inoculation of varieties Hoverla (24.8 nodules), Artemida (23.5 nodules), Ametyst (22.6 nodules), Femida (21.6 nodules), Vezha (21.4 nodules), Zolotysta (20.5 nodules), and Oriana (20.3 nodules). This was 7.2-8.7 nodules lower compared to non-inoculated seeds. The lowest number of active nodules was observed in the Kyiv Region in 2015 with seed inoculation of varieties Hoverla (10.6 nodules), Artemida (9.9 nodules), Vezha (9.6 nodules), Ametyst (8.7 nodules), Femida (8.6 nodules), Zolotysta (8.0 nodules), and Oriana (7.5 nodules). This was 2.3-3.4 nodules lower compared to non-inoculated seeds. To assess the effectiveness of the legume-rhizobia symbiosis, not only the number but also the mass of active nodules per plant is used. At BBCH microstage 51-59 in the Poltava Region in 2021, the highest active nodule mass was established in varieties Hoverla (68.6 mg), Artemida (66.9 mg), and Ametyst (65.7 mg) with seed inoculation (Table 5).

Table 5*. Active nodule mass (mg/plant) on soybean roots depending on variety, seed inoculation, and environmental conditions at the BBCH microstage 51-59*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	33.9	44.4	30.9	42.5	45.8	14.7	27.3	24.4	34.7	34.1	32.8	40.8
	i	46.9	56.6	46.7	55.7	59.2	28.7	43.4	37.6	50.9	46.6	46.9	53.9
Hoverla	w/i	38.7	46.4	34.4	42.6	48.2	17.2	33.1	26.2	38.7	35.3	34.0	41.7
	i	52.9	59.5	48.4	57.8	62.3	32.4	47.1	40.2	52.6	49.1	48.3	55.6
Artemida	w/i	35.7	45.7	35.3	45.2	45.2	15.9	28.4	23.7	37.0	34.8	34.0	42.1
	i	47.8	58.7	47.8	56.9	60.9	29.8	45.6	38.7	51.7	47.9	47.6	54.8
Femida	w/i	35.5	45.2	30.5	42.6	46.9	14.6	27.5	23.2	33.5	33.1	32.7	40.0
	i	45.2	54.7	44.7	53.9	58.4	26.8	39.8	35.2	47.9	45.1	44.9	52.7
Zolotysta	w/i	42.6	45.3	30.1	41.7	44.7	13.3	26.2	22.8	33.5	33.5	31.4	39.6
	i	44.6	53.2	43.4	53.2	56.7	25.7	38.7	34.8	46.8	44.6	43.7	51.6
Vezha	w/i	33.1	45.6	31.4	43.4	46.4	15.1	27.5	24.1	34.4	33.5	31.8	40.4
	i	45.8	55.9	45.6	54.6	58.6	27.9	40.9	37.2	48.7	45.9	45.8	53.9
Oriana-standart	w/i	31.0	44.7	27.5	39.1	44.7	12.5	25.8	21.5	31.6	30.1	29.7	40.0
	i	43.0	52.7	41.4	52.8	57.7	24.8	38.2	33.6	45.5	43.7	42.5	50.8
Poltava Region													
Ametyst	w/i	33.3	48.7	33.3	37.7	39.3	17.3	47.4	32.5	46.6	28.1	27.7	53.9
	i	46.8	60.9	46.7	50.6	51.8	30.6	59.7	45.8	60.7	43.7	41.7	65.7
Hoverla	w/i	35.0	51.0	35.4	38.0	40.6	19.9	50.0	35.8	50.5	31.1	29.4	55.2
	i	48.7	63.4	48.2	52.3	53.1	32.1	62.7	48.4	62.9	45.3	43.4	68.6
Artemida	w/i	35.7	47.7	35.3	39.1	39.2	16.8	47.3	32.3	47.7	27.5	26.7	51.2
	i	47.9	62.8	47.8	51.7	52.6	31.9	60.8	46.5	61.8	44.6	42.6	66.9
Femida	w/i	32.3	46.9	32.3	37.0	40.4	15.5	46.9	31.8	45.2	26.7	25.4	49.0
	i	44.5	59.3	45.7	49.4	52.4	28.9	58.2	44.0	58.2	42.4	39.8	63.6

Table 5. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Zolotysta	w/i	31.4	46.8	31.4	35.3	38.7	15.1	45.6	18.5	44.7	25.8	24.9	48.2
	i	43.6	58.6	44.9	48.3	50.4	27.6	57.4	39.6	57.6	40.9	38.7	61.9
Vezha	w/i	34.0	47.3	34.8	37.0	40.0	15.9	46.4	32.7	45.2	27.1	26.2	49.0
	i	46.3	59.7	46.1	49.9	51.1	29.7	58.9	44.9	59.4	43.1	40.9	64.4
Oriana-standart	w/i	31.4	45.6	30.1	34.8	38.7	13.8	45.2	30.5	43.0	24.9	23.7	48.6
	i	43.2	57.5	42.3	47.6	49.8	26.5	56.6	39.1	56.4	38.8	37.6	60.8
Vinnytsia Region													
Ametyst	w/i	39.1	38.6	28.0	38.1	39.1	18.5	39.1	38.4	49.9	38.1	38.0	48.0
	i	49.0	49.4	42.6	50.4	52.6	28.7	50.8	50.1	62.4	48.9	44.9	59.8
Hoverla	w/i	34.8	38.3	30.1	37.8	40.9	17.6	38.3	34.0	52.0	34.8	32.2	41.3
	i	50.9	51.3	44.5	51.8	54.2	30.9	52.3	51.2	66.0	50.6	46.7	62.4
Artemida	w/i	35.3	37.0	31.0	38.7	40.0	15.9	37.0	31.0	49.0	34.4	32.3	43.0
	i	49.3	50.6	43.4	50.9	53.1	29.6	51.6	50.9	63.9	49.7	45.6	61.8
Femida	w/i	33.1	36.1	27.5	37.4	41.3	14.6	36.1	30.5	45.6	32.3	29.2	39.6
	i	45.0	48.5	40.8	49.2	50.9	26.9	48.4	47.6	58.7	46.9	43.1	56.7
Zolotysta	w/i	32.3	35.7	26.7	36.6	40.0	14.2	35.3	30.1	45.6	32.7	20.2	38.7
	i	44.3	47.9	39.5	48.4	50.1	26.3	47.5	45.4	57.9	45.8	41.5	54.8
Vezha	w/i	34.4	37.0	30.5	37.4	40.9	14.6	36.1	31.0	46.4	32.8	30.1	40.0
	i	46.8	48.8	41.9	49.7	51.8	27.6	49.1	48.7	59.5	47.5	43.8	58.3
Oriana-standart	w/i	32.3	35.7	25.4	35.3	39.6	12.9	34.4	29.2	43.4	29.7	28.0	39.1
	i	44.3	47.2	38.4	47.2	49.2	25.4	46.2	44.3	56.4	44.7	40.3	53.9

Source: *developed by the authors*

In the non-inoculated variants, the active nodule mass decreased by 11.8-15.7 mg/plant depending on the variety. A high active nodule mass with seed inoculation was also observed in 2011 on the roots of varieties Hoverla (63.4 mg), Artemida (62.8 mg), and Ametyst (60.9 mg), which was 12.2-15.1 mg/plant higher compared to the non-inoculated variants. In 2016 and 2018, a high active nodule mass was observed with seed inoculation in varieties Hoverla (62.7 and 62.9 mg, respectively), Artemida (60.8 and 61.8 mg, respectively), and Ametyst (59.7 and 60.7 mg), which was 12.3-14.1 mg/plant higher compared to the non-inoculated variants. The highest active nodule mass was observed in the Vinnytsia Region in 2018 in varieties Hoverla (66.0 mg), Artemida (63.9 mg), and Ametyst (62.4 mg). In the non-inoculated variants, this value decreased by 12.5-15.7 mg/plant. In the Kyiv Region, the highest active nodule mass was observed in 2014 in varieties Hoverla (62.3 mg), Artemida (60.9 mg), and Ametyst (59.2 mg). In the non-inoculated variants, this value decreased by 13.4-15.7 mg/plant.

The formation of higher active nodule mass on the roots of soybean plants in different regions, depending on the favourable growing year, is supported by the hydrothermal coefficient values for each zone. The lowest active nodule mass following seed inoculation was observed in the Kyiv Region in 2015, which ranged from 24.8 mg/plant (Oriana) to 32.4 mg/plant (Hoverla). In the non-inoculated variants, this indicator decreased by 12.3-15.2 mg/plant. The lowest active nodule mass was also observed in 2015 in the conditions of the Vinnytsia and Poltava regions. Following seed inoculation, this value ranged from 25.4-26.5 mg/plant (Oriana) to 30.9-32.1 mg/plant (Hoverla). In the non-inoculated variants, the active nodule mass decreased by 12.2-13.3 mg/plant. An increase in active nodule mass was noted at the BBCH microstage 61-62 across all experimental variants (Table 6).

Table 6. *Active nodule mass (mg/plant) on soybean roots depending on variety, seed inoculation, and environmental conditions at the BBCH microstage 61-62*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	182.8	235.4	155.9	224.7	243.3	53.5	134.0	113.4	179.8	176.1	169.7	217.5
	i	386.7	409.4	349.6	411.2	421.3	228.6	328.7	300.5	353.4	350.5	333.8	381.8
Hoverla	w/i	210.4	246.3	172.8	233.3	259.4	67.0	164.2	127.8	204.1	183.6	174.7	225.7
	i	412.3	427.8	371.8	428.9	438.7	245.9	348.9	319.8	383.1	362.7	354.8	404.5
Artemida	w/i	191.6	235.9	170.6	231.6	246.1	59.9	137.0	110.2	192.4	181.7	166.6	220.0
	i	395.6	416.5	364.4	419.8	429.6	237.8	337.6	312.3	366.7	355.4	340.9	397.2

Table 6. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Femida	w/i	172.8	232.1	155.2	231.1	249.3	53.7	132.7	109.7	176.6	170.1	155.4	215.1
	i	364.8	398.5	332.7	397.8	402.3	212.3	312.8	285.4	340.9	334.6	319.8	357.9
Zolotysta	w/i	177.6	233.2	150.5	221.5	241.5	42.0	126.7	103.9	172.8	171.5	157.9	207.0
	i	351.2	387.6	327.9	389.7	389.8	206.5	309.5	277.6	329.8	327.8	312.7	348.7
Vezha	w/i	178.7	236.5	160.9	230.1	247.2	54.0	133.8	111.3	177.6	175.1	161.6	216.1
	i	377.8	404.1	341.6	401.2	411.5	219.7	321.4	292.4	351.6	342.3	325.5	368.6
Oriana-standart	w/i	161.7	225.8	140.7	212.1	236.1	37.8	120.8	96.6	158.4	153.3	146.6	203.9
	i	347.9	378.8	321.6	379.5	378.9	201.3	301.2	270.7	319.8	317.9	305.7	337.5
Poltava Region													
Ametyst	w/i	189.3	279.4	189.2	208.1	208.4	79.9	269.4	188.3	268.3	148.2	139.4	297.1
	i	369.8	452.1	354.7	391.5	408.3	254.9	443.4	362.4	455.8	322.7	329.8	476.7
Hoverla	w/i	192.8	288.9	196.1	221.9	212.7	88.6	279.7	193.5	288.9	151.9	147.3	317.2
	i	384.5	484.5	390.8	415.6	426.7	276.7	468.9	386.7	478.9	345.8	345.6	512.5
Artemida	w/i	190.8	274.9	195.1	216.9	205.4	74.2	268.8	173.2	273.2	137.8	140.2	298.4
	i	378.1	467.9	369.6	406.7	419.8	268.2	451.6	369.9	467.5	331.2	334.7	492.4
Femida	w/i	178.7	271.0	173.3	199.8	214.7	66.7	266.1	169.1	254.8	139.1	128.6	285.7
	i	357.9	433.4	339.6	374.5	378.9	245.6	450.1	343.5	431.2	304.6	307.9	449.8
Zolotysta	w/i	163.3	271.8	168.0	192.6	204.4	63.1	257.6	166.9	253.6	133.6	125.7	277.1
	i	345.6	425.6	325.9	376.6	367.5	237.9	439.6	334.6	425.6	317.6	297.6	441.5
Vezha	w/i	179.8	271.2	191.2	203.0	214.1	70.3	264.8	175.0	258.2	139.1	133.8	283.0
	i	361.4	443.4	345.5	384.5	391.5	250.8	435.5	348.9	445.2	312.5	316.7	461.0
Oriana-standart	w/i	169.1	261.5	156.5	185.1	205.4	56.6	252.0	162.6	240.6	123.9	116.0	280.3
	i	341.2	415.6	323.8	365.7	361.6	230.6	431.0	328.8	420.4	297.8	290.1	434.7
Vinnytsia Region													
Ametyst	w/i	187.6	210.7	159.7	211.1	219.2	67.7	197.4	178.9	287.2	188.9	168.2	228.5
	i	370.6	369.5	341.5	391.7	406.7	253.4	380.4	343.2	461.2	362.9	352.2	402.3
Hoverla	w/i	188.1	211.2	160.6	209.9	226.8	80.7	211.7	186.4	292.1	188.6	169.9	229.2
	i	379.8	399.8	354.8	403.6	416.7	269.8	398.7	376.5	477.8	383.4	364.5	423.2
Artemida	w/i	194.4	205.5	164.6	215.7	224.7	70.2	203.4	164.8	280.6	185.8	175.0	236.5
	i	374.5	378.6	345.6	394.5	412.3	258.9	388.9	358.8	469.5	375.7	348.9	410.5
Femida	w/i	178.6	200.0	144.9	207.4	230.0	58.9	198.2	161.3	259.3	172.4	150.9	221.5
	i	357.7	361.2	325.5	381.4	394.6	240.9	368.7	326.4	444.7	342.1	334.9	385.6
Zolotysta	w/i	172.5	199.0	139.9	199.0	221.5	54.6	188.5	158.7	257.9	173.8	155.2	217.2
	i	351.2	353.4	321.4	374.9	387.5	235.6	359.8	319.9	435.6	357.8	327.8	376.7
Vezha	w/i	185.1	202.3	159.2	205.4	225.8	59.9	199.0	167.5	264.2	176.1	160.8	223.6
	i	366.7	364.5	334.7	384.8	402.1	244.5	373.4	338.6	452.4	350.1	347.8	397.6
Oriana-standart	w/i	171.7	196.9	126.0	187.9	218.4	48.3	186.6	150.5	244.7	154.4	142.8	215.2
	i	345.6	346.7	312.9	370.3	376.5	230.9	348.7	305.1	426.4	331.5	315.7	369.3

Source: *developed by the authors*

The highest active nodule mass was observed in the conditions of the Poltava Region following seed inoculation for the varieties Hoverla, Artemida, and Ametyst in 2021 (476.7-512.5 mg), 2018 (455.8-478.9 mg), 2011 (452.1-484.5 mg), 2016 (443.4-468.9 mg), and 2014 (408.3-426.7 mg). In the non-inoculated variants, the active nodule mass on the roots of these varieties decreased by 172.7-214.4 mg/plant, depending on the growing year. In the Vinnytsia Region, the highest active nodule mass following seed inoculation was noted for the varieties Hoverla, Artemida, and Ametyst in 2018 (461.2-477.8 mg), 2021 (402.3-423.2 mg), 2014 (406.7-416.7 mg), and 2013 (391.7-403.6 mg/plant). This was higher compared to the non-inoculated variants by 173.8-194.0 mg/plant, depending on the growing year. In the Kyiv Region, the highest active nodule mass following seed inoculation was observed for the varieties Hoverla, Artemida, and Ametyst in 2014 (421.3-438.7 mg), 2013 (411.2-428.9 mg), 2011 (409.4-427.8 mg), and 2010 (386.7-412.3 mg). In the non-inoculated variants, this indicator decreased by 174.0-204.0 mg/plant, depending on the growing year. The lowest active nodule mass following seed inoculation in the conditions of the Kyiv Region was observed in 2015. This value ranged from 201.3 mg (Oriana) to 245.9 mg (Hoverla), which was 163.5 and 178.9 mg/plant higher compared to the non-inoculated variants. In the Poltava and Vinnytsia regions, the lowest active nodule mass following seed inoculation was also recorded in 2015 on the roots of all soybean varieties. This value ranged from 230.6 to 276.7 mg and from 230.9 to 269.8 mg/plant, respectively. In the non-inoculated variants, the active nodule mass on the roots of soybean plants decreased by 174.0-189.1 mg/plant, depending on the growing region. Thus, in all regions where a significant precipitation deficit and the lowest hydrothermal coefficient values were observed throughout the study years, the formation of the lowest active nodule mass and nodule count was noted. The highest values of active nodule mass on the roots of soybean varieties were achieved in all experimental variants at the BBCH microstage 68-69 (Table 7).

***Table 7**. Active nodule mass (mg/plant) on soybean roots depending on variety, seed inoculation, and environmental conditions at the BBCH microstage 68-69*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	223.3	283.4	201.5	275.9	295.3	93.0	183.0	158.5	230.2	225.6	217.2	266.8
	i	395.6	445.8	379.5	413.2	446.5	265.4	376.0	334.0	423.0	396.0	389.5	437.6
Hoverla	w/i	254.5	286.0	220.8	283.9	305.0	105.6	209.1	172.9	254.8	234.4	225.8	278.3
	i	422.5	476.5	396.7	448.9	482.9	285.6	394.0	356.0	449.0	423.0	413.7	463.0
Artemida	w/i	240.6	284.6	213.4	277.9	288.5	96.8	186.3	157.2	244.9	233.7	217.9	272.2
	i	412.3	455.7	388.7	423.8	462.1	274.9	387.0	348.0	431.0	412.0	401.0	449.8
Femida	w/i	221.8	282.2	202.9	282.2	302.7	90.6	182.9	156.4	224.6	218.9	206.3	266.3
	i	385.6	430.8	360.9	397.8	440.9	248.9	351.0	319.0	398.0	377.0	371.3	419.2
Zolotysta	w/i	219.8	281.1	200.1	277.1	296.4	82.9	176.0	151.8	223.3	221.0	208.9	263.3
	i	381.4	419.8	348.6	386.6	423.6	241.2	345.0	311.0	389.0	367.8	366.6	411.3
Vezha	w/i	226.0	284.5	210.5	282.7	301.8	91.5	183.2	158.2	228.9	224.3	211.5	270.3
	i	391.4	437.9	372.3	402.3	439.7	256.7	367.0	325.0	412.0	387.0	378.6	428.9
Oriana-standart	w/i	212.4	278.9	192.1	269.9	297.0	78.5	172.5	147.2	209.1	203.8	199.6	264.5
	i	374.6	429.6	340.5	375.4	439.8	236.4	338.0	304.0	375.0	352.9	357.6	402.4
Poltava Region													
Ametyst	w/i	238.3	327.2	237.1	257.6	258.9	108.9	328.6	199.3	318.9	186.6	188.3	347.0
	i	401.2	491.2	402.4	429.8	428.7	284.0	491.0	389.0	496.0	367.0	356.7	525.7
Hoverla	w/i	242.4	336.0	245.0	272.9	259.2	123.2	335.5	239.4	338.6	200.4	194.7	369.2
	i	419.8	513.8	423.8	450.9	447.8	301.3	509.0	419.0	517.0	389.0	382.6	547.8
Artemida	w/i	237.0	326.0	241.7	265.9	257.2	111.2	325.8	221.9	327.2	185.5	183.6	348.4
	i	409.6	498.7	411.7	443.5	439.6	289.4	495.0	406.0	508.0	378.0	371.5	536.4
Femida	w/i	224.4	322.1	219.2	251.5	262.0	101.5	322.0	219.3	307.3	183.9	174.2	335.6
	i	382.3	476.7	382.6	409.8	419.8	269.0	473.0	381.0	479.0	352.0	338.4	508.9
Zolotysta	w/i	216.8	321.8	214.7	242.7	256.5	92.3	314.6	213.6	305.9	178.0	170.9	330.8
	i	374.4	469.5	373.4	396.7	409.1	258.0	462.0	372.0	467.0	342.0	338.9	486.5
Vezha	w/i	231.3	324.9	237.5	251.1	260.1	105.2	321.5	223.6	310.4	185.0	179.8	336.7
	i	391.5	482.8	398.7	417.7	421.3	276.0	482.0	384.0	489.0	359.0	346.8	516.7
Oriana-standart	w/i	216.2	318.9	205.0	237.5	255.6	90.3	308.5	209.1	291.2	168.0	160.2	333.4
	i	366.5	456.6	362.9	385.5	403.6	249.0	454.0	361.0	456.0	331.0	329.2	481.0
Vinnytsia Region													
Ametyst	w/i	227.6	249.7	199.7	247.7	267.8	108.5	256.6	219.8	337.5	229.8	207.9	281.0
	i	398.4	419.8	365.4	418.9	438.6	278.0	421.0	389.0	501.0	392.0	376.9	439.0
Hoverla	w/i	236.9	257.7	204.5	256.3	276.0	116.6	260.8	229.3	342.8	236.0	217.8	280.3
	i	414.8	438.9	387.9	434.6	456.7	291.0	439.0	413.0	520.8	413.2	387.8	462.0
Artemida	w/i	241.3	252.4	208.8	262.0	273.9	104.8	250.2	211.9	332.3	234.2	221.2	284.0
	i	405.6	430.7	378.7	428.7	449.8	287.0	428.0	398.0	511.2	401.0	379.5	450.0
Femida	w/i	228.9	248.6	188.2	255.0	278.7	95.0	247.3	209.5	313.0	219.4	197.6	270.6
	i	381.5	406.7	349.6	389.9	423.4	263.0	405.0	367.0	481.0	371.0	361.0	419.0
Zolotysta	w/i	220.7	247.2	183.1	249.0	273.1	91.8	239.6	204.5	311.6	222.4	200.1	265.7
	i	368.9	398.5	340.5	378.6	411.9	254.0	398.0	354.0	473.0	364.0	352.0	408.0
Vezha	w/i	235.6	251.1	206.3	254.5	277.3	96.1	246.8	213.0	316.7	223.7	203.1	271.2
	i	389.7	413.6	356.7	402.5	431.2	269.0	412.0	376.0	487.0	382.0	369.0	428.0
Oriana-standart	w/i	220.4	244.7	172.1	239.9	272.6	83.5	234.1	199.0	299.5	203.8	190.4	267.8
	i	374.3	387.4	334.1	367.4	403.1	245.0	385.0	343.0	462.0	354.0	348.0	397.0

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

In the conditions of the Poltava Region, the highest active nodule mass was recorded in 2021, where, following seed inoculation, it ranged from 481.0 mg/plant (Oriana) to 547.8 mg/plant (Hoverla). That year, the highest active nodule mass following seed inoculation was observed on the roots of the soybean varieties Hoverla (547.8 mg), Artemida (536.4 mg), Ametyst (525.7 mg), Vezha (516.7 mg), and Femida (508.9 mg). In the non-inoculated variants, this value decreased by 173.7-188.0 mg/plant, depending on the variety. High values of active nodule mass were also observed in 2011 and 2018, following seed inoculation, for the varieties Hoverla (513.0 and 517.0 mg), Artemida (498.7 and 508.0 mg), and Ametyst (491.2 and 496.0 mg). These values were 164.0-180.8 mg/plant higher compared to the non-inoculated variants, depending on the variety and year. In the Poltava Region, high active nodule mass was observed in 2016 following seed inoculation in the soybean varieties Hoverla (509.0 mg), Artemida (495.0 mg), and Ametyst (491.0 mg). These values were 162.4-173.5 mg/plant higher compared to the non-inoculated variants. In the conditions of the Vinnytsia Region, the highest values of active nodule mass were recorded in 2018 following seed inoculation for the soybean varieties Hoverla (520.8 mg), Artemida (511.2 mg), and Ametyst (501 mg/plant). These values were 163.5-178.09 mg/plant higher compared to the non-inoculated variants. In the Kyiv Region, the highest values of active nodule mass were observed in 2014 in the variants where seed inoculation was carried out for the soybean varieties Hoverla (482.9 mg), Artemida (462.1 mg), and Ametyst (446.5 mg/plant). These values were 151.2-177.9 mg/plant higher compared to the non-inoculated variants. The lowest active nodule mass was recorded in the conditions of the Kyiv Region in 2015 on the roots of all soybean varieties. This value ranged from 236.4 mg/plant (Oriana) to 285.6 mg/plant (Hoverla) following seed inoculation, which was 157.9-180.0 mg/plant higher compared to the non-inoculated variants. At the BBCH microstage 80-90, a decrease in active nodule mass was observed on the roots of the soybean plants (Table 8).

***Table 8**. Active nodule mass (mg/plant) on soybean roots depending on variety, seed inoculation, and environmental conditions at the BBCH microstage 80-90*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	44.9	50.5	39.5	46.7	52.1	25.4	39.6	37.4	49.3	47.1	45.3	54.6
	i	81.9	88.5	81.5	95.6	90.2	62.3	75.5	76.0	84.0	81.0	80.1	90.1
Hoverla	w/i	56.1	63.0	47.7	55.9	62.4	32.4	46.4	40.0	52.9	49.0	47.7	55.5
	i	90.1	101.0	90.7	100.8	104.3	71.2	85.1	84.0	89.0	87.2	87.2	95.3
Artemida	w/i	49.0	60.3	50.6	61.7	59.8	29.9	40.9	34.4	51.5	48.4	48.0	56.8
	i	81.1	97.3	87.6	99.6	98.7	67.8	78.5	78.0	86.0	83.1	84.5	93.4
Femida	w/i	47.0	56.8	41.6	54.2	59.3	25.2	39.6	32.8	44.5	43.3	43.4	52.1
	i	84.0	92.8	75.6	90.2	91.3	57.0	73.4	71.0	79.0	75.6	73.0	86.2
Zolotysta	w/i	54.2	53.7	37.8	51.7	49.8	23.0	34.4	30.7	42.0	45.2	39.5	48.0
	i	91.2	89.7	71.8	87.6	85.8	55.1	70.1	68.0	75.0	73.0	71.3	82.1
Vezha	w/i	43.0	55.4	39.2	58.5	57.5	28.8	39.1	36.1	47.3	42.1	41.2	53.8
	i	78.0	93.4	76.2	94.4	88.5	59.6	74.0	75.0	82.0	78.1	76.0	90.3
Oriana-standart	w/i	39.5	51.6	33.1	46.4	51.5	20.8	31.9	28.5	38.8	37.2	36.4	50.0
	i	73.5	85.6	69.1	82.4	87.6	51.4	67.5	63.0	72.0	70.3	68.6	79.9
Poltava Region													
Ametyst	w/i	42.8	62.9	42.4	44.5	43.7	26.9	57.6	36.7	57.6	38.1	38.7	62.2
	i	79.8	99.9	80.4	89.4	86.7	63.5	96.1	89.0	95.0	81.3	74.2	95.4
Hoverla	w/i	48.6	69.0	48.2	52.2	52.4	32.1	64.4	46.5	62.4	43.0	44.1	70.8
	i	86.5	108.0	91.2	101.1	96.2	71.0	102.0	87.0	104.0	89.4	83.0	106.7
Artemida	w/i	50.6	64.8	49.7	56.6	50.3	28.4	60.7	43.1	60.2	39.5	37.4	65.8
	i	84.6	102.8	88.7	95.5	89.3	66.2	97.0	82.0	98.1	84.2	76.5	102.3
Femida	w/i	41.4	55.8	45.2	47.3	54.1	23.6	58.5	41.6	56.3	35.9	33.2	55.6
	i	77.4	92.8	78.2	85.3	81.1	59.3	92.1	79.0	89.2	72.3	69.4	89.5
Zolotysta	w/i	39.2	54.0	40.6	42.6	45.6	22.2	52.9	27.0	55.5	34.2	31.2	51.1
	i	75.2	91.0	76.6	78.6	77.6	58	87.6	63.0	86.4	68.7	65.3	85.6
Vezha	w/i	46.9	60.2	46.6	48.8	52.0	25.4	55.4	45.6	56.8	37.2	35.7	57.4
	i	83.9	98.2	79.6	87.7	85.0	61.2	93.9	81.0	93.3	76.5	72.6	92.2
Oriana-standart	w/i	37.8	51.1	36.7	40.8	47.2	20.1	50.8	39.4	53.3	29.6	28.9	49.8
	i	73.8	86.1	72.7	76.9	75.2	56.0	86.1	72.0	83.6	64.1	62.7	81.1
Vinnytsia Region													
Ametyst	w/i	44.1	46.6	38.6	46.9	45.6	26.7	48.2	44.3	59.8	45.2	41.0	53.6
	i	80.1	83.6	80.6	87.9	83.5	62.5	84.8	76.0	96.0	81.3	78.3	88.7
Hoverla	w/i	48.2	52.4	43.4	52.0	55.9	30.4	54.9	48.8	68.9	48.6	47.1	58.9
	i	87.2	92.4	85.4	98.0	94.8	69.2	94.0	85.0	107.2	88.5	85.4	104.5

Table 8. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Artemida	w/i	50.6	48.6	44.7	52.5	52.0	26.0	51.5	42.4	63.8	46.9	43.7	56.3
	i	87.6	87.6	82.7	91.5	89.0	63.5	89.2	80.0	102.4	84.6	81.2	96.8
Femida	w/i	42.6	44.7	36.9	50.3	55.0	22.8	46.6	38.4	57.6	43.0	36.3	49.9
	i	78.6	79.7	73.9	86.3	81.0	58.0	81.8	74.0	90.1	75.2	73.1	82.3
Zolotysta	w/i	40.4	42.4	34.8	47.7	48.4	21.5	42.8	37.1	54.1	43.9	35.0	44.8
	i	76.4	77.4	70.8	83.7	77.3	57.6	77.9	72.0	87.0	73.1	70.5	78.4
Vezha	w/i	46.9	47.3	42.6	49.0	52.5	23.8	45.1	40.2	57.5	44.3	38.8	51.9
	i	83.9	81.3	77.6	85.0	81.4	59.2	82.6	76.0	94.3	79.8	75.6	85.6
Oriana-standart	w/i	39.0	41.0	32.0	45.6	44.1	19.4	40.6	35.0	50.4	39.6	33.9	47.9
	i	74.0	75.0	68.0	81.5	75.2	55.1	76.1	69.0	85.0	70.2	68.1	75.7

Source: *developed by the authors*

Nitrogen fixation gradually decreases as soybean plants approach maturity. However, the best variants identified in earlier microstages of the soybean development scale continued to yield higher values even at the latest microstage, BBCH 80-90. The highest mass of active nodules at BBCH microstage 80-90 was observed in the conditions of the Poltava Region. For seed-inoculated varieties, such as Hoverla, Artemida, and Ametyst, the active nodule mass in 2021 ranged from 95.4 to 106.7 mg/plant; in 2011, from 99.9 to 108.0 mg/plant; in 2018, from 95.0 to 104.0 mg/plant; in 2016, from 96.1 to 102.0 mg/plant; and in 2013, from 89.4 to 101.1 mg/plant. In the non-inoculated variants, this value decreased by 33.2 to 48.9 mg/plant, depending on the year of cultivation. High values of active nodule mass were also recorded in the Vinnytsia Region with seed inoculation in 2018, for the soybean varieties Hoverla (107.2 mg/plant), Artemida (102.4 mg/plant), and Ametyst (96.0 mg/plant). These values were 36.2 to 38.6 mg/plant higher than in the non-inoculated variants. High active nodule mass was also observed in 2021 for the varieties Hoverla (104.5 mg), Artemida (38.6 mg), and Ametyst (36.2 mg/plant). In the Kyiv Region, the highest active nodule mass was observed in 2014 for seed-inoculated varieties, with Hoverla (104.3 mg), Artemida (98.7 mg), and Ametyst (90.2 mg/plant). These values were 38.1 to 41.9 mg/plant higher than in the non-inoculated variants. The studies recorded the highest active symbiotic potential in the Poltava Region in 2021 for seed-inoculated soybean varieties: Hoverla (25,109 thousand kg·day/ha), Artemida (24,267 thousand kg·day/ha), Ametyst (23,522 thousand kg·day/ha), and Vezha (22,868 thousand kg·day/ha). These values were 5,824 to 6,456 thousand kg·day/ha higher than in the non-inoculated variants (Table 9).

Table 9*. Active symbiotic potential (ASP) on soybean roots, depending on variety, seed inoculation, and environmental conditions at BBCH microstage 51-90, thousand kg·day/ha*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	11,311	14,313	10,019	13,780	14,863	4,405	9,018	7,820	11,550	11,295	10,874	13,510
	i	18,664	20,255	17,368	20,006	20,644	11,723	16,549	15,102	18,158	17,597	17,016	19,335
Hoverla	w/i	13,013	14,839	11,100	14,373	15,667	5,188	10,545	8,592	12,855	11,749	11,280	14,047
	i	20,008	21,472	18,437	21,116	21,718	12,715	17,611	16,141	19,480	18,460	18,097	20,450
Artemida	w/i	12,092	14,544	10,891	14,282	14,845	4,732	9,205	7,661	12,295	11,676	10,895	13,779
	i	19,138	20,791	18,050	20,488	21,185	12,234	17,043	15,682	18,700	18,008	17,466	20,018
Femida	w/i	11,124	14,334	10,084	14,252	15,342	4,330	8,989	7,595	11,224	10,902	10,238	13,406
	i	17,911	19,795	16,492	19,284	19,938	10,904	15,666	14,336	17,330	16,761	16,207	18,310
Zolotysta	w/i	11,330	14,266	9,840	13,864	14,815	3,825	8,564	7,306	11,067	11,029	10,287	13,086
	i	17,589	19,253	16,100	18,843	19,348	10,582	15,412	13,942	16,795	16,388	15,888	17,845
Vezha	w/i	11,276	14,464	10,386	14,329	15,239	4,434	9,010	7,745	11,430	11,144	10,467	13,580
	i	18,259	20,081	16,924	19,532	20,204	11,287	16,152	14,725	17,890	17,176	16,541	18,843
Oriana-standart	w/i	10,464	14,014	9,305	13,352	14,762	3,569	8,297	6,978	10,292	9,994	9,721	13,102
	i	17,043	19,040	15,731	18,296	19,033	10,284	15,023	13,537	16,245	15,842	15,495	17,350
Poltava Region													
Ametyst	w/i	11,852	16,737	11,805	12,856	12,897	5,436	16,486	10,527	16,162	9,377	9,267	17,698
	i	18,205	22,369	17,792	19,449	19,890	12,780	22,023	17,988	22,442	16,373	16,278	23,522

Table 9. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Hoverla	w/i	12,158	17,308	12,297	13,725	13,155	6,147	17,031	12,050	17,267	9,974	9,720	18,920
	i	19,033	23,796	19,347	20,672	20,873	13,803	23,156	19,089	23,592	17,509	17,268	25,109
Artemida	w/i	11,996	16,643	12,202	13,503	12,907	5,421	16,442	11,045	16,563	9,165	9,109	17,811
	i	18,664	23,010	18,521	20,202	20,427	13,308	22,347	18,307	23,014	16,832	16,671	24,267
Femida	w/i	11,195	16,280	11,002	12,558	13,305	4,889	16,236	10,856	15,521	9,071	8,518	16,983
	i	17,532	21,478	17,039	18,599	18,825	12,209	21,883	17,120	21,358	15,460	15,284	22,378
Zolotysta	w/i	10,624	16,254	10,675	12,057	12,780	4,511	15,740	10,291	15,438	8,752	8,325	16,586
	i	17,016	21,113	16,479	18,345	18,257	11,797	21,337	16,370	20,977	15,616	14,896	21,745
Vezha	w/i	11,534	16,453	11,942	12,634	13,198	5,104	16,135	11,179	15,690	9,131	8,840	16,999
	i	17,905	21,957	17,453	19,045	19,263	12,499	21,622	17,368	21,991	15,873	15,727	22,868
Oriana-standart	w/i	10,692	15,911	10,079	11,721	12,780	4,281	15,405	10,373	14,692	8,173	7,763	16,705
	i	16,753	20,544	16,166	17,838	17,959	11,412	20,943	16,222	20,610	14,778	14,485	21,373
Vinnytsia Region													
Ametyst	w/i	11,555	12,709	10,002	12,657	13,408	5,197	12,697	11,150	17,152	11,659	10,523	14,190
	i	18,233	18,552	16,867	19,282	19,924	12,609	18,929	17,255	22,709	17,947	17,320	20,016
Hoverla	w/i	11,893	13,063	10,265	12,986	13,998	5,752	13,215	11,634	17,583	11,882	10,927	14,234
	i	18,878	19,876	17,667	20,045	20,689	13,416	19,892	18,722	23,719	18,981	17,982	21,263
Artemida	w/i	12,192	12,718	10,503	13,285	13,820	5,100	12,662	10,558	16,932	11,742	11,067	14,448
	i	18,587	19,053	17,211	19,567	20,345	12,919	19,363	17,914	23,229	18,511	17,324	20,583
Femida	w/i	11,359	12,420	9,337	12,865	14,129	4,523	12,386	10,344	15,806	10,950	9,738	13,616
	i	17,546	18,052	16,041	18,556	19,301	11,938	18,286	16,404	21,800	16,923	16,484	19,100
Zolotysta	w/i	10,948	12,316	9,041	12,473	13,668	4,317	11,888	10,117	15,673	11,088	9,812	13,290
	i	17,141	17,666	15,724	18,159	18,863	11,650	17,848	15,974	21,361	17,230	16,086	18,595
Vezha	w/i	11,769	12,593	10,283	12,789	13,960	4,593	12,354	10,604	16,015	11,180	10,143	13,714
	i	18,043	18,273	16,448	18,802	19,642	12,154	18,540	16,931	22,194	17,395	17,020	19,654
Oriana-standart	w/i	10,895	12,175	8,283	11,937	13,514	3,896	11,639	9,769	14,972	10,057	9,313	13,373
	i	17,003	17,269	15,324	17,819	18,375	11,334	17,302	15,327	20,889	16,265	15,618	18,171

Source: *developed by the authors*

In the Poltava Region, high values of active symbiotic potential were recorded in 2011 for seed-inoculated soybean varieties: Hoverla – 23,796; Artemida – 23,010; Ametyst – 22,369; and Vezha – 21,957 thousand kg·day/ha. In the non-inoculated variants, this value decreased by 5,504 to 6,488 thousand kg·day/ha. In 2018, high values of active symbiotic potential were also observed for seed-inoculated varieties Hoverla, Artemida, Ametyst, and Vezha, which were 6,301 to 6,451 thousand kg·day/ha higher compared to the non-inoculated variants. The increase in active symbiotic potential can be explained by the high values of the hydrothermal coefficient in these years of research. In the Vinnytsia Region, the active symbiotic potential in 2018 for seed-inoculated varieties Hoverla, Artemida, Ametyst, and Vezha ranged from 22,194 to 23,719 thousand kg·day/ha, which was 5,557 to 6,297 thousand kg·day/ha higher compared to the non-inoculated variants. In 2021, for seed-inoculated varieties Hoverla, Artemida, and Ametyst, this indicator increased by 5,826 to 7,029 thousand kg·day/ha compared to the non-inoculated variants. In the Kyiv Region, the highest values of active symbiotic potential were recorded in 2014 for the soybean varieties Hoverla (21,718), Artemida (21,185), Ametyst (20,644), and Vezha (20,204 thousand kg·day/ha). These values were 4,965 to 6,340 thousand kg·day/ha higher compared to the non-inoculated variants. The lowest values of active symbiotic potential were observed in 2015 in the Kyiv Region. For seed-inoculated varieties, this indicator ranged from 10,284 (variety Oriana) to 12,715 (variety Hoverla), which was directly related to the lowest values of the hydrothermal coefficient in that year. The most significant positive effect on the formation of the active symbiotic potential indicator was achieved through the use of seed inoculation. This promoted a more intensive colonisation of soybean plant roots by symbiotic bacteria, leading to an increase in the number of nodules and their potential mass, which in turn contributed to a higher symbiotic potential. The magnitude of the active symbiotic apparatus was influenced by hydrothermal and edaphic conditions, seed inoculation, and the variety, all of which had a significant impact on the amount of biologically fixed nitrogen in soybean crops (Table 10).

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Table 10. Amount of biologically fixed nitrogen depending on variety, seed inoculation, and ecological growing conditions, kg/ha													
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	58.8	74.4	52.1	71.8	77.3	22.9	46.9	40.7	60.1	58.7	56.5	70.3
	i	97.1	105.3	90.3	104.0	107.3	60.9	86.1	78.5	94.4	91.5	88.5	100.5
Hoverla	w/i	67.7	77.2	57.7	74.7	81.5	27.0	54.8	44.7	66.8	61.1	58.7	73.0
	i	104.0	111.7	95.9	109.8	112.9	66.1	91.6	83.9	101.3	96.0	94.1	106.3
Artemida	w/i	62.9	75.6	56.6	74.3	77.2	24.6	47.9	39.8	63.9	60.7	56.7	71.7
	i	99.5	108.1	93.9	106.5	110.2	63.6	88.6	81.5	97.2	93.6	90.8	104.1
Femida	w/i	57.8	74.5	52.4	74.1	79.8	22.5	46.7	39.5	58.4	56.7	53.2	69.7
	i	93.1	102.9	85.8	100.3	103.7	56.7	81.5	74.6	90.1	87.2	84.3	95.2
Zolotysta	w/i	58.9	74.2	51.2	72.1	77.0	19.9	44.5	38.0	57.5	57.4	53.5	68.0
	i	91.5	100.1	83.7	98.0	100.6	55.0	80.1	72.5	87.3	85.2	82.6	92.8
Vezha	w/i	58.6	75.2	54.0	74.5	79.2	23.1	46.9	40.3	59.4	57.9	54.4	70.6
	i	94.9	104.4	88.0	101.6	105.1	58.7	84.0	76.6	93.0	89.3	86.0	98.0
Oriana-standart	w/i	54.4	72.9	48.4	69.4	76.8	18.6	43.1	36.3	53.5	52.0	50.6	68.1
	i	88.6	99.0	81.8	95.1	99.0	53.5	78.0	70.4	84.5	82.4	80.6	90.2
Poltava Region													
Ametyst	w/i	61.6	87.0	61.4	66.9	67.1	28.3	85.7	54.7	84.0	48.8	48.2	92.0
	i	94.7	116.3	92.5	101.1	103.4	66.5	114.5	93.5	116.7	85.1	84.6	122.3
Hoverla	w/i	63.2	90.0	63.9	71.4	68.4	32.0	88.6	62.7	89.8	51.9	50.5	98.4
	i	98.9	123.7	100.6	107.5	108.5	71.8	120.4	99.3	122.7	91.0	89.8	130.6
Artemida	w/i	62.4	86.5	63.5	70.2	67.1	28.2	85.5	57.4	86.1	47.7	47.4	92.6
	i	97.1	119.7	96.3	105.0	106.2	69.1	116.2	95.2	119.7	87.5	86.7	126.2
Femida	w/i	58.2	84.7	57.2	65.3	69.2	25.4	84.4	56.4	80.7	47.2	44.3	88.3
	i	91.2	111.6	88.6	96.7	97.9	63.5	113.8	89.0	111.1	80.4	79.5	116.4
Zolotysta	w/i	55.2	84.5	55.5	62.7	66.5	23.5	81.8	53.5	80.3	45.5	43.3	86.2
	i	88.5	109.8	85.7	95.4	94.9	61.3	111.0	85.1	109.1	81.2	77.5	113.1
Vezha	w/i	60.0	85.6	62.1	65.7	68.6	26.5	83.9	58.1	81.6	47.5	46.0	88.4
	i	93.1	114.2	90.8	99.0	100,2	65.0	112.4	90.3	114.4	82.5	81.8	118.9
Oriana-standart	w/i	55.6	82.7	52.4	61.0	66.6	22.3	80.1	53.9	76.4	42.5	40.4	86.9
	i	87.1	106.8	84.1	92.8	93.4	59.3	108.9	84.4	107.2	76.8	75.3	111.1
Vinnytsia Region													
Ametyst	w/i	60.1	66.1	52.0	65.8	69.7	27.0	66.0	58.0	89.2	60.6	54.7	73.8
	i	94.8	96.5	87.7	100.3	103.6	65.6	98.4	89.7	118.1	93.3	90.1	104.1
Hoverla	w/i	61.8	67.9	53.4	67.5	72.8	29.9	68.7	60.5	91.4	61.8	56.8	74.0
	i	98.2	103.4	91.9	104.2	107.6	69.8	103.4	97.4	123.3	98.7	93.5	110.6
Artemida	w/i	63.4	66.1	54.6	69.1	71.9	26.5	65.8	54.9	88.0	61.1	57.5	75.1
	i	96.6	99.0	89.5	101.7	105.8	67.2	100.7	93.2	120.8	96.3	90.1	107.0
Femida	w/i	59.1	64.6	48.6	66.9	73.5	23.5	64.4	53.8	82.2	56.9	50.6	70.8
	i	91.2	93.9	83.4	96.5	100.4	62.1	95.1	85.3	113.4	88.0	85.7	99.3
Zolotysta	w/i	56.9	64.0	47.1	64.9	71.1	22.4	61.8	52.6	81.5	57.7	51.0	69.1
	i	89.1	91.9	81.8	94.4	98.2	60.6	92.7	83.1	111.1	89.6	83.6	96.7
Vezha	w/i	61.2	65.5	53.5	66.5	72.6	23.9	64.2	55.1	83.3	58,1	52.7	71.3
	i	93.8	95.0	85.7	97.8	102.1	63.2	96.4	88.0	115.4	90.5	88.5	102.2
Oriana-standart	w/i	56.7	63.3	43.6	62.1	70.3	20.3	60.5	50.8	77.9	52,3	48.4	69.5
	i	88.4	89.8	79.7	92.7	95.5	58.9	90.0	79.7	108.6	84.6	81.2	94.5

Source: *developed by the authors*

The highest values of biologically fixed nitrogen were recorded in the Poltava Region in the experimental variant where seed inoculation was applied in 2021 for the varieties Hoverla (130.6 kg/ha), Artemida (126.2 kg/ha), Ametyst (122.3 kg/ha), and Vezha (118.9 kg/ha). These values were 30.3–33.6 kg/ha higher compared to the non-inoculated variants. High levels of biologically fixed nitrogen were also observed in 2011 for the varieties Hoverla (123.7 kg/ha), Artemida (119.7 kg/ha), Ametyst (116.3 kg/ha), and Vezha (114.2 kg/ha). These values were higher by 33.7, 33.2, and 29.3 kg/ha, respectively, compared to the non-inoculated variants. Similarly, high levels of biologically fixed nitrogen were observed in 2018 for the varieties: Hoverla (122.7 kg/ha), Artemida (119.7 kg/ha), and Ametyst (116.7 kg/ha). These values were higher than those in the non-inoculated variants by 32.9, 33.6, and 32.7 kg/ha, respectively. It is worth noting the relatively high amounts of biologically fixed nitrogen in 2016 in the experimental variants with seed inoculation for the varieties: Hoverla (120.4 kg/ha), Artemida (116.2 kg/ha), and Ametyst (114.5 kg/ha). These values were higher by 31.8, 30.7, and 28.8 kg/ha, respectively, compared to the non-inoculated variants. In the Vinnytsia Region, high levels of biologically fixed nitrogen were recorded in 2018 with seed inoculation for the varieties Hoverla (123.3 kg/ha), Artemida (120.8 kg/ha), and Ametyst (118.1 kg/ha). In the non-inoculated variants, this value decreased by 28.9-32.8 kg/ha. The lowest amount of biologically fixed nitrogen was observed in 2015 with seed inoculation. This value ranged from 53.5 kg/ha (variety Oriana) to 71.8 kg/ha (variety Hoverla), which was 34.9-39.8 kg/ha higher compared to the non-inoculated variants. Seed inoculation with nitrogen-fixing bacteria has a significant impact on nitrogen fixation (Fig. 2).

Seed inoculation had the most significant impact on biological nitrogen fixation, accounting for 96.89% of the variation. Hydrothermal conditions contributed 2.3% and varietal differences 0.76%. The interaction effects of these factors on biological nitrogen fixation did not exceed 1%. The average amount of biologically fixed nitrogen with and without seed inoculation under various soil and hydrothermal conditions for different soybean varieties is presented in Figure 3.

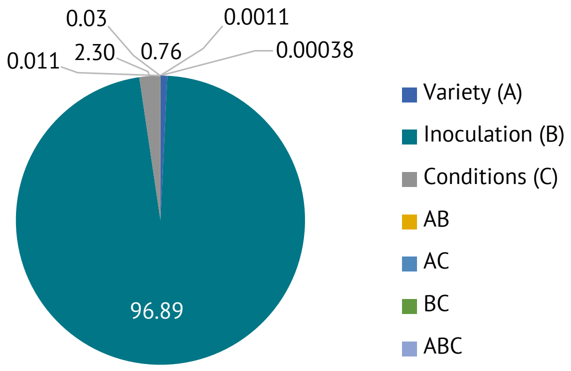

Figure 2. *The contribution of factors and their interactions to nitrogen fixation in soybean plants*
Source: *developed by the authors*

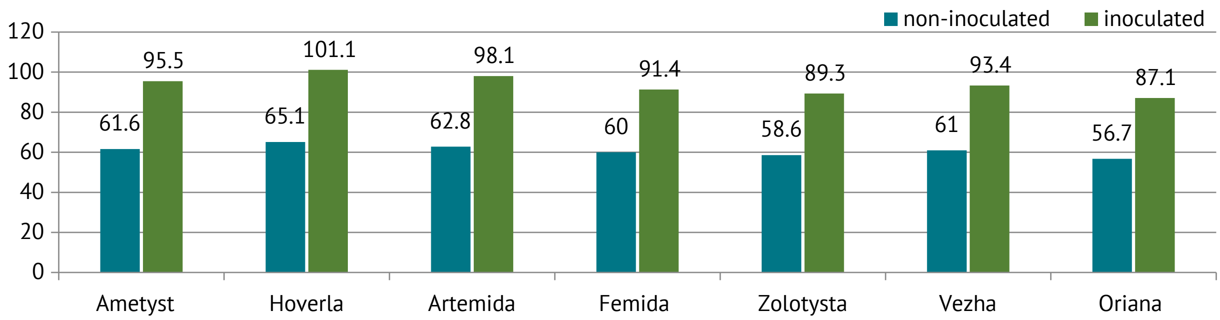

Figure 3. *Average amount of biologically fixed nitrogen under different ecological conditions of cultivation*
Source: *developed by the authors*

The highest amount of biologically fixed nitrogen was recorded in the Hoverla variety, both in the non-inoculated variant (65.1 kg/ha) and with seed inoculation (101.2 kg/ha). For the Ametyst and Artemida varieties, the amount of biologically fixed nitrogen with seed inoculation was 95.5 and 98.1 kg/ha, respectively. Seed inoculation increased the amount of biologically fixed nitrogen by 36.1 kg/ha (Fig. 4).

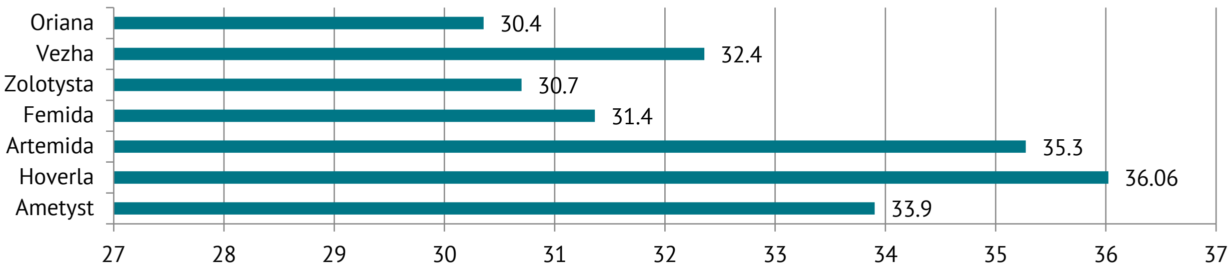

Figure 4. *Increase in the amount of biologically fixed nitrogen depending on seed inoculation and the response of soybean varieties, kg/ha*
Source: *developed by the authors*

Seed inoculation in the Artemida variety led to an increase in biologically fixed nitrogen by 35.3 kg/ha. In the Ametyst variety, the amount of biologically fixed nitrogen increased by 33.9 kg/ha compared to the non-inoculated variant. Thus, the selected soybean varieties – Hoverla, Artemida, and Ametyst – showed a strong response to treatment with nitrogen-fixing bacteria, which facilitated the influx of biologically fixed nitrogen. These varieties are recommended for cultivation in various ecological conditions to support the effective functioning of the soybean's legume-rhizobia symbiosis, which will contribute to the increased resilience of agroecosystems.

DISCUSSION

Legumes are competitive crops due to their environmental and socio-economic benefits, such as nitrogen fixation, soil enrichment with high-quality organic matter, promotion of nutrient cycling, and water retention in the soil. *Rhizobium* bacteria play a crucial role in nitrogen fixation and sustainable agriculture (Soumare et al., 2020). Rhizobia colonise the root system of legumes, forming nodules where nitrogen fixation occurs, converting atmospheric nitrogen into a plant-available form (Coba de la Pena *et al.,* 2018). nodules are primarily formed on the main root, where they are larger in size and mass. Most of them are located in the topsoil. Under favourable conditions, a single plant can form 21 to 80 or more nodules (Roy Choudhury *et al.,* 2019). The number and mass of active nodules on plant roots, especially during periods of peak photosynthetic activity, are important indicators of successful legume-rhizobia symbiosis (Savala *et al.*, 2022). According to research by M. Vasconcelos *et al.* (2024), biological nitrogen fixation by legumes varies from 21 to 389 kg/ha. This is corroborated by the results obtained from the study of the impact of the investigated factors on biological nitrogen fixation in soybean plants, which varied from 36.3 to 130.6 kg/ha.

The activity of rhizobia is influenced by weather conditions that affect the bacteria through the plant, as they live in symbiosis. Water scarcity slows down plant photosynthesis, while waterlogging causes oxygen deficiency in nodules, reducing nitrogen fixation rates (Sinclai & Nogueira, 2018). The current research has established a relationship between nodule formation on soybean roots and the hydrothermal coefficient of the growing region. During periods of moisture deficiency across all years of the study, the lowest mass and number of nodules were observed. The increase in the number of active nodules on plant roots depending on the growth stage of soybeans aligns with the findings of other researchers (Cigelske *et al.*, 2020). In the studies by A. Korobko *et al.* (2024), the highest number of active nodules on soybean roots was also confirmed at the BBCH microstage 68-69. The study also highlighted a decrease in the number of active nodules on plant roots during soybean maturation.

The publication by D. Krutylo *et al.* (2021) highlights the dependence of the diversity of local rhizobia on the environmental conditions of the growing region and host plant genotypes. According to B. Cigelske *et al.* (2020), the average number of nodules per plant varied significantly among different soybean varieties depending on the growing year. The researchers attributed this variation to factors such as soil type, preceding crop, rainfall, and soil nitrogen levels. This confirms the data obtained on the variation in the number of nodules depending on the region and year of cultivation of soybean varieties. In the studies of C.E.N. Savala *et al.* (2022), the soybean variety TGx 1904-6F formed more nodules than the variety Storm. This number varied depending on the year and growing region. Overall, the application of bioinoculants promoted greater nitrogen uptake by plants in areas with the lowest abundance of native rhizobia.

Seed inoculation of soybean varieties resulted in a significant increase in both the number (by 10-45%) and mass (by 11-86%) of nodules on plant roots. Researchers have also reported increased levels of symbiotic nitrogen fixation (by 1.2-4.2 times) and seed weight per plant (by 6-29%), depending on the soybean variety (Krutylo, 2023). The experimental data obtained regarding the increase in the number of active nodules on soybean roots following inoculation with bio-preparations is confirmed by the results of other researchers. The increase in both the number and mass of nodules on soybean roots upon inoculation with *Rhizobia* has been observed in studies by Z. Getachew Gebrehana and L. Abeble Dagnaw (2020) and R. Omari *et al.* (2022). In the article by E. Szpunar-Krok *et al.* (2023), the relationship between increased nodule number and mass following inoculation with *Bradyrhizobia* soybean varieties is discussed. The maximum formation of active nodule mass on the roots of different soybean varieties in the studies is consistent with the findings of other researchers (Korobko *et al.*, 2024).

N.M. Gitonga *et al.* (2021) found that some soybean varieties responded better to inoculation than others. The variety SC Squire showed a positive response to seed inoculation with rhizobia across all studied parameters, compared to the varieties SB 19 and Gazelle. This is confirmed by the results obtained from the study of the impact of seed inoculation on the formation of the legume-rhizobia symbiosis in soybeans and atmospheric nitrogen fixation. D. Miljaković *et al.* (2022) also highlighted the impact of soybean inoculation with *Bradyrhizobia* on increased plant height, nodule number, and nodule mass. In the studies of C.E.N. Savala *et al.* (2022), nodule mass per plant increased from 7.7 to 167.6 mg for two soybean varieties, depending on growing conditions. Scientists believe that the effectiveness of inoculants in symbiosis depends on the compatibility of the strain with a specific soybean variety. An assessment of the symbiotic effectiveness of eight *Bradyrhizobium* strains with five soybean varieties (Gishama, Awassa-95, Boshe, Hawassa-04, and Jalale) showed a significant impact on nodule number and mass (Beruk *et al.,* 2024). The formation of a legume-rhizobia symbiosis induces specific responses that enhance the functional level of the host plant's metabolism and improve its adaptive properties to adverse growing conditions (Nyzhnyk & Kots, 2023). According to M.D. Nakei *et al.* (2024), the effectiveness of soybean-rhizobia symbiosis depends on the rhizobium species, variety characteristics, and biotic factors. This is corroborated by the obtained data concerning the variation in inoculation effectiveness across different soybean varieties inoculated with the same strain.

For the effective functioning of the soybean-rhizobia symbiosis, careful selection of symbiotic partners is necessary, requiring continuous updating of soybean varieties and nitrogen-fixing bacterial strains. According to T. Nyzhnyk and S. Kots (2023), the resilience of the soybean-rhizobia symbiosis to water deficit depends on the active participation of both symbiotic partners, as well as the ability of the host plant and bacteria to activate adaptive defence systems for regulating key enzymatic processes involved in the metabolism of phenolic compounds. Therefore, the research findings confirm those of other scientists regarding the influence of inoculation, varietal characteristics, and ecological growing conditions on the formation of the legume-rhizobia symbiosis in soybeans. Optimising the management of biological nitrogen fixation is crucial for addressing the challenges of providing plants with nitrogen, reducing the use of nitrogen fertilisers, and preserving soil fertility. The use of sustainable alternatives will contribute to sustainable agriculture and biodiversity conservation.

CONCLUSIONS

The number of active nodules formed on plants across different years of research primarily depended on the hydrothermal coefficient of the soybean growing region and its varietal characteristics. The highest number of active nodules at BBCH microstage 51-59 was formed on the roots of soybean varieties in the Poltava Region in 2021, Vinnytsia Region in 2018, and Kyiv Region in 2014 on the varieties Hoverla, Artemida, and Ametyst, after seed inoculation with the biopreparation Optimize 200. At BBCH microstage 61-62, an increase in the number of active nodules on the roots of different soybean varieties was observed after seed inoculation compared to BBCH microstage 51-59, depending on the year and growing region. The highest number of active nodules on the roots of different soybean varieties after seed inoculation was recorded at BBCH microstage 68-69, depending on the year and growing region. In the Poltava Region under favourable conditions (2021), the number of active nodules after seed inoculation ranged from 46.7 to 50.3 mg/plant depending on the variety, which is 17.0-18.4 more compared to non-inoculated variants. At BBCH microstage 80-90, a decrease in the number of active nodules on the roots of different soybean varieties was observed compared to the previous microstages (BBCH 61-62 and BBCH 68-69).

The highest active nodule mass at BBCH microstage 51-59 was observed on plant roots in Poltava Region in 2021, Vinnytsia Region in 2018, and Kyiv Region in 2014, specifically on the varieties Hoverla, Artemida, and Ametyst following seed inoculation. These findings are supported by the hydrothermal coefficient values for each region during the favourable growing year. An increase in active nodule mass was observed at BBCH microstage 61-62 across all varieties following seed inoculation compared to BBCH microstage 51-59, depending on the year and growing region. The maximum active nodule mass on soybean roots was recorded at BBCH microstage 68-69 in Poltava, Vinnytsia, and Kyiv regions. The most favourable hydrothermal conditions for all soybean varieties were observed in 2021 in Poltava Region. The mass of active nodules following seed inoculation ranged from 508.9 to 547.8 mg/plant, depending on the variety, which is 173.7-188.0 mg/plant higher compared to non-inoculated variants. At BBCH microstage 80-90, a decrease in active nodule mass on the roots of different soybean varieties was observed compared to the previous microstages.

Seed inoculation had the greatest impact on the formation of active symbiotic potential. The increase in active symbiotic potential in certain years of the study can be explained by high hydrothermal coefficient values. The highest active symbiotic potential was determined in soybean varieties Hoverla, Artemida, Ametyst, and Vezha. Cultivation of soybean varieties Ametyst, Artemida, and Hoverla contributed to the maximum accumulation of biologically fixed nitrogen when using seed inoculation with nitrogen-fixing bacteria under various ecological conditions. Biological nitrogen fixation by soybean varieties was significantly dependent on seed inoculation (96.89%). Varieties Ametyst, Artemida, and Hoverla provided the highest amount of biologically fixed nitrogen (95.5-101.2 kg/ha) when seeds were inoculated. With seed inoculation of varieties Ametyst, Artemida, and Hoverla, biological nitrogen fixation increased by 33.9-36.1 kg/ha compared to the non-inoculated variant. The results of this study confirm the prospects for further research on the effectiveness of legume-rhizobia symbiosis under the influence of seed inoculation in various ecological conditions, which will contribute to increasing the sustainability of agroecosystems.

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CONFLICT OF INTEREST

None.

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Дослідження бобово-ризобіального симбіозу сої для стійкості агроекосистем

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Анотація. Дослідження інноваційних методів регуляції бобово-ризобіального симбіозу є важливим для покращення азотфіксації, що сприяє збереженню здоров›я ґрунтів та підвищенню врожайності. Це забезпечує стале сільське господарство, знижуючи потребу в хімічних добривах і підвищуючи стійкість агроекосистем. Метою роботи було з'ясувати вплив інокуляції насіння, екологічних умов і сортових особливостей сортів сої на накопичення біологічного азоту. Дослідження проводили у екологічних умовах Київської, Полтавської та Вінницької областей протягом 2010-2021 рр. Агротехніка вирощування сортів сої була загальноприйнята для умов регіонів дослідження. Наведено результати досліджень впливу інокуляції насіння на динаміку формування та продуктивність соєво-ризобіального симбіозу за наявності в ґрунті фонових популяцій ризобій сої. Визначено азотфіксувальний потенціал сортів сої за дії інокуляції. Інокуляція підвищує ефективність симбіотичної системи сої. Доведено, що в різних екологічних умовах інокуляція насіння Bradyrhizobium japonicum покращує формування і функціонування симбіотичного апарату сої навіть на фоні ґрунтової популяції бульбочкових бактерій. Дія інокуляції насіння залежить від гідротермічного режиму року, екологічних умов і сорту сої. Застосування інокуляції насіння сприяє формуванню більшої маси активних бульбочок на коренях рослин, що позитивно вплинуло на азотфіксацію. Найвищі показники азотфіксації встановлено у сортів сої Аметист, Артеміда і Говерла у різних екологічних умовах. Інокуляція насіння забезпечила збільшення кількості біологічного азоту цих сортів на 33.9-36.1 кг/га. Сорти сої Аметист, Артеміда і Говерла відзначилися вищою реакцією на інокуляцію насіння азотфіксувальними бактеріями і рекомендуються для вирощування у різних екологічних умовах. Інноваційні рішення підвищення ефективності функціонування бобово-ризобіального симбіозу сої за використання біологічних препаратів на основі азотфіксувальних бактерій дозволять розробити біологізовані технології вирощування культури для стійкості агроекосистем

Ключові слова: кількість і маса бульбочок; азотфіксація; симбіотичний потенціал; інокуляція; гідротермічний коефіцієнт; ризобії; біологічно-фіксований азот

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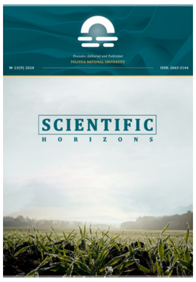

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Ecological and toxicological condition of militarily degraded chernozems: A case study of the Chkalovsk territorial community

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Abstract. This study aimed to assess the ecological and toxicological condition of militarily degraded chernozems in the Chkalovsk territorial community of the Chuhuiv District in the Kharkiv Region. This involved conducting a detailed, comprehensive survey of the ecological and toxicological condition of the chernozems in the Chkalovsk territorial community, which were affected by military actions, and determining their suitability for agricultural use. If necessary, recommendations for soil remediation measures were provided. An improved system for classifying and assessing the degree of military degradation of soils, based on indicators of chemical contamination by organic and inorganic compounds, was proposed. It was established that on recently demined areas of the de-occupied territory, there is a trend of slight increases in the content of lead (1.4 times), cobalt (1.3 times), iron (1.6 times), and zinc (2.6 times) relative to pre-war (background) levels. The observed exceedances of heavy metals in the soil, while present, are not critical for agriculture and do not necessitate land conservation or the implementation of overly complex and costly soil remediation measures. A slight decrease in mobile cadmium, lead, nickel, cobalt, and iron was recorded after demining, accompanied by an increase in plant-available chromium and zinc. The concentrations of bioavailable manganese and copper remained almost unchanged during this period. These changes may also indicate the ongoing processes of self restoration in chernozem soils, which are typically characterised by high buffering capacity against heavy metals. The results obtained demonstrate very low concentrations of all polycyclic aromatic hydrocarbons, explosive substances, and related nitroaromatic compounds in the studied soils. The findings can be used when developing a post-war soil restoration programme and the rational use of land in agricultural production

Keywords: soil contamination; ecological safety; Russian-Ukrainian war; heavy metals; petroleum products; military soil degradation; agricultural production

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INTRODUCTION

Ukraine has a unique soil cover, with more than 60% of its territory occupied by chernozem soils, which are unparalleled in their properties, fertility potential, and suitability for growing a variety of field crops. The area covered by chernozems exceeds 24 million hectares. Ukrainian chernozem is a national brand, a cornerstone of food and economic security, and a foundation for human prosperity. Chernozem is the gold standard of soils, a natural phenomenon characterised by distinctive morphological, physical, and chemical properties, and exceptionally high fertility. Thanks to the resource potential of naturally fertile chernozems, Ukraine holds a leading position in the global export of grain, sunflower, and other crops. Chernozems are classified as Black soils, considered the most valuable for food security. They are characterised by high organic carbon content (over 1.2%), a top dark-coloured horizon thickness of at least 25 cm, cation exchange capacity exceeding 25 mmol/kg, and base saturation of over 50% (FAO, 2022).

The impact of warfare on the agricultural sector and land resources has become a focal point for scientific research. Notably, J. Teixeira da Silva *et al*. (2023) investigated the effects of the Russian-Ukrainian war on agricultural production and food security at various levels of governance. V. Zhuk *et al.* (2023) substantiated the utility of accounting methods for assessing the damages inflicted upon Ukrainian agricultural businesses by the war, however, the issue of evaluating the damage to land remained unaddressed in their study. S. Baliuk *et al.* (2024) conducted a pilot assessment and mapping of the impact of warfare on Ukraine's soil resources. A. Kucher and L. Kucher (2024) undertook an economic evaluation of the harm and losses incurred by soils and lands as a result of the Russian-Ukrainian war.

The problem of soil contamination in Ukraine was pressing even before the war, but its significance has increased substantially following the Russian invasion. For instance, according to Ye. Ulko *et al.* (2022), a quantitative assessment of the impact of soil contamination by mobile forms of lead and cadmium on land use efficiency and normative monetary valuation of arable land revealed the potential for improvement if the contamination issue were addressed. As noted by H. Kireitseva *et al.* (2023), the environmental impact of war may seem secondary amidst human suffering and daily destruction, but the consequences of environmental crimes are long-lasting and their remediation can take many years.

The ecological risks associated with warfare have been exacerbated by the ongoing conflict, posing significant threats to the environment, particularly soil and water resources, as well as the quality of agricultural produce. The intense anthropogenic pressures resulting from military activities can induce processes of military degradation in soils, including chemical degradation caused by contamination with toxic substances. This has a detrimental impact on the eco-toxicological status of soils, their health, and the ecosystem services they provide. Prolonged warfare results in widespread damage to agricultural lands, especially chernozems, and intensifies chemical contamination of soils and water sources due to the detonation of explosives, destruction of heavy machinery, spills and burning of petroleum products. Moreover, as J. Hupy and

R. Schaetz (2006) noted, explosions can disrupt the soil profile and mix the fertile topsoil with underlying Quaternary deposits (bombturbation), leading to alterations in the geochemical background of the soil cover in active conflict zones. An ecological and toxicological review conducted by A. Rodríguez-Seijo *et al.* (2024) revealed that military activities are a significant source of contamination of water and soil with inorganic and organic pollutants.

These factors can lead to a range of negative consequences for public health, agricultural product quality, water resources, and the flora and fauna of Ukraine. The risk of land contamination arises not only from the destruction of industrial enterprises, processing complexes, buildings, and structures. Direct sources of contamination of agricultural land during combat operations include various calibres of munitions containing a wide range of toxic compounds, the burning of heavy machinery, and spills of fuel, lubricants, and organic solvents.

The intense fighting that took place over several months during the liberation of the Chkalovsk territorial community and the urgent need to return these lands to agricultural production to ensure the country's food security and maintain its export potential necessitates a detailed assessment of the condition of agricultural lands. This requires the development and implementation of a restoration program, including recommendations for the reclamation of disturbed lands using comprehensive soil remediation measures. Therefore, this study aims to assess the impact of warfare on the eco-toxicological condition of chernozems using the Chkalovsk territorial community of the Chuhuiv District of Kharkiv Region as a case study.

MATERIALS AND METHODS

The soil sampling network encompassed agricultural lands within the Chkalovsk territorial community. Sampling points were georeferenced using a GPS-12 satellite positioning device with the WGS 84 datum. The study employed both remote sensing and field methods, utilising modern technical equipment and geographic information systems. Soil sampling schemes are presented in Figure 1. Soil samples from suspected contaminated areas were collected between September and November 2023 following DSTU ISO 10381-1:2004 (2006), DSTU ISO 10381-2:2004 (2006), DSTU ISO 10381-5:2009 (2011), and DSTU ISO 16133:2005 (2007), considering the recommendations of the current international ISO 18400 series standards. Transportation and preparation for physicochemical analyses were conducted according to DSTU ISO 11464-2007 (2009). The selection of soil sampling points within the Chkalovsk territorial community was based on the following principles: demining, accessibility, coverage of the community's territory, and sufficiency of information.

a

b

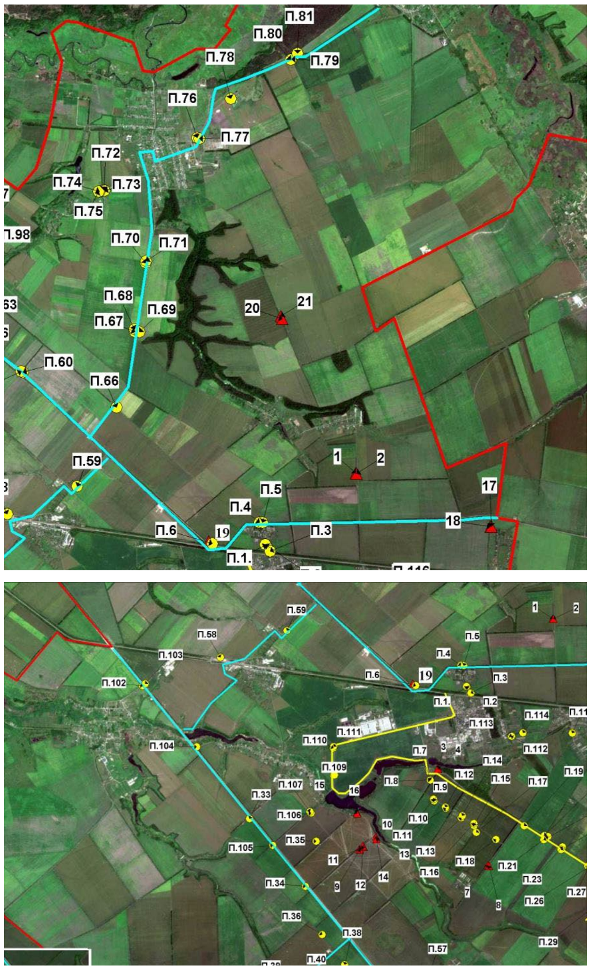

***Figure 1**. Scheme of soil sampling points in the Chkalovsk territorial community*
***Note:** a – northern part of the community, b – southern part of the community*
***Source:** developed by the authors*

While the foundational standards underlying DSTU ISO 10381-5:2009 (2011) and DSTU ISO 19258:2014 (2015) do not provide detailed guidance on the collection of background soil samples, they permit the use of other national standards for this purpose. In Ukraine, DSTU 7243:2011 (2012) serves as a reference. Moreover, the nationally approved DSTU 17.4.3.01:2019 (2019) and DSTU 17.4.4.02:2019 (2019) offer quite specific recommendations in this regard. However, despite their highly detailed requirements and ease of practical application, these standards are adaptations of older Soviet-era GOST standards, primarily focused on cases of industrial and accidental soil contamination.

An integrated approach combining systematic, structural-genetic, and comparativegeographic methods, as well as synthesis, infometry, critical analysis, and generalisation was employed to investigate the landscape and geochemical characteristics of contaminant distribution in the studied soils and their bioavailability to plants. To assess the level of soil contamination by heavy metals, benz[*a*]pyrene, and petroleum products, their MPCs were considered by Resolution of the Cabinet of Ministers of Ukraine No. 1325 (2021), and the requirements of DSTU 7243:2011 (2012). The presence of explosive residues and their toxic metabolites was evaluated as an indication of contamination with new hazardous substances (naturally absent in soils), according to the Order of the Ministry of Environmental Protection and Nuclear Safety of Ukraine No. 171 (1997).

According to DSTU 7243:2011 (2012), if the soil contains a contaminant at a level exceeding the MPC and three times the background level, the land is classified as technologically contaminated. In cases of soil contamination with multiple hazardous substances, the land is considered technologically contaminated if the total pollution index (Zc) exceeds 16.

The total pollution index is calculated using the formula:

$$Zc = \sum_1^n Cc - (n - 1), \quad (1)$$

where $Cc = \frac{Ca}{Cb}$ (C_a is the actual content of the *i*-th element; C_b is the background content of the *i*-th element)

All parts of land plots where at least a moderately hazardous or hazardous level of technological contamination is determined must be conserved for a period determined by the persistence class of the substance, ranging from 3 to 10 years. If a smaller number of pollutants are detected but exceed the translocation hazard index, the land is considered to have limited suitability for agricultural use and requires a set of preventive measures to prevent product contamination. In such cases, if the area with a high content of toxicants is less than 50% of the land plot, only that specific part may be classified as technologically contaminated (DSTU 7243:2011, 2012).

Radial soil sampling for the determination of total petroleum hydrocarbons, PAHs (polycyclic aromatic hydrocarbons), and residual amounts of explosives was conducted in areas affected by battles involving burning machinery and fuel spills. Samples were collected following a modified scheme with distances of 1 m, 3 m, 5 m, 7 m, and 10 m from the local source of contamination. Laboratory analysis of the collected samples was performed using gas chromatography/mass spectrometry (GC/MS). The instrument used was a Hewlett Packard HP6890/5972A gas chromatograph equipped with a mass-selective detector. Component separation was carried out on an Rxi-5MS capillary column (5% diphenyl) with dimensions of 30 m×0.25 mm×0.25 μm. The chemical composition of the compounds was identified by comparing the obtained mass spectra with reference spectra from the Wiley 138 and NIST 02 electronic libraries.

During the investigation of organic pollutants in the community's soils, the content of 16 polycyclic aromatic hydrocarbons (PAHs) was determined. These included naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, chrysene, benzo[*ghi*]perylene, benzo[*a*]pyrene, benzo[*a*] anthracene, dibenzo[*a,h*]anthracene, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene, and indeno(1,2,3-*cd*)pyrene. Additionally, residues of explosives were analysed, encompassing four nitrotoluenes: 1,3-dinitrotoluene (DNT) benzene, 2methyl-1,3-dinitro-, 1,3-dinitrotoluene (DNT) benzene, 2-methyl-1,3-dinitro, 1,3,5trinitrotoluene (TNT), also known as trotyl. Furthermore, hexogen (1,3,5trinitro1,3,5*triazacyclohexane*, also known as cyclonite or RDX) and octogen (homocyclonite or HMX) were assessed.

RESULTS AND DISCUSSION

Military degradation of chernozems can manifest in various ways and degrees. Assessing the extent of military degradation was based on clearly defined parameters to avoid subjectivity. To unify approaches to determining degradation types and objectively assessing the degree caused by hostilities, scientists from the National Scientific Centre "Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky" have developed an improved system for classifying and assessing the degree of military degradation. A fragment of this system, which relates to the chemical degradation of soils, is presented in Table 1.

***Table 1**. Fragment of an improved system for classifying and assessing the degree of military degradation of soils based on indicators of chemical contamination with organic and inorganic compounds*

Type of degradation	Subtype	Form	Assessment indicator	Degree of degradation				
				Absent	Mild	Moderate	Severe	Catastrophic
Chemical	Military	Pollution by toxic inorganic substances	Total Hg content*, mg/kg	⩽ 1.0	1.1-2.1	2.2-4.1	4.2-6.2	⩾ 6.3
			Mobile Zn content*, mg/kg	⩽ 11.0	11.1-23.0	23.1-46.0	46.1-69.0	⩾ 69.1
			Mobile Mn content*, mg/kg	⩽ 50.0	50.1-100.0	100.1-200.0	200.1-300.0	⩾ 300.1
			Mobile Cu content*, mg/kg	⩽ 1.5	1.6-3.0	3.1-6.0	6.1-9.0	⩾ 9.1
			Mobile Co content*, mg/kg	⩽ 2.5	2.6-5.0	5.1-10.0	10.1-15.0	⩾ 15.1
			Mobile Pb content*, mg/kg	⩽ 3.0	3.1-6.0	6.1-12.0	12.1-18.0	⩾ 18.1
			Total Cd content, mg/kg	⩽ 3.0	3.1-5.0	5.1-7.0	7.1-10.0	⩾ 10.1
			Mobile Cd content, mg/kg	⩽ 0.35	0.36-0.7	0.7-1.4	1.5-2.0	⩾ 2.1
			Mobile Cr content, mg/kg	⩽ 3.0	3.1-6.0	6.1-12.0	12.1-18.0	⩾ 18.1
			Mobile Ni content, mg/kg	⩽ 2.0	2.1-4.0	4.1-8.0	8.0-12.0	⩾ 12.1

Table 1. Continued

Type of degradation	Subtype	Form	Assessment indicator	Degree of degradation				
				Absent	Mild	Moderate	Severe	Catastrophic
Chemical	Military	Pollution by toxic inorganic substances	Mobile W content, mg/kg	≤ 5.0	5.1-10.0	10.1-20.0	20.1-30.0	≥ 30.1
			Mobile F content, mg/kg	≤ 1.4	1.5-2.8	2.9-5.4	5.5-8.4	≥ 8.5
			Total As content, mg/kg	≤ 1.0	1.0-2.0	2.1-4.0	4.1-6.0	≥ 6.1
			Total Sb content, mg/kg	≤ 2.2	2.3-4.5	4.6-9.0	9.1-13.5	≥ 13.6
		Pollution by toxic organic substances	Benzo[*a*]pyrene content, mg/kg	≤ 0.01	0.011-0.020	0.021-0.040	0.040-0.060	≥ 0.061
			Benzene content, mg/kg	≤ 0.15	0.16-0.30	0.31-0.60	0.61-0.90	≥ 0.91
			Phenol content, mg/kg	≤ 2.0	2.1-4.0	4.1-8.0	8.0-12.0	≥ 12.1
			Formaldehyde content, mg/kg	≤ 3.5	3.6-7.0	7.1-14.0	14.1-21.0	≥ 21.0
			Toluene content, mg/kg	≤ 0.15	0.16-0.30	0.31-0.60	0.61-0.90	≥ 0.90
			Oil and petroleum product content*, mg/kg	≤ 2000.0	2000.1-4000.0	4000.1-8000.0	8000.1-12 000.0	≥ 12 000.1

Note: ** – regulatory references from DSTU 7872:2015 (2016)*
Source: *developed by the authors*

The systematic analysis of experimental data on heavy metal content in the soils of the community involved comparisons with the MPCs established by the Resolution of the Cabinet of Ministers of Ukraine, No. 1325 (2021). Additionally, the degree of soil contamination was assessed according to DSTU 7243:2011 (2012). This standard requires background levels of potential contaminants to be determined from samples collected at least 20 km from the pollution source or outside the visually defined area of local technogenic contamination. However, this standard was developed during the pre-war period, and the collection of background samples in de-occupied and/or conflict-affected areas remains subject to unresolved issues requiring further scientific investigation. These include challenges in systematising and classifying areas and determining the radius of potential contamination from explosions of munitions of various calibres. Under these circumstances, the most appropriate approach appears to involve using pre-war data on soil analysis as baseline or initial reference information. This ensures the use of reliable benchmarks while addressing current limitations in background sampling in post-conflict regions. For this purpose, during the study of community lands, the available data from the Soil Conservation Department on the survey of chernozem soils within the Grakivske experimental field for the content of heavy metals and microelements were summarised. The results of pre-war field studies, which included control plots as well as variants with the application of standard doses of macro-mineral and organic fertilisers for growing legumes and cereals (soybeans, wheat, barley), were processed. In total, the quantitative characteristics of 36 background soil samples were processed to determine average values for further research. The main statistical characteristics of the studied indicators are presented in Table 2. The results of the analytical testing of soil samples collected within the Chkalovsk territorial community in 2023 indicate that one year after the de-occupation of this area, the concentrations of heavy metals and trace elements do not exceed the maximum allowable limits and show no significant deviations from background levels. Moreover, the concentrations of mobile forms of toxicants such as Cd, Cr, and Ni, as well as essential elements like Mn and Cu, remain within the "minimum-maximum" range of pre-war background data from uncontaminated areas, accounting for analytical error (Table 2).

Table 2*. Statistical characteristics of heavy metal content in soils at the studied and background sites of the Chkalovsk territorial community*

Indicator	Mean	+95% Confidence interval	-95% Confidence interval	Standard deviation	Minimum	Maximum	Median	Standard error	MPC
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Cd content (demining)	0.04867	0.02885	0.06848	0.04692	0.00500	0.18900	0.04050	0.009578	0.7
Cd content (postdemining)	0.02171	0.01465	0.02878	0.02238	0.00080	0.08900	0.01270	0.003495	0.7
Cd content (background)	0.07867	0.05803	0.09930	0.05526	0.00000	0.19000	0.06000	0.010088	0.7
Cr content (demining)	0.09863	0.02522	0.17203	0.17383	0.00500	0.76200	0.02500	0.035483	6.0
Cr content (postdemining)	0.20491	0.14570	0.26413	0.18760	0.00280	0.65120	0.14210	0.029298	6.0

Table 2. Continued

Indicator	Mean	+95% Confidence interval	-95% Confidence interval	Standard deviation	Minimum	Maximum	Median	Standard error	MPC
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Cr content (background)	0.95133	0.70845	1.19421	0.65045	0.01000	2.35000	0.73000	0.118755	6.0
Ni content (demining)	0.51563	0.41636	0.61489	0.23508	0.14100	1.03700	0.46550	0.047986	4.0
Ni content (postdemining)	0.24932	0.18816	0.31048	0.19375	0.04810	0.79300	0.20520	0.030259	4.0
Ni content (background)	0.41033	0.31133	0.50933	0.26513	0.03000	1.00000	0.34500	0.048406	4.0
Pb content (demining)	1.54571	1.18340	1.90802	0.85802	0.06600	3.25000	1.61400	0.175143	6.0
Pb content (postdemining)	1.26701	1.02149	1.51253	0.77785	0.02880	2.85500	1.29200	0.121479	6.0
Pb content (background)	0.95133	0.70845	1.19421	0.65045	0.01000	2.35000	0.73000	0.118755	6.0
Co content (demining)	0.34321	0.25940	0.42702	0.19848	0.02400	0.78600	0.34550	0.040515	5.0
Co content (postdemining)	0.25129	0.18894	0.31363	0.19751	0.00300	1.02040	0.21450	0.030845	5.0
Co content (background)	0.27556	0.21799	0.33312	0.17013	0.01000	0.61000	0.25500	0.028356	5.0
Cu content (demining)	0.23333	0.16777	0.29890	0.15527	0.00200	0.61300	0.22300	0.031695	3.0
Cu content (postdemining)	0.22638	0.18296	0.26979	0.13756	0.01330	0.62200	0.20270	0.021483	3.0
Cu content (background)	0.23389	0.17844	0.28934	0.16389	0.01000	0.60000	0.23500	0.027314	3.0
Zn content (demining)	0.33825	0.19632	0.48018	0.33612	0.00400	1.58600	0.23550	0.068610	23.0
Zn content (postdemining)	0.49702	0.37159	0.62245	0.39739	0.00100	1.81250	0.47530	0.062062	23.0
Zn content (background)	0.13278	0.08616	0.17940	0.13779	0.01000	0.60000	0.08500	0.022965	23.0
Fe content (demining)	2.46000	2.14503	2.77497	0.74590	1.00800	4.58700	2.40650	0.152257	-
Fe content (postdemining)	1.82786	1.55574	2.09998	0.86212	0.83930	4.64900	1.55080	0.134641	-
Fe content (background)	0.84083	0.58559	1.09608	0.75437	0.12000	2.84000	0.55000	0.125729	-
Mn content (demining)	5.69392	4.64625	6.74159	2.48108	2.32000	12.53000	5.73800	0.506449	140.0
Mn content (postdemining)	5.56266	4.48113	6.64419	3.42647	1.19020	17.52200	4.31010	0.535124	140.0
Mn content (background)	30.56133	24.54379	36.57888	16.11529	10.51000	80.10000	26.92000	2.942235	140.0

Source: *developed by the authors*

During the research, concentration factors of elements in soil samples were determined as the ratio of actual to average background values (Table 3). Due to the absence of a threefold exceedance of background values for several heavy metals simultaneously, the overall soil pollution index Zc was not determined. For example, the concentration factors for Cd were only 0.01-2.36, Co – 0.01-3.6, Cr – 0.01-2.8; Cu – 0.01-2.7; Fe – 1.0-5.5; Mn – 0.05-0.67; Ni – 0.1-2.5; Pb – 0.033.4. Only for plant-available forms of Zn did they reach 12.0-13.9 in some cases, which is largely due to very low background concentrations of this element in the pre-war period. The low provision of soils with mobile zinc, which is often found on agricultural lands in the Kharkiv Region, is often a consequence of the presence of carbonates and increased concentrations of PO^{3-}_4 due to the application of phosphorus fertilisers.

***Table 3**. Concentration coefficients of heavy metals in the soils of the Chkalovsk territorial community, 2023*

Crop	**Concentration coefficients of heavy metals (AAB with pH 4.8)**								
	Cd	***Co***	***Cr***	***Cu***	***Fe***	***Mn***	***Ni***	***Pb***	***Zn***
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
weeds (demining)	0.61	1.84	2.8	1.2	1.9	0.1	0.8	1.2	1.3
weeds (demining)	0.06	1.02	0.1	0.3	3.2	0.2	1.1	1.0	0.4
arable land (demining)	0.06	0.3	0	1.4	3.5	0.4	0.3	1.7	2.4
barley (demining)	0.06	1.83	0.1	0.9	2.9	0.1	2.5	1.3	4.6
sunflower (demining)	0.13	2.81	0.3	0.5	2.6	0.2	0.8	0.1	3.4
weeds (demining)	0.06	1.19	0.1	1.6	3.0	0.1	0.7	2.2	3.9
sunflower (demining)	1.51	1.73	0.6	1.0	3.8	0.1	1.5	0.6	1.0
weeds (demining)	0.5	1.29	0	0.7	2.5	0.1	0.6	2.5	1.5
sunflower (demining)	0.06	1.3	0	0	4.0	0.1	2.4	2.3	2.4
arable land (demining)	0.51	2.17	0.1	2.1	2.7	0.5	1.2	1.9	1.2
arable land (demining)	0.9	1.28	0	0.4	4.0	0.4	1.4	1.9	5.0
arable land (demining)	0.19	2.08	0	1.0	3.6	0.3	1.1	2.3	1.7
arable land (demining)	1.35	0.98	0.1	0.7	2.2	0.2	1.1	2.2	3.7
sunflower (demining)	0.51	0.84	0.1	0.2	3.1	0.2	0.8	0.6	1.2
arable land (demining)	0.31	0.86	0.5	0.2	2.9	0.2	0.9	1.7	0.9
arable land (demining)	0.23	0.21	0.1	1.0	2.6	0.2	1.5	3.4	2.8
arable land (demining)	2.36	1.83	0.1	0.4	2.2	0.2	1.0	0.5	0.3
arable land (demining)	0.79	1.46	0.1	1.4	3.3	0.3	1.4	1.4	0
arable land (demining)	0.75	0.2	0.6	0.7	2.2	0.2	0.9	2.5	2.4
arable land (demining)	0.06	0.09	0.2	1.2	3	0.3	0.9	0.9	1.9
arable land (demining)	0.81	1.06	1.0	1.5	1.2	0.3	1.6	3.4	1.1
arable land (demining)	0.33	0.32	1.6	2.1	2.8	0.2	2.4	1.5	6.2
sunflower (demining)	1.21	1.88	0.1	2.7	5.5	0.3	1.6	1.9	12
arable land (demining)	1.23	0.87	0.2	1.3	1.7	0.2	1.6	0.2	0.8
sunflower (demining)	0.8	0.32	0	1.1	2.0	0.1	0.9	2.0	0
sunflower (demining)	0.11	0.01	0.1	0.7	1.5	0.2	0.9	2.0	1.1
sunflower (demining)	1.05	0.27	0	2.1	3.3	0.2	1.3	2.4	2.5
sunflower (demining)	0.58	1.83	0.8	1.1	5.5	0.7	1.7	1.4	9.8
sunflower (demining)	0.24	0.63	1.3	1.4	2.1	0.3	1.9	1.4	0.5
winter cereal (demining)	0.26	1.09	1.6	0.6	3.7	0.3	0.4	0.5	0.7
arable land (demining)	0.01	1.62	1.1	0.5	1.8	0.4	0.5	0.6	5.9
maize	1.11	1.82	0.8	2.7	3.3	0.2	0.7	3.0	2.6
maize	0.06	1.11	0.6	2.3	2.5	0.1	0.5	1.4	2.9
maize	0.76	0.45	0.5	1.1	2.7	0.2	1.7	2.6	1.3
maize	0.24	0.23	0.3	0.5	2.0	0.2	0.5	0.1	4.1
arable land after sunflower	0.37	0.78	1.5	0.4	1.7	0.3	0.5	2.7	5.7
winter cereal	0.05	1.26	0.1	0.8	1.9	0.2	0.8	0.3	0.6

Table 3. Continued

Crop	Concentration coefficients of heavy metals (AAB with pH 4.8)								
	Cd	***Co***	***Cr***	***Cu***	***Fe***	***Mn***	***Ni***	***Pb***	***Zn***
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
sunflower	0.3	0.77	0	1.0	3.3	0.2	0.5	1.6	2.3
maize	0.06	0.15	0.4	0.4	1.7	0.1	0.3	1.8	3.9
sunflower	0.39	1.33	0.4	0.9	1.7	0.1	0.1	0.3	6.2
arable land	0.59	0.1	0.4	0.1	2.0	0.3	0.1	2.7	5.0
arable land	0.06	1.46	0.7	0.4	1.6	0.2	0.1	0.6	4.7
arable land after sunflower	0.06	1.18	1.7	0.5	1.6	0.5	0.3	0.7	3.7
arable land after sunflower	0.35	1.25	0.5	1.4	1.8	0.3	0.5	1.5	0.4
sunflower	0.06	0.41	0.2	0.5	2.1	0.2	0.2	2.3	1.0
arable land	0.45	1.46	0.7	0.7	1.6	0.3	0.1	2.8	4.2
winter arable land	0.22	0.15	0.5	1.0	1.4	0.1	0.5	0.2	14.0
sunflower	0.06	1.55	0.2	0.4	1.4	0.2	0.3	1.1	12.0
sunflower	0.06	1.46	0.2	1.3	1.5	0.2	0.5	1.8	2.0
winter arable land	0.06	0.5	2.1	1.7	1.1	0.2	0.2	0.5	3.6
maize	0.06	0.71	0.4	1.2	1.9	0	0.9	1.3	3.9
sunflower	0.16	0.49	0	0.9	1.8	0.1	0.7	1.7	1.5
winter arable land	0.48	1.04	2.0	0.9	3.0	0.2	0.1	1.1	8.4
sunflower	0.45	0.06	1.8	1.3	3.2	0.1	0.5	1.0	4.1
sunflower	0.06	0.15	0	0.2	3.1	0.2	0.9	1.2	4.4
maize	0.06	0.76	0.1	1.4	1.7	0.1	0.1	1.5	3.1
maize	0.06	0.96	0.7	1.7	5.5	0.1	0.7	2	2.7
arable land	0.01	0.33	0	1.6	2	0.6	0.2	1.1	4.1
sunflower	0.13	0.67	1.5	0.1	1.6	0.2	0.6	1.4	0.5
sunflower	0.06	1.59	0.4	0.8	1.5	0.1	1.6	0.6	1.5
sunflower	0.25	3.64	2.2	0.1	1.6	0.1	1.1	1.3	7.0
sunflower stubble	0.06	1.47	2.4	1.3	1.2	0.3	0.7	1.4	0.5
sunflower	0.33	1.27	0.8	0.8	2.3	0.1	0.4	0	4.1
sunflower	0.06	0.33	1.4	1.6	1.0	0.1	0.3	0	5.5
arable land	0.51	0.15	0.6	0.7	1.0	0.1	0.1	0.6	5.4
Average (demining)	*0.62*	*1.25*	*0.1*	*1*	*2.9*	*0.2*	*1.3*	*1.6*	*2.5*
Average (post-demining)	*0.28*	*0.91*	*0.2*	*1*	*2.2*	*0.2*	*0.6*	*1.3*	*3.7*

Source: *developed by the authors*

A clearer understanding of the changes in the ecological and toxicological state of soils in such areas can be obtained through statistical processing of point information without prior averaging (Table 2, Fig. 2). Under these conditions, the difference between the content of mobile forms of pollutants in soils before the war and after de-occupation is significantly smaller. In particular, in recently demined areas of this de-occupied territory, there is a tendency towards a slight increase in the content of lead (by 1.4 times), cobalt (1.3 times), iron (1.6 times) and zinc (2.6 times) relative to the pre-war (background) content. Such excesses are not considered critical for agriculture and do not require land conservation or the application of overly complex and costly soil remediation measures.

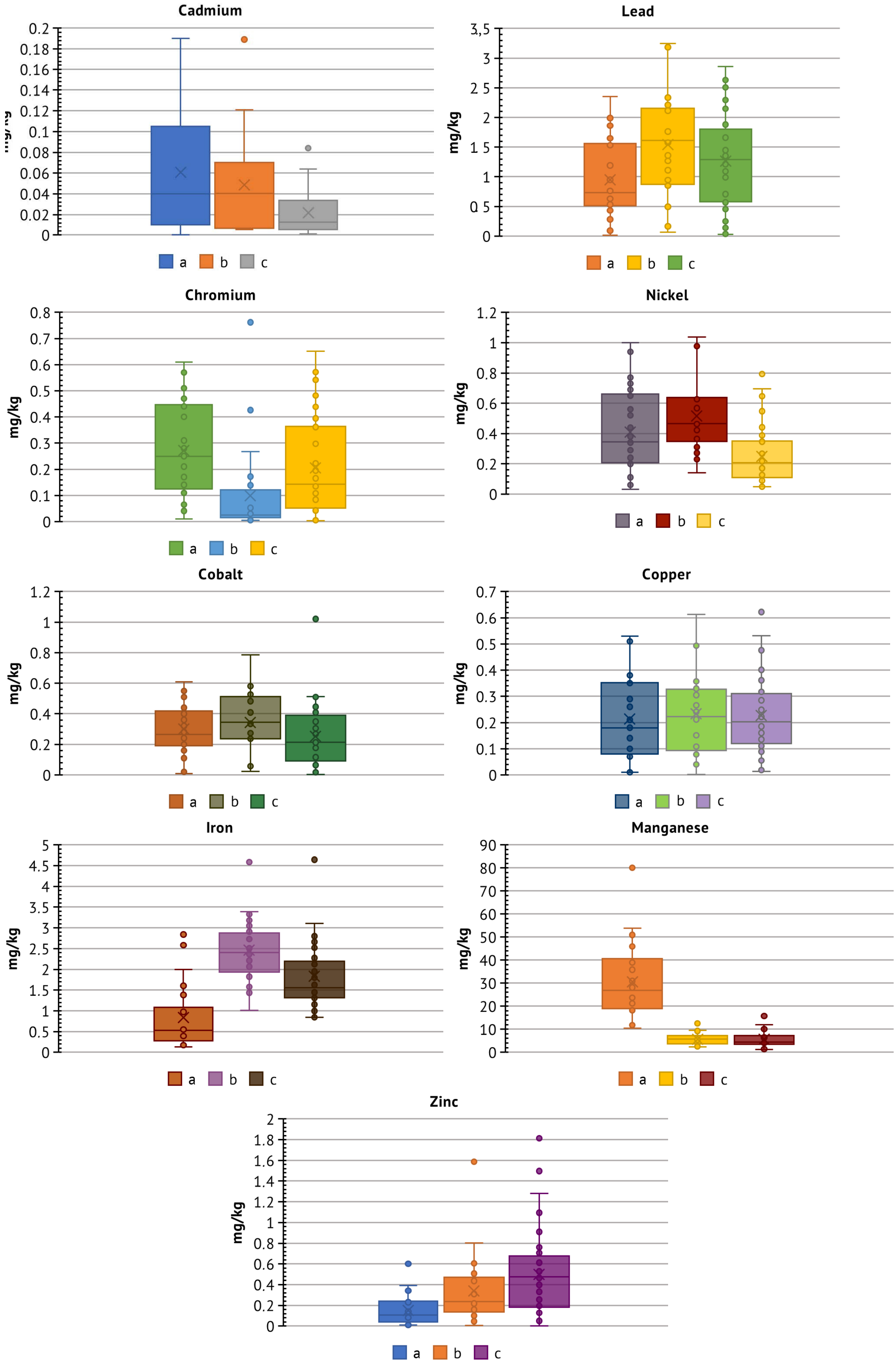

Figure 2. *Dynamics of mobile forms of heavy metals and microelements in soils of the Chkalovsk territorial community*
Note: *a) recent demining; b) a few months after demining (in agricultural production); c) background content (prewar data)*
Source: *developed by the authors*

Both the statistical characteristics (Table 2) and graphical representations (Fig. 2) reveal a certain difference in the content of heavy metals and microelements between soils that were demined beforehand and are already used in agricultural production, and those where demining occurred recently. Over time, after demining, a slight decrease in the content of mobile cadmium, lead, nickel, cobalt, and iron can be observed, accompanied by an increase in the amount of plantavailable chromium and zinc. The concentrations of bioavailable forms of manganese and copper have remained almost unchanged during this time. The observed changes may also indicate ongoing processes of self-restoration of chernozem soils, which are typically characterised by high buffering capacity concerning heavy metals. It should be noted separately that the content of petroleum products in the collected soil samples a few months after the hostilities was quite low and ranged from 2.6 to 23.2 mg/kg of soil, which is significantly less than the maximum permissible concentration for agricultural land – 500 mg/kg of soil (Table 4).

***Table 4**. Content of petroleum products in soils at the site of fuel spill and tanker fire*

No.	Sampling location	Petroleum product content, mg/kg
1	Tanker, soil layer 0-30 cm	20.6
2	Tanker, soil layer 30-60 cm	20.8
3	Tanker, 1 m (azimuth 1), layer 0-30 cm	16.8
4	Tanker, 1 m (azimuth 1), layer 30-60 cm	13.2
5	Tanker, 1 m (azimuth 2), layer 0-30 cm	22.8
6	Tanker, 1 m (azimuth 2), layer 30-60 cm	2.6
7	Tanker, 3 m (azimuth 1), layer 0-30 cm	15.2
8	Tanker, 3 m (azimuth 1), layer 30-60 cm	12.0
9	Tanker, 3 m (azimuth 2), layer 0-30 cm	18.4
10	Tanker, 3 m (azimuth 2), layer 30-60 cm	23.2
11	Tanker, 5 m (azimuth 1), layer 0-30 cm	12.0
12	Tanker, 5 m (azimuth 1), layer 30-60 cm	15.4
13	Tanker, 5 m (azimuth 2), layer 0-30 cm	14.0
14	Tanker, 5 m (azimuth 2), layer 30-60 cm	12.3
15	Tanker, 7 m (azimuth 1), layer 0-30 cm	21.8
16	Tanker, 7 m (azimuth 1), layer 30-60 cm	16.2
17	Tanker, 7 m (azimuth 2), layer 0-30 cm	13.2

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

The results obtained indicate very low concentrations of all polycyclic aromatic hydrocarbons, explosives, and related nitroaromatic compounds in the analysed soils (Table 4). The content of these substances in all analysed soil samples was below the method's detection limit (<0.002 for polycyclic aromatic hydrocarbons and <0.005 for explosives and their metabolites), indicating their practical absence. Considering the obtained data from 2023 in the context of providing soils of the Chkalovsk territorial community with physiologically necessary microelements, it can be noted that the soils are very low in zinc (even for low-demanding crops) and have insufficient levels of available copper and manganese for high-demanding crops. The low content of microelements indicates the need for the application of micronutrients, which not only significantly increases crop yields but also becomes an important factor in improving their micronutrient composition.

Returning to the issue of soil contamination risks in the community, it should be noted that the ranges of heavy metal content variations in soils, as well as in geological formations, are typically quite broad due to their natural variability. Narrowing the range of variability of background values to a minimum during their combination/averaging leads to obtaining significantly higher concentration factors for heavy metals than when operating with a full sample of initial background data. In general, to classify land as technogenically contaminated, the content of a substance polluting the soil must exceed the MPC and be three times higher than the background content. Since none of the soil samples analysed in 2023 contained heavy metals in the specified concentrations, it can be stated that, according to DSTU 7243:2011 (2012), the surveyed soils in the community cannot be considered technogenically contaminated. However, full conclusions about the ecological state of soils in terms of heavy metal content in the community require additional information on the content of heavy metals in soils of other land plots and test plants from various agricultural crops.

The likely reasons for such low concentrations of hydrocarbons could include the burning of petroleum products during the tanker fire, the reduction of light hydrocarbon fractions due to their high volatility (which increases with temperature), and possible leaching down the soil profile during rainfall events.

The intensity of contamination by these substances is significantly influenced by the detonation level of munitions, i.e., the amount of explosive that burns during the explosion and the amount that remains in the soil.

Furthermore, as previously noted by S. Baliuk *et al.* (2024), complex chemical compounds, such as explosives, can undergo partial decomposition on the soil surface through processes like photolysis and hydrolysis, be adsorbed by the soil, or leach into groundwater and surface water sources along with atmospheric precipitation. The rate and extent of migration and transformation of explosives are influenced by the physicochemical properties of these compounds (e.g., solubility, vapour pressure, Henry's law constant), environmental factors (weather conditions), soil characteristics (including pH, redox status), and biological factors (populations of microorganisms that degrade explosives). The processes affecting the fate of explosives in the environment can be divided into two groups: a) influence on migration and sorption (dissolution, evaporation, adsorption); b) influence on transformation (photolysis, hydrolysis, reduction, and biodegradation).

The most well-known and widely used explosives found in military munitions that remain in soils after incomplete detonation of projectiles are trinitrotoluene (TNT), hexogen (RDX), and octogen (HMX), as well as their transformation products (1,3-DNT, 2,4-DNT, 2,6-DNT, 4-DNT, MNX, DNX, TNX), which are toxic to humans and other organisms. Additionally, according to J. Pichtel (2012) and B. Heerspink *et al.* (2017), soils in combat zones are contaminated with residues of primary (initiating) explosives and propellants containing low-explosive materials that propel rockets or accelerate projectiles from guns, as well as a wide range of associated organic and mineral pollutants from munitions and equipment, with heavy metals, polycyclic aromatic hydrocarbons, and other petroleum products being the primary ones. Notably, the adsorption processes of TNT, RDX, HMX, 2,4-DNT, DNAN, and their metabolites are significantly dependent on hydro-thermal conditions (precipitation and temperature), granulometric composition (especially the content of clay minerals), the quantity and fractional composition of humus, the content of exchangeable cations (especially K^+ and NH^{4+}), and the number of functional groups in nitroaromatic compounds (Brannon & Pennington, 2002; Qin *et al.*, 2021).

According to S. Baliuk *et al.* (2022), a survey of soils conducted in spring 2022 in areas of active hostilities in the Kharkiv Region revealed elevated levels of heavy metals such as nickel (1.34.0 clarks), copper (1.4-12.8 clarks), chromium (1.2-3.4 clarks), cadmium (2-18 clarks), and lead (2.6-22 clarks) compared to background levels. A significant portion of the aforementioned toxicants, including elements like cadmium, lead, nickel, and chromium, as well as organic pollutants such as formaldehyde, nitrotoluenes, and polycyclic aromatic hydrocarbons, are classified as dangerous carcinogens for humans and animals, causing irreversible changes or damage to the parts of the genetic apparatus that control somatic cells. As land is the primary means of agricultural production, some of these substances can accumulate in commercial plant products, posing a health risk to consumers.

A particular problem is the high mobility of certain chemical elements and organic compounds (especially hexogen) and their transformation products in soils, which, according to A. Lorenz *et al.* (2013), lead to further contamination of groundwater and pose a threat to the drinking water supply for the population. Based on the results of environmental monitoring studies in the Kharkiv District of the Kharkiv Region in autumn 2022 and their comparison with data from 20182021, specialists from the National Scientific Centre "Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky" noted unusually high concentrations (above the MPC) of cadmium, chromium, and lead in groundwater and surface water in the surveyed area due to their migration from the soil environment under the influence of prolonged precipitation.

In a study by O. Datsko *et al.* (2024) analysing the impact of aerial bombings on agricultural land in Sumy and Chernihiv regions, it was found that these soils were not always contaminated with heavy metals such as barium, zirconium, rubidium, zinc, and vanadium. The content of barium, zirconium, and manganese on crater slopes did not show a clear increase compared to control areas. Strontium, rubidium, and zinc did not always demonstrate excess in craters. According to M. Solokha *et al.* (2023), an increase in the content of heavy metals (manganese, iron, cobalt, copper, cadmium, chromium, lead, and nickel) was found in soils subjected to bombing compared to areas that were not bombed. Subsequently, M. Solokha *et al.* (2024) established that fragments of destroyed military equipment, ammunition, and fuel residues lead to soil contamination, with the highest levels of contamination recorded for Pb, Zn, and Cd; the contamination distribution was as follows: Pb > Zn > Cd > Cu. According to K. Petrushka *et al.* (2024), as a result of rocket attacks, all soil samples in the Lviv Region showed a significant excess of the MPC of titanium, zinc, lead, and nickel. A cumulative assessment of the impact of all elements on the environment showed significant contamination of the study area.

However, the conclusions of the current study do not entirely align with the following research. I. Bulba *et al.* (2024) found that in Dnipropetrovsk Region, as a result of hostilities, soil contamination with lead exceeded the MPC by 3 times, and with fluorine by 1.5 times; in Mykolaiv Region, the lead content in the soil exceeded the MPC by 5 times, the content of zinc, copper, fluorine, and petroleum products by 25%; in Zaporizhzhia Region, the lead content exceeded the MPC by 11.2 times, the content of zinc, fluorine increased by 50%, petroleum products by 35%, and phosphates by

30%. According to O. Shebanina *et al.* (2023), the illegal disposal of chemical waste and active hostilities led to significant contamination of soils with heavy metals and petroleum products: in Kharkiv Region, cadmium contamination increased by 200%; in Kherson and Zaporizhzhia regions, an increase in oil spills of 139% and 156% was recorded. Differences in the results regarding soil contamination with heavy metals are likely related to different types of military impacts (bombing, rocket attacks, fragments of destroyed equipment, etc.), different soils, and other spatiotemporal factors. For example, in the study of G. Trokhymenko *et al.* (2023), it was established that loams and chernozems are more prone to the accumulation of heavy metals than sandy soils. In loam, the rate of metal release decreases from 16.7% to 69.7% compared to sandy soil; in comparison of chernozem to loam, this rate slows down from 17.85% to 32.08%. At the same time, the rate of spread of barium, cobalt, arsenic, lead, mercury, manganese, strontium, and titanium does not depend on the type and mechanical parameters of the soil.

The observed changes may also indicate the occurrence of self-recovery processes in chernozem soils, which are typically characterised by high buffering capacity, especially concerning heavy metals. The obtained results also confirm that a significant portion of chernozem soils in former combat zones may undergo restoration without the application of costly remediation measures, which has a significant positive impact on the development of agriculture in such regions and the preservation of the country's export potential.

CONCLUSIONS

This study assessed the ecological and toxicological state of militarily degraded chernozems using the Chkalovsk territorial community in the Chuhuiv District of Kharkiv Region as an example. An improved system for classifying and assessing the degree of military degradation of soils has been proposed, focusing on indicators of chemical contamination by organic and inorganic compounds. This system is recommended for comprehensive assessments of the ecological and toxicological state of soil cover.

The results of the study indicate that the military degradation of soils in the Chkalovsk territorial community is more associated with physical damage, such as bomb craters than with chemical contamination of soils. It was found that in recently demined areas of the de-occupied territory, there is a tendency for a slight increase in the content of lead (by 1.4 times), cobalt (1.3 times), iron (1.6 times), and zinc (2.6 times) relative to the pre-war (background) content. However, such excesses are not critical for agriculture, therefore, the examined chernozems in the community cannot be considered technogenically (chemically) contaminated, neither according to the comparison with the maximum permissible concentrations (MPC) established by the current Resolution of the Cabinet of Ministers of Ukraine, No. 1325 dated 15 December 2021, nor according to the requirements of DSTU 7243:2011, nor according to the gradations of the improved system for classifying and assessing the degree of military degradation of soils.

Some time after demining, a slight decrease in the content of mobile cadmium, lead, nickel, cobalt, and iron was recorded on average, with an increase in the amount of chromium and zinc available to plants. The concentrations of bioavailable forms of manganese and copper remained almost unchanged during this period. The observed changes may also indicate the occurrence of self-recovery processes in chernozem soils, which are typically characterised by high buffering capacity concerning heavy metals without the application of expensive remediation measures. The obtained data allow for a positive assessment of the future potential of agricultural production on chernozem soils in combat zones. For a comprehensive assessment of the ecological state of soils in terms of heavy metal content in the community, additional information is needed on the content of heavy metals in soils of other land plots and test plants from various crops. This could be one of the promising directions of research.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Еколого-токсикологічний стан мілітарно деградованих чорноземів: кейс Чкаловської територіальної громади

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Анотація. Метою цього дослідження було оцінювання еколого-токсикологічного стану мілітарно деградованих чорноземів на прикладі Чкаловської територіальної громади Чугуївського району Харківської області. Для цього було передбачено провести детальне комплексне обстеження еколого-токсикологічного стану чорноземних ґрунтів Чкаловської територіальної громади, постраждалих унаслідок воєнних дій і визначити придатність обстежених ґрунтів для ведення сільського господарства та, за необхідності, запропонувати заходи з ремедіації забруднених ґрунтів. Запропоновано удосконалену систему класифікації та оцінювання ступеня мілітарної деградації ґрунтів у частині показників хімічного забруднення органічними та неорганічними сполуками. Установлено, що на нещодавно розмінованих ділянках деокупованої території відмічається тенденція незначного збільшення вмісту плюмбуму (у 1,4 рази), кобальту (1,3 рази), заліза (1,6 рази) і цинку (2,6 рази) відносно довоєнного (фонового) вмісту. Однак такі перевищення не є критичними для ведення сільського господарства, і не потребують консервації земель або застосування надскладних і дороговартісних заходів з очищення ґрунтів. Через деякий час після розмінування в середньому зафіксовано незначне зменшення вмісту рухомого кадмію, плюмбуму, нікелю, кобальту і феруму за збільшення кількості доступних рослинам хрому й цинку. Концентрації біодоступних форм мангану та купруму за цей час майже не змінилися. Визначені зміни можуть також свідчити про протікання процесів самовідновлення чорноземних ґрунтів, які зазвичай характеризуються високою буферністю щодо важких металів. Одержані результати свідчать про дуже низькі концентрації усіх поліароматичних вуглеводнів і вибухонебезпечних речовин та споріднених нітроароматичних сполук у досліджених ґрунтах. Результати дослідження можуть бути використані під час розробки програми післявоєнного відновлення ґрунтів і раціонального використання земель в аграрному виробництві

Ключові слова: забруднення ґрунтів; екологічна безпека; російсько-українська війна; важкі метали; нафтопродукти; мілітарна деградація ґрунтів; аграрне виробництво

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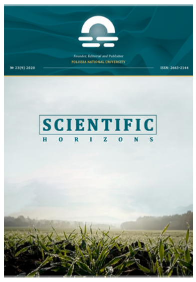

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Agrolandscapes and their role in ensuring environmental safety

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Abstract. The purpose of the study was to analyse in depth the role of agrolandscapes in ensuring environmental safety and to investigate their impact on the environment, with a special emphasis on aspects of biodiversity, soil protection, and water management. The study covered a wide range of activities, including the collection and systematisation of scientific materials, a comparative analysis of different management approaches, and the development of a theoretical model of environmental safety that allows assessing the effectiveness of existing practices. The main results of the study indicated that agrolandscapes characterised by a high level of integration of

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natural elements and agricultural components can provide a significantly higher level of biodiversity compared to less integrated counterparts. In particular, forest and forest-steppe agrolandscapes have proven to be the most effective in conserving species, which is critical for maintaining ecological balance. However, steppe and dry steppe landscapes require urgent and comprehensive measures to improve the state of biodiversity, as their ecological sustainability is under threat. Thus, the results of the study emphasised the need to introduce innovative approaches to agrolandscape management that can contribute to the conservation of natural resources and improve environmental safety. The developed theoretical model revealed that the most sustainable agrolandscapes are those where natural ecosystems are harmoniously combined with agricultural land. The results confirmed the hypothesis that effective management of agrolandscapes contributes to improving environmental safety and reducing negative environmental impacts, in particular, by controlling erosion and managing water resources. The conclusions emphasised the need to implement agroforestry, support environmental approaches in policies and a system of monitoring the state of agrolandscapes for the sustainable development of agricultural regions, which would facilitate adaptation to the challenges of climate change

Keywords: ecological safety; biosafety; life safety; agrolandscapes; soil cultivation; fertilisers

INTRODUCTION

Ensuring environmental safety has become a priority in the context of global environmental challenges such as climate change, land degradation, loss of biodiversity, and increasing anthropogenic pressure on natural resources. In the context of intensive agricultural use of land, maintaining the ecological stability of agrolandscapes has become critical. Agrolandscapes that combine elements of natural ecosystems with agricultural activities have played a key role in maintaining environmental stability. They had the potential to contribute to the conservation of biodiversity, protect soils from erosion, and ensure the rational use of water resources. However, improperly organised management of agrolandscapes could worsen the state of ecosystems, reduce their sustainability, and create risks to environmental safety.

The relevance of this study was determined by the need to determine how different types of agrolandscapes, such as arable land, pastures, orchards, vineyards, etc., affect key components of environmental safety. The purpose of the study was to assess the impact of agrolandscapes on the environment and analyse how their use can contribute or, conversely, negatively affect the conservation of biodiversity, soil quality, water resources, and the overall state of ecosystems. This study is an important step in the development of strategies for sustainable management of agricultural territories, which would ensure a balance between the production of agricultural products and the preservation of environmental safety.

There are a number of problems in the field of agrolandscapes that have already attracted the attention of researchers. For example, R. Plokhikh *et al.* (2023) investigated the impact of various agrolandscapes on environmental sustainability and found that an integrated approach to managing such landscapes can significantly improve their ecosystem functions. Analyses performed by D.D. Burra *et al.* (2021) pointed out a strong link between restoring ecological balance in African agrolandscapes and improving public health. This demonstrates the importance of agrolandscapes for the conservation of biodiversity and for the social and economic aspects of life. Restoring ecosystems can lead to improved access to clean water, increased agricultural productivity, and the overall well-being of the population (Floqi *et al.*, 2009). Thus, effective management of agrolandscapes is critical to ensuring sustainable development and improving the quality of life in communities. However, there are gaps in understanding the relationships between different types of agrolandscapes and their impact on biodiversity conservation, soil and water protection. I. Myskovets *et al.* (2024) investigated the impact of agroforestry on the structure of forest ecosystems, but did not sufficiently consider the elements of integrating agronomic and environmental practices. The importance of water management was emphasised by L. Kuzmych (2024), who stated that effective soil and water management practices are critical to ensuring food security. The study by M.A. Altieri *et al.* (2024) emphasised the need to develop a strategy for designing sustainable agroecosystems, but did not cover all aspects related to environmental safety. In addition, Z. Mustafayev *et al.* (2024) improved the methodology for assessing the agricultural resource potential of agrolandscapes, but insufficient attention was paid to specific ecological and economic indicators that are necessary to ensure their effectiveness.

Despite numerous studies, the complex relationships between different types of agrolandscapes and their impact on biodiversity conservation, soil and water resources protection remained poorly understood. Existing approaches often focused only on individual aspects, without considering the interaction between environmental safety components. This created the need to develop more holistic models for managing agrolandscapes, which would simultaneously increase productivity and ensure environmental sustainability. This study examined the impact of various types of agrolandscapes on environmental safety, in particular, their role in biodiversity conservation, soil protection, and efficient use of water resources. The main goal of the study was to determine the best approaches to managing agrolandscapes that would contribute to ensuring environmental safety and minimise the risks of degradation. The study also tested the hypothesis that an integrated approach to managing agrolandscapes, considering their type and specific impact on environmental resources, would contribute to improving ecosystem functions and the sustainability of natural processes. The study offers recommendations for implementing integrated management practices that would ensure a balance between agricultural productivity and environmental safety.

As a result, this study has helped to develop recommendations for farmers, agronomists and policy makers to implement sustainable agrolandscape management practices. The established links between different types of agrolandscapes and environmental safety contributed to a better understanding of ecosystem functions, which allowed the authors to develop more effective strategies for ensuring sustainable agricultural development in the face of modern environmental challenges.

MATERIALS AND METHODS

This study was conducted from June to September 2024 and was based on an analysis of scientific literature and theoretical approaches describing the interaction of agrolandscapes with the natural environment. The study covered several stages: collection and systematisation of scientific materials, comparative analysis of approaches to managing agrolandscapes, development of theoretical models of environmental safety and identification of gaps in scientific literature. The study used comparative analysis to investigate approaches to managing agrolandscapes in various climatic conditions, in particular, in steppe, forest, and dry steppe regions. The analysis focused on key factors affecting environmental safety: controlling erosion processes and soil degradation, maintaining water balance and regulating water flows, and promoting the conservation of native plant and animal species. This approach helped to determine the best ways to manage landscapes for each natural and climatic zone, ensuring long-term environmental safety.

The study systematised data on key ecosystem services provided by agrolandscapes. Special attention was paid to three aspects: biodiversity conservation, erosion control and soil protection, and water resources management. Biodiversity conservation has been studied through the combination of agricultural land with natural ecosystems, which contributes to the restoration of ecological balance. In terms of soil protection, the role of forest belts and agroforestry, which reduce erosion processes and increase soil fertility, was analysed. Water management has been studied through agrotechnical measures aimed at reducing the risks of flooding and droughts, in particular, by introducing water-retaining elements in landscapes. Such approaches contribute to environmental stability and increase the adaptability of agricultural systems to climate change. Based on the conducted comparative analysis and generalisation of data, a theoretical model was developed that reflected the relationship between the components of agrolandscapes and their impact on environmental safety. The model considered such variables as the type of agrolandscape (forest, forest-steppe, steppe, dry steppe), the level of integration of natural and agricultural elements, and ecosystem services that ensure the stability and balance of the landscape. This helped to assess how the interaction of these components contributes to biodiversity conservation, erosion control, increased soil fertility, and effective water management. The model demonstrated that agrolandscapes with a high level of integration of natural and anthropogenic elements are more resistant to environmental challenges and better perform the functions of environmental protection.

The study also involved regulatory documents governing the use of agrolandscapes to ensure environmental safety, in particular: Law of Ukraine No. 2775-IX "On Environmental Protection" (1991), Law of Ukraine No. 2973-IX "On Amendments to Certain Legislative Acts of Ukraine on the State System of Environmental Monitoring, Information on the State of the Environment (Environmental Information) and Information Support for Environmental Management" (2023, March). The study followed the standards of Convention on Biological Diversity (CBD) (1992) and Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973, March). An integrated approach was used, which included an analysis of ecosystem services of agrolandscapes and an assessment of their impact on biodiversity conservation, soil protection and water resources management. This provided a comprehensive understanding of the role of agrolandscapes in enhancing environmental security and helped to identify the best methods of integrating natural and agricultural elements for the long-term sustainability of agricultural systems.

RESULTS

The study showed that agrolandscapes have a significant impact on the environmental safety of regions. This is conditioned by their ability to maintain biodiversity, maintain soil fertility, and manage water resources. Different types of agrolandscapes, such as forest, forest-steppe, steppe, and dry steppe, show different levels of ecological sustainability depending on the integration of natural and anthropogenic elements.

Forest agrolandscapes are among the most biodiversity-rich ecosystems, which are of great importance for preserving natural resources and maintaining ecological balance (Yanitskyi, 2024). They provide numerous ecosystem services, including habitat for many species of flora and fauna, especially rare and endangered ones, making them important for preserving biological diversity. The presence of diverse microenvironments in forests, such as wetlands, oak groves, and coniferous forests, contributes to the development of ecological niches, which increases overall species diversity. Forests also play a critical role in climate regulation, because they absorb carbon dioxide, reducing the greenhouse effect and helping to reduce global warming. They affect the local climate by providing shade, lowering temperatures, and regulating humidity. Tree roots retain moisture in the soil, which prevents erosion and improves water quality, supporting the health of ecosystems. These functions of forests are important for the natural environment and for human well-being, as they provide clean water, air, and resources for life.

Forest-steppe agrolandscapes that combine elements of forests and steppes create unique and favourable conditions for the existence of a greater variety of flora and fauna species. These agrolandscapes support a much larger number of species than their purely steppe or forest counterparts, due to the presence of various ecological niches and resources. They provide optimal conditions for the existence of pollinators such as bees, which play a critical role in the pollination processes of plants, which, in turn, is indispensable for the successful development of agriculture. Forest-steppe agrolandscapes show higher adaptability to climate change. This is conditioned by the diversity of vegetation that can withstand different climatic conditions, and the availability of more available resources, such as water and nutrients. Because of this, forest steppes can be more resilient to extreme weather events, making them important for food security and biodiversity conservation in the face of global climate change.

Steppe agrolandscapes, despite their high productivity, show increased vulnerability to erosion processes and ecosystem degradation. These territories can provide significant yields of agricultural crops due to optimal conditions for plant growth. However, overexploitation of land caused by intensive agriculture can lead to severe depletion of natural resources such as soil and water (Gavkalova *et al.*, 2024). Without proper management and implementation of sustainable agronomic practices, steppe landscapes face numerous problems, in particular, erosion. Vegetation cover, which performs an important function of soil retention, can be destroyed due to irrational use of land, which leads to further deterioration of soil quality and a decrease in their fertility. Although these agrolandscapes have some adaptation to arid conditions, constant climate changes, including rising temperatures and changes in precipitation patterns, endanger their stability and productivity. Therefore, it is important to take steps to preserve these valuable ecosystems by implementing sustainable development strategies that will help preserve their fertility and environmental value.

Dry steppe agrolandscapes, for their part, face serious challenges related to water scarcity, which is one of the key problems for the sustainable development of agriculture in these regions. Water scarcity not only limits the diversity of species, but also significantly affects the overall productivity of agricultural systems, which can lead to reduced yields and economic losses for farmers. Adaptive strategies are required to preserve biodiversity in these challenging environments, such as introducing water-retaining elements, which may include irrigation systems, the use of mulch, and the choice of crops that require less water. Although these agrolandscapes may contain adapted plant and animal species, their abundance and diversity are usually limited, making them vulnerable to climate change and other environmental stresses. Therefore, it is important to develop and implement comprehensive natural resource management programmes that will contribute to the conservation of biodiversity and increase the resilience of agrolandscapes to water scarcity. The main results related to the impact of agrolandscapes on biodiversity are presented in Table 1, which demonstrates species diversity, conservation levels, and key ecosystem services for each type of agrolandscape. This provides a comprehensive view of their contribution to environmental sustainability and importance for the conservation of natural resources.

***Table 1**. Impact of different types of agrolandscapes on biodiversity*

Type of agrolandscape	Number of plant species	Number of animal species	Species conservation level	Basic ecosystem services	Management features
Forest	200+	100+	85%	Biodiversity support, air purification, water storage	Forest conservation, agroforestry
Forest-steppe	150+	80+	75%	Promotion of diversity, control of erosion	Integration of natural elements
Steppe	100+	50+	50%	High performance but low stability	Measures to reduce erosion
Dry steppe	80+	30+	40%	Adaptation to dry conditions, limited diversity	Water resources management

***Source:** created by the authors based on T. S. Priyadarshana et al. (2024)*

In general, agrolandscapes with a high level of integration of natural elements provide significantly higher levels of biodiversity than their less integrated counterparts. Forest and forest-steppe agrolandscapes show the greatest efficiency in species conservation, while steppe and dry steppe landscapes require urgent measures to improve the state of biodiversity. These data highlight the need for active management of agrolandscapes to maintain environmental sustainability. Agrolandscapes play an important role in providing a range of ecosystem services that contribute to maintaining ecological balance and sustainable agricultural development. One of the key ecosystem services is soil conservation and erosion control, which is crucial for long-term farming. Data analysis shows that agrolandscapes that integrate natural elements such as forest belts and watersheds show significant advantages in controlling erosion.

Firstly, the use of forest belts in agrolandscapes is an effective method for reducing the rate of wind and water erosion. Forest belts located along the fields serve as natural barriers that hold the soil in place, preventing it from leaching out. This approach not only preserves soil fertility, but also contributes to the preservation of biodiversity, because it creates conditions for the existence of various plant and animal species. Secondly, agroforestry is an important tool for integrating trees and shrubs into agricultural land. It improves the structure of the soil and increases its fertility, and helps to retain moisture. Studies show that in the regions where these methods are used, there is a significant reduction in erosion processes, which makes agricultural systems more resistant to climate change. In addition, contour treatment is another effective method that helps reduce surface water runoff. This method consists of cultivating the soil along the contours of the field, which allows retaining moisture in the soil and reduces the loss of fertility. This is especially important in areas with heavy rainfall, where the risk of erosion is high. It is also important to introduce water-retaining elements, such as terracing and irrigation systems. These methods help to control the water balance in agrolandscapes, preventing both flooding and droughts. Effective water management contributes to the sustainable development of agricultural systems by improving their productivity and reducing the risks associated with climate change (Table 2).

***Table 2**. Basic methods of soil conservation and erosion control in agrolandscapes*

Method	Description	Advantages
Forest belts	Planting of trees along the fields	Reduction of wind and water erosion
Agroforestry	Integration of forest elements into agricultural systems	Improve fertility and moisture retention
Contour processing	Tillage along field contours	Reduction of water runoff, maintenance of fertility
Water-retaining elements	Use of terraces and irrigation systems	Water balance control, erosion prevention

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

In general, agrolandscapes that actively implement these methods demonstrate significant advantages in controlling erosion and preserving soils. Systematisation of ecosystem services of agrolandscapes shows that the integration of natural elements not only improves agricultural productivity, but also contributes to the preservation of the environment. Active management of agrolandscapes should include these approaches to ensure long-term stability and resilience to climate change and anthropogenic impacts. Water management is a critical aspect of agrolandscapes, as it affects agricultural productivity, ecosystem conservation, and overall environmental sustainability. In the face of climate change and the increasing frequency of extreme weather events, such as droughts and floods, effective water management is becoming particularly relevant.

The introduction of water-retaining elements, such as terracing, can significantly improve water management. Terraces that are formed on slopes help to slow down water runoff, which prevents erosion and improves soil moisture absorption. This is especially important in regions with dry climates, where moisture retention is crucial for successful crop cultivation. Irrigation systems provide control over the water regime in the fields. Modern irrigation technologies, such as drip irrigation, can optimise water use, reducing the risk of exceeding the irrigation rate. This increases water efficiency by reducing water costs and minimising the risk of flooding. Monitoring of water resources is important. The use of modern technologies, such as remote sensing and data management systems, allows agricultural producers to obtain accurate information about the state of soils and humidity levels. This allows making informed decisions about irrigation and the use of water resources, contributing to the preservation of their quality and quantity (Table 3).

***Table 3**. Basic methods of water resources management in agrolandscapes*

Method	Description	Advantages
Water-retaining elements	Terraces that slow down water runoff	Prevention of erosion, preservation of soil moisture

Table 3. Continued

Method	Description	Advantages
Irrigation systems	Technologies that provide irrigation control	Optimisation of water use, reduction of costs
Monitoring of water resources	Use of technologies for humidity analysis	Timely decision-making, improved water management

Source: *created by the authors*

Water management in agrolandscapes is a key factor affecting their sustainability and productivity. The introduction of innovative methods, such as water-retaining elements, irrigation systems, and monitoring, ensures not only the conservation of water resources, but also increases the adaptability of agricultural systems to climate change. This highlights the importance of active water management to achieve sustainable development in the agricultural sector. Agrolandscapes vary depending on the geographical location, climatic conditions, and methods of farming. These factors have a significant impact on their productivity, sustainability, and ability to provide ecosystem services. In this context, it is important to analyse different types of agrolandscapes, such as forest, forest-steppe, steppe, and dry steppe, to understand their advantages and disadvantages in the context of environmental safety.

Forest agrolandscapes are characterised by the presence of a significant area of forests that are integrated with agricultural land. They provide high biodiversity due to the availability of natural habitats for rare plant and animal species. Forest agrolandscapes effectively control erosion, due to forest coverings that prevent soil leaching. Forest-steppe agrolandscapes combine elements of forests and steppes, creating favourable conditions for a variety of species. They provide a moderate balance between agricultural productivity and biodiversity conservation. This type of agrolandscape is particularly effective for growing crops that require a diverse environment.

Steppe agrolandscapes are characterised by high productivity, but they have an increased vulnerability to soil erosion and degradation. The main problems faced by steppe agrolandscapes are soil depletion due to intensive agriculture and climate change. To improve their condition, it is necessary to introduce special measures, such as agroforestry. Dry steppe agrolandscapes are affected by water deficiency, which requires specific management strategies. This type of agrolandscape requires special attention to the conservation of water resources and the introduction of technologies that will help retain moisture in the soil. Biodiversity conservation in such conditions can be achieved by integrating agricultural land with natural ecosystems.

Table 4. *Comparison of the main types of agrolandscapes*

Type of agrolandscape	Main features	Advantages	Disadvantages
Forest	High biodiversity, availability of forests	Erosion control, conservation of rare species	Requires significant territories for conservation
Forest-steppe	Combination of forests and steppes	Variety of species, good performance	Possible conflicts between agriculture and nature conservation
Steppe	High performance, vulnerability to degradation	High yield, ease of cultivation	Prone to erosion, requires soil improvement
Dry steppe	Water deficiency, need for specific measures (irrigation)	Potential for agronomic innovation	Risks of resource depletion, need for conservation measures

Source: *created by the authors*

Comparison of different types of agrolandscapes highlights the importance of adapting management strategies to the specific conditions of each type. Effective management of agrolandscapes contributes to increasing agricultural productivity and ensures environmental sustainability, which is critical in the current conditions of climate change and increasing anthropogenic loads. Understanding the characteristics and benefits of each type of agrolandscape allows for more effective implementation of strategies for preserving biodiversity and ensuring environmental safety.

Agrolandscapes play a critical role in ensuring environmental safety, in particular, through the maintenance of biodiversity, soil conservation, and effective water resources management. The results of the study confirm the need to preserve and develop forest and forest-steppe agrolandscapes, and implement measures to improve the state of steppe and dry steppe regions. These actions will help to ensure the resilience of agricultural systems to environmental challenges and climate change. Agrolandscapes play an important role in providing a comprehensive set of ecosystem services that are critical to maintaining not only the natural environment, but also socio-economic systems (Dovgal *et al.*, 2024). Data analysis has confirmed that the main ecosystem services of agrolandscapes can be divided into several key categories.

The combination of agricultural land with natural ecosystems contributes to the maintenance of ecological balance and the conservation of local species. This is especially noticeable in forest-steppe regions, where natural landscapes complement agriculture. For example, the presence of forest belts, shrubs, and protected areas provides habitat for rare animal and plant species. These elements create conditions for the migration of species, their restoration and preservation of genetic diversity. Studies have shown that agrolandscapes with high levels of biodiversity are more resistant to environmental changes, such as climate change, due to natural mechanisms of population regulation. Agrolandscapes also play an important role in controlling erosion processes and protecting soils. The use of forest belts that function as barriers to wind and rain has proven effective in reducing the rate of erosion. Agroforestry methods, such as planting trees and shrubs, are actively used in steppe regions to improve soil fertility. These methods not only prevent erosion, but also help retain moisture in the soil, which is crucial for agricultural production. Studies have shown that the regions where these measures are implemented have more stable agricultural systems with increased productivity.

Effective water management is another important ecosystem service provided by agrolandscapes (Shuka *et al.*, 2011). Agrotechnical measures, such as the introduction of water-retaining elements (for example, terracing, contour treatment), help to reduce the risk of flooding and droughts. These measures contribute to a more balanced water regime in agrolandscapes, which is especially important in the context of climate change. The use of such methods can increase the efficiency of water use, conserving resources and ensuring stable irrigation of crops. According to the study, agrolandscapes where these agronomic practices are actively implemented show better resistance to climate stress.

In general, agrolandscapes that integrate natural elements with agricultural practices provide a wide range of ecosystem services that promote biodiversity conservation, erosion control, and effective water management. These services not only improve the environmental sustainability of agrolandscapes, but also contribute to the sustainable development of the agricultural sector, increasing its adaptability to climate change and anthropogenic impacts. Therefore, active management of agrolandscapes is necessary to ensure their efficiency and long-term stability. Based on the analysis, a theoretical model of environmental safety of agrolandscapes (Fig. 1) was developed, which reflects the complex relationships between various components of agricultural landscapes and their impact on the environmental sustainability of the environment. This model is an important tool for evaluating and planning agricultural production, considering environmental factors.

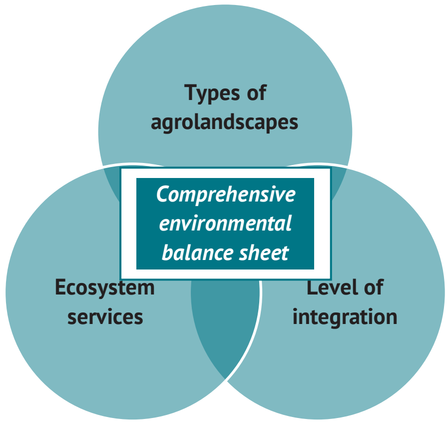

Figure 1*. Theoretical model of environmental safety of agrolandscapes*
Source: *created by the authors*

The model considers several key variables. Firstly, the type of agrolandscapes: forest, forest-steppe, steppe, and dry steppe agrolandscapes have their own specific ecological characteristics that affect their ability to provide ecosystem services and adapt to climate change. Secondly, the level of integration of natural and agricultural elements is an important aspect. High integration indicates an effective combination of agriculture with natural ecosystems, which allows maintaining biodiversity, maintaining soil fertility, and ensuring sustainable water resources management. The model also considers the main ecosystem services that are critical for environmental safety. This is the conservation of biodiversity, which supports the functioning of ecosystems and ensures the sustainability of agrolandscapes, soil protection, which includes reducing erosion and maintaining fertility, and regulating water flows, which is important in the context of climate change.

The developed model demonstrated that agrolandscapes with a high level of integration of natural and agricultural elements are the most stable. This is conditioned by the increased adaptability of such agricultural systems to climate change, which reduces the risks associated with droughts and floods. In addition, such integration helps to reduce the negative impact of anthropogenic factors, such as soil and water pollution, and also contributes to the restoration of natural resources. This model of environmental safety is an important tool for assessing the sustainability of agrolandscapes and determining optimal management strategies. It is aimed at improving environmental sustainability, preserving biodiversity and efficient use of natural resources. This, in turn, contributes to the achievement of sustainable development of the agricultural sector in the context of modern environmental challenges.

Based on the results of the study, a number of recommendations were developed aimed at improving the environmental safety of agrolandscapes and sustainable development of agriculture. The first important recommendation is to optimise the management of agrolandscapes by introducing agroforestry and restoring natural ecosystems in agricultural regions. This includes the use of forest belts, trees and shrubs to improve environmental conditions. For example, creating forest belts will help to protect against wind erosion and improve the microclimate. The restoration of natural reservoirs and wetlands can serve as hotbeds of biodiversity, and the use of cover crops will increase soil fertility and preserve moisture. These measures will not only improve environmental conditions, but also increase agricultural productivity.

The second recommendation is to develop holistic policies that support agricultural enterprises implementing ecological approaches to soil and water management. An important aspect of such policies is to provide financial support to farmers who are switching to organic farming or implementing innovative water conservation technologies. This may include subsidies, grants, or tax breaks that will encourage farmers to adopt sustainable practices. Educational programmes and trainings for farmers will significantly increase their awareness of environmental practices. Such programmes can cover topics related to the management of natural resources, biodiversity, and the latest technologies in agriculture. This would allow farmers to gain new knowledge and exchange experience with colleagues, which will contribute to the overall development of the agricultural sector. The introduction of regulations that promote biodiversity conservation and the rational use of natural resources will be an important step in supporting environmental initiatives. Such regulations may include requirements for farming that consider environmental aspects, and mechanisms for monitoring their compliance, which will contribute to the responsible environmental behaviour among farmers and ensure sustainable development of rural areas.

The third important aspect is the need to monitor the state of agrolandscapes to respond in a timely manner to environmental challenges associated with climate change. The introduction of monitoring systems will allow identifying problems at an early stage, such as soil degradation, reduced biodiversity, and other negative consequences that may threaten ecosystems. Monitoring systems can include both stationary and mobile platforms that provide constant monitoring of changes in agrolandscapes. The use of modern technologies, such as remote sensing and geographic information systems (GIS), will help in collecting and analysing data on the state of ecosystems. These technologies provide detailed information on land use, changes in vegetation, and the impact of agricultural practices on the environment. By integrating data from different sources, agronomists and environmentalists will be able to develop more effective management strategies aimed at reducing the negative impact on nature.

Regular assessment of the impact of agricultural practices on the environment will allow adapting management strategies in accordance with the identified environmental problems. This, in turn, will contribute not only to the conservation of natural resources, but also to increasing agricultural productivity. These recommendations are aimed at ensuring an integrated approach to agrolandscape management, which will help to maintain ecological balance and ensure sustainable agricultural development in the face of climate change. It is also important to involve local communities in the monitoring process, which will help raise awareness and address environmental issues. The results obtained confirmed the hypothesis that effective management of agrolandscapes really contributes to improving environmental safety and reducing the negative impact on the environment. The study found that integrated approaches to landscape management are key to achieving sustainability in agricultural ecosystems. This, in turn, ensures the conservation of biodiversity, which is an important aspect of environmental stability.

The use of agroforestry methods, the creation of forest belts and the restoration of natural ecosystems has proved particularly effective in preventing soil erosion and maintaining their fertility. Such practices allow the conservation of natural resources, reducing the risk of degradation and reducing greenhouse gas emissions. Water management through the introduction of water-retaining elements and optimisation of irrigation systems contributes to balanced water use, which is critical in the face of climate change. Effective management of agrolandscapes improves the ecological situation and supports the socio-economic development of agricultural regions (Hartmane *et al.*, 2024). This is achieved by increasing agricultural productivity, ensuring food security and increasing farmers' incomes. Accordingly, the integration of environmental practices into agricultural production creates conditions for sustainable development, where economic progress does not occur at the expense of environmental damage.

The Law of Ukraine No. 2775-IX "On Environmental Protection" (1991) is a fundamental regulation that defines the foundations of the state's environmental policy. In the context of the study of agrolandscapes, this law focuses on ensuring environmental safety, preserving natural resources and biodiversity. It sets out the obligations of government bodies, enterprises and citizens to comply with environmental norms and standards. The law also provides for environmental pollution control mechanisms, which are particularly important in the agricultural sector, where the use of pesticides and fertilisers can negatively affect the environment. Considering the conducted research, this law emphasises the importance of integrating environmental requirements into agrolandscape management strategies, which reduces their negative impact on the environment and ensures sustainable development.

Law of Ukraine No. 2973-IX "On Amendments to Certain Legislative Acts of Ukraine on the State System of Environmental Monitoring, Information on the State of the Environment (Environmental Information) and Information Support for Environmental Management" (2023) is an important tool for implementing systematic monitoring of the ecological state in agricultural landscapes. It provides an opportunity to create an effective system for collecting, analysing and distributing environmental information, which allows detecting negative changes in the natural environment in time. This law is critical for the study of agrolandscapes, since monitoring environmental indicators, such as soil quality, water and the state of biodiversity, is crucial for the assessment of the environmental safety of agricultural systems. It supports the implementation of measures to improve the state of the environment and the efficient use of natural resources, which is consistent with the purpose of the study – optimise the management of agrolandscapes to ensure their sustainability and safety.

Both laws support the theoretical basis of the study and define practical steps that are necessary for the implementation of environmental principles in agriculture, which contributes to the establishment of environmentally friendly agrolandscapes. Thus, the results of the study indicate the importance of an integrated approach to the management of agrolandscapes, which allows preserving natural resources, supporting biodiversity and ensuring the sustainable development of agricultural regions. This highlights the need to implement state policies and programmes that support farmers in switching to environmental practices, which can lead to an improvement in the overall state of the environment.

DISCUSSION

The findings confirmed that agrolandscapes play a critical role in ensuring environmental safety. In particular, it was found that the integration of natural elements into agriculture is key to preserving biodiversity and improving the state of the environment. Forest and forest-steppe agrolandscapes have demonstrated the greatest efficiency in species conservation. The study by J. Zhao *et al.* (2024) examines the impact of various agricultural practices on biodiversity in both agricultural lands and natural environments. The authors emphasise that intensive land use, accompanied by a high level of anthropogenic pressure, significantly reduces species diversity, while environmentally oriented approaches such as agroforestry, conservation of natural areas, and integration of natural elements into agricultural landscapes can minimise the negative impact. The paper offers a detailed analysis of adaptation strategies that contribute to maintaining ecological sustainability and creating favorable conditions for rare species in agricultural systems. The findings of J. Zhao *et al.* (2024) are in harmony with the conclusions of our study, which emphasizes the critical role of preserving natural elements in agricultural landscapes to ensure ecological sustainability.

The article by P. Batáry *et al.* (2020) provides an overview of the role of agrolandscapes in the conservation of biodiversity in agricultural areas. The authors emphasize the importance of a landscape approach to ensure environmental sustainability, which includes the integration of natural elements such as forest belts and perennial plantations into agricultural systems. The focus is on how different types of agricultural landscapes affect biodiversity, climate change resilience, and the provision of ecosystem services. The authors note that agricultural landscapes with a high level of natural integration, such as forest-steppe systems or lands with forest elements, are the most favorable for biodiversity conservation. They contribute to the formation of conditions for the existence of rare species, climate stabilization, regulation of water balance and reduction of erosion processes. The findings of P. Batáry *et al.* (2020) are consistent with the conclusions of our study, demonstrating the commonality of approaches to assessing the importance of agricultural landscapes for biodiversity conservation and environmental sustainability. Both studies emphasize the importance of integrating natural elements into agricultural systems, including the use of forest belts, perennial plantings, and other nature-based solutions that help reduce erosion, improve water quality, and maintain species diversity. Both studies also emphasize the role of biodiversity as a key factor in increasing the resilience of agricultural systems to climate change and anthropogenic impacts.

This issue was discussed in detail in by V.Š. Kremsa (2021), which emphasised the importance of sustainable resource management, which includes not only efficient land use, but also water conservation and maintenance of soil fertility. Such management is critical for ensuring long-term crop production that meets modern requirements for environmental safety and economic efficiency of the agricultural sector. The results highlight the need for active management of agrolandscapes to maintain environmental sustainability. This is consistent with the conclusions obtained by I. Soloviy *et al.* (2021), who states that integrating ecosystem services assessment into land use planning can be an effective tool for improving natural resource management. The researcher claims that the correct use of these services allows preventing negative consequences associated with anthropogenic impact. The developed model of environmental safety showed the importance of integrating natural and agricultural elements to increase the sustainability of agricultural systems. The results of the study confirmed the importance of agrolandscapes in ensuring environmental safety and their impact on biodiversity, soils, and water resources. This was confirmed by V. Belolipskyi and M. Poluliakh (2020), who analysed the ecological efficiency of agrolandscapes, focusing on drainage systems. They pointed out that properly designed agrolandscapes can significantly reduce the risks of land degradation and increase their productivity, which is also consistent with the results of this study.

T.S. Priyadarshana *et al.* (2024) conducted a global review and meta-analysis of the impact of landscape and crop heterogeneity on biodiversity in agricultural regions. The study demonstrates that landscape and cultural diversity are key factors in biodiversity conservation, especially in the context of intensive agricultural land use. The authors emphasise that the creation of mosaic landscapes that combine natural elements such as forest strips, perennial plantations, and diverse crops significantly increases species diversity and ensures the stability of agroecosystems. An important finding is that species richness not only improves the resilience of agricultural systems to climate change, but also contributes to the provision of important ecosystem services.

The study also highlighted the importance of management practices in agriculture to reduce negative environmental impacts. For example, D. Ladychuk *et al.* (2021) pointed out the importance of determining the typicality of agrolandscapes for water supply design. This suggests that effective water management is critical to maintaining the sustainability of agrolandscapes. The results of the study emphasised that agrolandscapes with integrated natural elements play a key role in ensuring environmental safety. This is consistent with the conclusions of the study by L. Kuzmych (2024), which focused on the practices of sustainable soil and water management. The findings confirm that such practices increase the productivity of agricultural crops, preserve natural resources, and ensure environmental sustainability.

S. Tanchyk *et al.* (2024) discussed the concept of environmentally friendly agricultural systems in Ukraine, which confirms the results obtained in this study on the importance of ecological approaches to agricultural production. The introduction of such systems can become one of the key aspects of sustainable development of agricultural regions. The study by S.L. Cappelli *et al.* (2022) emphasizes the importance of plant biodiversity for sustainable agricultural development. It is noted that biodiversity contributes to increasing the productivity of agricultural systems by improving soil quality, regulating water balance, reducing erosion processes, and preserving ecosystem services. Particular attention is paid to underground processes that ensure the functionality of soil ecosystems and help maintain fertility in the long term. The study emphasizes that plant biodiversity contributes to the resilience of agricultural landscapes to climate change and anthropogenic impacts. The results of the study are consistent with the conclusions about the role of biodiversity in agricultural landscapes, which is reflected in the analysis of the impact of forest and forest-steppe systems on soil fertility and ecosystem stability. Data on the positive impact of nature-based practices, such as agroforestry and the use of perennial plants, confirm the importance of measures to reduce erosion and improve soil characteristics. The subsurface processes identified by S.L. Cappelli *et al.* (2022) are consistent with findings on the importance of water-holding elements and their role in soil moisture retention.

The role of fiscal instruments in the implementation of low-carbon agriculture, discussed by O. Butrym *et al.* (2023), is another important aspect that links economic and environmental goals. This can be useful in the context of developing policies that support agricultural enterprises that implement environmental practices. It also highlights the role of digitalisation in reducing the carbon footprint of agricultural production, which can be an important tool for optimising agrolandscapes (Butrym *et al.*, 2024). The integration of digital technologies into agricultural production can contribute to better monitoring and management of resources, which, in turn, will increase the resilience of agricultural systems to climate change. A. Silva-Caballero *et al.* (2024) pointed out the importance of agrolandscapes for the conservation of species such as the jaguar. This is consistent with the results of this study, which highlighted the role of agrolandscapes in preserving biodiversity, which is important for maintaining environmental safety.

The coordination of the findings with previous studies provides grounds for the assertion that the integration of natural and agricultural elements is an important condition for achieving sustainable development of agricultural regions. Further research may focus on implementing digital solutions in conventional agronomic practices, and monitoring the impact of technological innovations on the environmental safety of agrolandscapes. This will not only reduce the negative impact on the environment, but also ensure more efficient use of natural resources in agriculture.

CONCLUSIONS

The study confirmed the importance of agrolandscapes in ensuring environmental safety, finding that agrolandscapes with a high level of integration of natural and agricultural elements provide a significantly higher level of biodiversity than their less integrated counterparts. In particular, it was found that forest and forest-steppe agrolandscapes demonstrate the highest efficiency in species conservation, which emphasises their role in maintaining ecological balance. Quantitative indicators obtained as a result of the study indicate the need for urgent measures to improve the state of biodiversity in steppe and dry steppe agrolandscapes, which turned out to be the most vulnerable. As part of the analysis of ecosystem services, it was determined that the integration of natural ecosystems into agricultural practices can significantly reduce the risks of soil erosion and improve water management, which, in turn, will have a positive impact on the productivity of agricultural systems. The results obtained confirm the hypothesis that effective management of agrolandscapes significantly reduces the negative impact on the environment. This is achieved, in particular, through the introduction of such innovative practices as agroforestry, which involves the integration of forest stands into agricultural systems and the creation of forest belts that serve as natural barriers. These measures not only help reduce soil erosion and improve water quality, but also ensure the adaptability of agricultural systems to climate change. Consequently, they play an important role in promoting the sustainable development of agricultural regions, which is critical in the context of global environmental challenges and the need for food security.

The recommendations resulting from the study include the active implementation of environmental approaches in support policies for agricultural enterprises, which can significantly contribute to the sustainable development of agriculture. This includes not only adapting existing programmes, but also developing new initiatives that focus on preserving natural resources and maintaining ecosystems. Another important aspect is the creation and implementation of monitoring systems for the state of agrolandscapes, which will facilitate timely detection of negative changes in the environment and take appropriate measures to neutralise them. One of the key areas of further research is the need to develop specific measures aimed at improving biodiversity in steppe and dry steppe regions. Since these areas have proven to be the least resilient to current environmental challenges, it is important to focus on studying the ecosystem processes occurring in these regions, and implementing practices that can contribute to the restoration and conservation of natural diversity. This includes not only agronomic practices, but also environmental initiatives that can be implemented at the local community level.

Limitations of the study associated with insufficient data for all agrolandscapes significantly complicate the possibility of generalising the results obtained to wider geographical areas. This can lead to underestimation or, conversely, exaggeration of the impact of agrolandscapes on environmental processes. In the future, it is important to expand the study to include additional analysis methods such as geographic information systems (GIS) and remote sensing, and to attract more regions with different climatic and environmental conditions. This would provide a more comprehensive and integrated understanding of the impact of agrolandscapes on environmental safety. As a result, such efforts will contribute to more effective adaptation of agrolandscape management practices to constantly changing conditions, ensuring the sustainability of agricultural systems and the conservation of natural resources.

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CONFLICT OF INTEREST

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Агроландшафти та їх роль у забезпеченні екологічної безпеки

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Анотація. Мета дослідження полягала в глибокому аналізі ролі агроландшафтів у забезпеченні екологічної безпеки, а також у вивченні їхнього впливу на навколишнє середовище, з особливим акцентом на аспекти біорізноманіття, захисту ґрунтів і управління водними ресурсами. Дослідження охоплювало широкий спектр діяльності, включаючи збір та систематизацію наукових матеріалів, проведення порівняльного аналізу різних управлінських підходів, а також розробку теоретичної моделі екологічної безпеки, що дозволяє оцінити ефективність існуючих практик. Основні результати дослідження вказують на те, що агроландшафти, які характеризуються високим рівнем інтеграції природних елементів та сільськогосподарських компонентів, здатні забезпечувати значно вищий рівень біорізноманіття в порівнянні з менш інтегрованими аналогами. Зокрема, лісові та лісостепові агроландшафти виявилися найбільш ефективними у збереженні видів, що є критично важливим для підтримання екологічної рівноваги. Водночас, степові та сухостепові ландшафти потребують термінових і комплексних заходів для покращення стану біорізноманіття, оскільки їхня екологічна стійкість знаходиться під загрозою. Таким чином, результати дослідження підкреслюють необхідність впровадження інноваційних підходів до управління агроландшафтами, що можуть сприяти збереженню природних ресурсів та покращенню екологічної безпеки. Розроблена теоретична модель виявила, що найбільш стійкими є агроландшафти, де природні екосистеми гармонійно поєднані із сільськогосподарськими угіддями. Отримані результати підтвердили гіпотезу про те, що ефективне управління агроландшафтами сприяє підвищенню екологічної безпеки та зменшенню негативного впливу на довкілля, зокрема шляхом контролю ерозії та управління водними ресурсами. Висновки підкреслюють необхідність впровадження агролісомеліорації, підтримки екологічних підходів у політиках та системи моніторингу стану агроландшафтів для сталого розвитку аграрних регіонів, що дозволить адаптуватися до викликів зміни клімату

Ключові слова: екологічна безпека; біобезпека; безпека життєдіяльності; агроландшафти; обробіток ґрунту; удобрення

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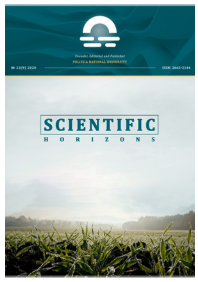

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Use of food additives in bakery products

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Abstract. The influence of various food additives including emulsifiers (mono- and diglycerides of fatty acids (E471), lecithin (E322), sodium stearoyl-2-lactylate (E481) and preservatives (potassium sorbate (E202), sodium propionate (E281)) on the quality and shelf life of bakery products was investigated. The study was conducted on the basis of the enterprise in Gulistan (Uzbekistan) in order to improve organoleptic characteristics of products and extend their shelf life. To conduct the experiment, test batches of bread with the addition of the specified food additives in various combinations were made. The effect of additives on such parameters as softness and elasticity of crumb, porosity, moisture, as well as resistance to microbiological spoilage (yeast and mould) was analysed. Microbiological analysis showed that the addition of preservatives significantly reduced the number of colony-forming units (CFU) of yeasts and moulds in bakery products. The control group reached 500 CFU/g by day 7, while the combination group had the lowest levels of only 50 CFU/g on day 7, which confirmed the effectiveness of the preservatives. It was also observed that the use of the combination of emulsifiers E471 and E481 resulted in a significant improvement in bread texture, increased bread volume and improved crumb porosity. The addition of lecithin (E322) contributed to moisture retention, which slowed down the staling process. The addition of potassium sorbate and sodium propionate significantly increased the shelf life of the bakery products, preventing

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the development of mould and yeast during 7-10 days of storage in a climate-controlled chamber. Thus, the use of combinations of food additives in conditions of industrial production allowed improving the physical and chemical properties of bakery products, increased their shelf life and ensured microbiological safety of products. The results of the study may be useful for further implementation of these technologies in the bakery industry of the Republic of Uzbekistan

Keywords: lecithin; bread texture; food technology; preservatives; microbiological spoilage

INTRODUCTION

The problem of improving the quality and properties of bakery products remains one of the topical issues in the food industry. Every year consumers' requirements to organoleptic and physical characteristics of bread, such as softness, elasticity, resistance to staling, as well as shelf life of products, are increasing. Modern technologies offer a wide range of solutions related to the use of food additives, in particular emulsifiers and preservatives, which play a key role in improving the quality of bakery products and extending their shelf life.

A. Islam and S. Islam (2024) describe in detail all the pros and cons of this technology. Another interesting solution is the technology of adding honeysuckle powder to the formulation, which was proposed by Chinese scientists in their research work (Çobanoğlu *et al*., 2022; Ran *et al*., 2023). Another innovative solution is the use of nanomaterials as food additives, but as stated by the authors of the article, such solutions can negatively affect the ecological state of the region (Gerardo-Rodríguez *et al*., 2021). Although these modifications of bakery products are already used in the production of different countries, the risks that may arise in the production processes have not yet been comprehensively studied.

Different types of emulsifiers and their effect on the structure and texture of baked goods have been reported in several studies (Cauvain, 2020; Ardoin *et al*., 2023). Thus, the literature indicates that the use of mono- and diglycerides of fatty acids (E471) contributes to increasing the porosity and softness of the breadcrumb and slows down the staling process (Faccioli *et al*., 2021; Valsalan *et al*., 2023). This is because emulsifiers enhance the interaction between the fat and water phases in the dough, stabilise the gluten mesh and make the dough more elastic. The study by R.P. Guiné and S.G. Florença (2024) focused on the development and characterisation of functional bakery products, where different additives were used to increase the nutritional value and improve the physicochemical properties of the products. Their results showed that proper selection of food additives such as antioxidants, preservatives, and emulsifiers can significantly improve the quality of finished products and increase their shelf life. An essential part of this study was the introduction of functional components, which not only improved the quality of bakery products, but also gave them additional beneficial properties.

Other studies such as the work of E. Debonne *et al.* (2023) aimed to study the effect of potassium sorbate preservative (E202) on the shelf life of bakery products. They showed that the use of potassium sorbate effectively inhibits the growth of mould fungi and yeast, which can significantly extend the shelf life of bakery products, especially in humid conditions (Yazdanfar *et al*., 2023; Melin, 2024). This confirms the importance of the choice of preservatives in preserving the freshness of bread. Lecithin (E322) plays an important role in improving the physicochemical characteristics of bread, as shown in the work by A. Kumar and G. Sharma (2018), where it was shown that the addition of lecithin helped to increase the volume of bread and improve its texture. Lecithin stabilizes the dough structure and facilitates moulding, which also improves the economic efficiency of production (Byeon *et al*., 2024).

Thus, the reviewed studies demonstrate the relevance of the use of additives in the bakery industry to improve the properties of dough and finished products. Considering the relevance of this topic, it is worth noting the work of S. Sadikhov (2024), where it is noted that the Azerbaijani food industry has a significant potential for export, especially if innovative approaches to improving the quality and safety of products are introduced. Nevertheless, despite the large number of studies in this area, the question of the complex effect of various food additives on bakery products under conditions of industrial production remains open. The application of modern technologies and the study of their combined effect require additional attention, especially in the context of developing countries such as Azerbaijan and Uzbekistan, where bread remains one of the key foodstuffs.

This study was aimed at investigating the effect of food additives such as emulsifiers (E471, E322, E481) and preservatives (E202, E281) on organoleptic properties and shelf life of bakery products produced under the conditions of an industrial enterprise in Gulistan (Uzbekistan). The aim of the work was to identify the optimal combinations of these additives to improve the physical and chemical characteristics of the products, as well as to assess their impact on microbiological safety.

MATERIALS AND METHODS

The scientific study was conducted at MPS Rayhon facility in Gulistan city using raw materials and equipment to obtain the most accurate and reproducible results.

Components of samples and reagents for biochemical analysis. For the study, all materials were purchased from certified suppliers and met the standards and requirements for the food industry and laboratory testing. The main suppliers were leading international and local companies accredited to supply food, food additives and laboratory equipment. Mono- and diglycerides of fatty acids (E471), lecithin (E322), sodium stearoyl-2-lactylate (E481), potassium sorbate (E202 and sodium propionate (E281) were purchased from distributors specializing in food ingredients such as Merck, Sigma-Aldrich. The main suppliers of raw materials for the production of samples were local enterprises accredited for the production and supply of ingredients for the baking industry in Uzbekistan. The flour was purchased from local mills that specialize in the production of high-quality wheat flour. The supplier was selected based on the flour's compliance with quality standards and requirements for bakery products, including protein, moisture, and gluten content.

Baker's yeast was used and also purchased from a local producer that meets the requirements of the O'z DSt 950:2011 standard. The manufacturer was selected based on compliance with the requirements for yeast activity and product purity. Sugar, salt and sunflower oil for the manufacture of the samples were purchased from local food suppliers that met health and hygiene standards. These ingredients ensured the flavour characteristics and balance of the bread recipe. All ingredients were thoroughly tested to meet the quality standards adopted in the Republic of Uzbekistan to ensure consistent and high-quality of finished products. Selective nutrient media for microbiological analyses, such as Sabouraud medium and yeast extract medium, were purchased from international suppliers of laboratory materials such as Oxoid and Merck.

Equipment. Laboratory equipment (incubators, shakers, autoclaves and sterile containers) was purchased from manufacturers specializing in equipment for microbiological and chemical laboratories. Companies such as Thermo Fisher Scientific and Eppendorf supplied the necessary equipment for the experiments. The dough mixer was purchased from Kemper through a local distributor in Uzbekistan that provides equipment for the bakery industry. The baking ovens for baking the test batches were purchased from MIWE. A Stable Micro Systems texture meter was also used to measure the physical properties of bakery products such as softness and elasticity. The moisture analyser (Sartorius), microbiological equipment for the analysis of yeast and mould levels in bakery products, which included incubators, autoclaves and PCR analysers (Thermo Fisher Scientific, Eppendorf and Merck), and climate-controlled storage chambers for shelf-life studies (Memmert) met the requirements and standards for research in the food industry and were purchased through certified suppliers who provide support and service in Uzbekistan.

Preparing dough and baking product. For each experiment, the dough was prepared according to the standard recipe, with the addition of appropriate ingredients. Control samples were prepared without food additives. For each sample, different food additives (emulsifiers and preservatives) were selected in the prescribed proportion. After kneading, the dough was fermented and baked under standard conditions in baking ovens at 200°C for 30 minutes. The products were evaluated for several physical and chemical parameters such as: crumb volume and porosity, softness and elasticity (in Newtons), and moisture content. In order to assess the taste and consumer qualities of the products, a tasting was conducted. A group of experts (bakers and specialists of the company) consisting of 20 people evaluated the bakery products according to several criteria, such as taste, texture, and aroma. Each criterion was evaluated on a 10-point scale, where 10 is the maximum score.

Microbiological analysis of bakery products was carried out to evaluate the effectiveness of preservatives. The samples were stored at 20°C for 7 days, after which the content of microorganisms (yeasts and moulds) was analysed. For this purpose, the technique of sowing on selective media was used, followed by counting the number of colony-forming units (CFU). Microbiological analysis of bakery products was carried out to evaluate their microbiological purity and the effectiveness of preservatives in preventing the growth of microorganisms such as mould and yeast during storage. Samples were taken on the 1st, 4th and 7th day of product storage. Each sample weighing about 10 g was taken from the central part of the product to exclude possible external contamination. The samples were chopped with a sterile knife and then placed in sterile containers. The samples were then diluted in sterile physiological solution (0.85% NaCl) at a ratio of 1:10 (1 g of product per 9 ml of solution). The resulting suspensions were stirred vigorously for 2 minutes for uniform distribution of microorganisms. Selective nutrient media were used to evaluate the growth of microorganisms. From each diluted suspension, 0.1 ml was taken and then samples were plated on the surface of agar in Petri dishes by surface seeding method. For each type of medium, 3 cups were used for each time point and experimental group. The seeded Petri dishes were placed in an incubator at 25°C for moulds and at 30°C for yeast. The incubation time was 48 hours for yeast and 5-7 days for mould. After incubation, visual observations of the Petri dishes were made. Yeast and mould colonies were counted using the standard DRE counting method. The number of DREs was counted per sample weight and expressed as DRE/g product.

To study the shelf life, the samples were stored at different temperature conditions (20°C and 5°C) for 7 days. Parameters such as moisture, texture, and mould appearance were monitored at regular intervals. All the data obtained were processed using descriptive and inferential statistics techniques. To test the significance of differences between the experimental groups and the control group, methods of analysis of variance with a significance level of $p < 0.05$ were used. This allowed us to determine the extent to which the use of food additives influenced the main quality parameters of bakery products. The economic analysis of the cost of products with the addition of emulsifiers and preservatives was carried out. The impact of these additives on the final price of bakery products was studied, and the potential benefits of extending the shelf life of products and improving their quality were evaluated.

RESULTS

In the course of the study on the basis of bakery enterprise "MPS Rayhon" the effects of the use of various food additives, including emulsifiers and preservatives, on the quality of bakery products were studied. The main objective was to evaluate the effect of additives on physicochemical, organoleptic properties and shelf life of the products. Several test batches of bakery products were prepared with the addition of mono- and diglycerides of fatty acids (E471), lecithin (E322), sodium stearoyl-2-lactylate (E481), and preservatives. The control group consisted of products prepared without the use of food additives. The study selected certain food additives based on their functional properties and wide application in the bakery industry. The main objective was to improve the quality, extend shelf life, improve the texture of bakery products, and ensure the microbiological safety of the products.

To achieve these objectives, emulsifiers such as fatty acid mono- and diglycerides (E471), lecithin (E322) and sodium stearoyl-2-lactylate (E481) were used. These emulsifiers played a key role in improving bread texture, and volume and prolonging freshness. Mono- and diglycerides of fatty acids, due to their ability to improve the interaction between fats and water, ensured an even distribution of fats in the dough, which contributed to the formation of a softer and more porous crumb structure. Lecithin, as a natural emulsifier, strengthened the dough structure, improved moisture retention and stabilized the moulding process (Chechitko *et al.*, 2024). Sodium stearoyl-2-lactylate stabilized the gluten mesh, which had a positive effect on increasing the volume of the finished product and improving its texture. These emulsifiers were chosen because of their proven effectiveness in prolonging freshness and improving organoleptic characteristics of bakery products.

Preservatives also played an important role in the study. Potassium sorbate (E202) and sodium propionate (E281) were used to prevent microbiological spoilage of the products. Potassium sorbate, widely used in the food industry, was chosen for its high effectiveness in inhibiting mould and yeast growth, which is particularly important for products with long shelf life in high-humidity environments. Sodium propionate was also found to be effective against microbiological spoilage, inhibiting the growth of mould fungi and bacteria that cause bread spoilage, while not affecting its taste and odour. These preservatives were selected due to their safety, neutral effect on organoleptic properties and high effectiveness in extending shelf life. The combined use of emulsifiers and preservatives allowed achieving a synergetic effect. Together they not only improved physical and organoleptic characteristics of products, but also significantly extended their shelf life. This ensured stable high quality of bakery products during the whole shelf life, reducing the risks of microbiological spoilage and slowing down the processes of staling.

The study showed that the addition of emulsifiers had a significant effect on the volume of the products. Control samples had an average volume of 600 cm^3, whereas products with the addition of mono- and diglycerides of fatty acids (E471) showed a 15% increase in volume (to 690 cm^3). The use of lecithin (E322) also resulted in a significant increase in volume to 670 cm^3, while the combined use of all emulsifiers gave the maximum result of 710 cm^3, which is 18% higher than the control group (Table 1).

***Table 1**. Effect of emulsifiers on physical characteristics of bakery products*

Indicator	Control group	E471 (mono- and diglycerides)	E322 (lecithin)	E481 (sodium stearoyl-2-lactylate)	Combined group
Volume of products (cm^3)	600	690	670	680	710
Crumb porosity (%)	35	42	40	41	45
Softness (H)	10	7	8	7.5	6.5
Elasticity (units)	65	75	70	72	80

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

Measurement of crumb porosity showed that the emulsifiers improved the uniformity of pore distribution in the baked goods. In the control group, the porosity was 35% and the pores were less uniform. In the samples with mono- and diglycerides, the porosity reached 42% and in the products with lecithin it was 40%. The most homogeneous structure was observed in the samples with combined additives (porosity – 45%). This indicated a softer and airier crumb structure when emulsifiers were used. One of the key quality indicators of bakery products is their texture. According to texture meter testing, the products with emulsifiers had a softer texture compared to the control group. In the control group, the compressive force required to deform the crumb was 10 N, whereas in the samples with the addition of mono- and diglycerides of fatty acids it was reduced to 7 N. Lecithin also contributed to reduce the stiffness of the products, showing a result of 8 N. The highest effect was obtained with the combined use of additives – 6.5 N. When the concentration of emulsifiers was varied from 0.5% to 2%, it was observed that an optimum improvement in softness and texture of bakery products was observed when their content was increased to 1.5%. Higher concentrations (above 2%) resulted in excessive softness, which negatively affected the consumer properties and product perception. These results demonstrated the importance of accurate additive dosage to maximize the improvement effect.

In addition, the effect of food additives on the microstructure of bakery products was studied. Microscopic analysis showed that the addition of emulsifiers improved the structure and even distribution of air bubbles in the dough, which provided a lighter and airier texture of the finished products. This phenomenon was particularly noticeable when lecithin and monoglycerides were used, which contributed to the creation of a more stable foam in the dough, improving its airiness and elasticity. Measurement of the elasticity of the products showed that the emulsifiers contributed to the increase of this index. The elasticity of the control samples was 65 units, while the products with mono- and diglycerides showed a result of 75 units and lecithin 70 units. The combined additives increased this value to 80 units, indicating airier and more elastic crumb structure. This is particularly important for consumer perception, as soft and elastic products are favoured by customers.

In addition, this study evaluated the weight change of the products after baking, which is directly related to moisture loss during heat treatment. The addition of emulsifiers and preservatives reduced the weight loss of the products during baking (Table 2). This is due to the fact that these additives promoted moisture retention in the dough. Products with complex additives showed the lowest weight loss, indicating that the additives were highly effective in preventing the products from drying out during baking.

***Table 2**. Change in weight of bakery products after baking*

Product	Initial dough weight (g)	Weight after baking (g)	Weight loss (%)
Product A (without additives)	1,000	870	13
Product B (with emulsifiers)	1,000	880	12
Product C (with preservatives)	1,000	875	12.5
Product D (with complex additives)	1,000	885	11.5

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

To evaluate the taste characteristics of the modified bakery products, organoleptic analysis by tasting method was carried out to evaluate the taste, aroma, and texture of the bakery products. The control group obtained average taste scores of 7 for flavour, 6.8 for texture and 6.5 for aroma. At the same time, products with added emulsifiers received higher scores. Thus, the flavour of samples with mono- and diglycerides was rated 7.5, and texture – 8 points. Products with lecithin received 7.3 points for flavour and 7.5 for texture, which also indicated an improvement in organoleptic characteristics (Table 3). The highest scores were awarded to products with combined additives: 7.8 for flavour, 8.3 for texture and 7.2 for aroma. This indicated that the use of several types of emulsifiers had a positive effect on the overall evaluation of the products, making them more attractive to consumers. Thus, it can be concluded that the addition of emulsifiers improves the flavour and texture perception of bakery products, making them softer and more aromatic.

***Table 3**. Organoleptic properties of bakery products*

Indicator	Control group	E471 (mono- and diglycerides)	E322 (lecithin)	E481 (sodium stearoyl-2-lactylate)	Combined group
Flavour (points out of 10)	7	7.5	7.3	7.4	7.8
Texture (points out of 10)	6.8	8	7.5	7.7	8.3
Flavour (points out of 10)	6.5	7	7.2	7.1	7.2

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

In addition to organoleptic analysis, studies on the change in colour characteristics of bakery products with the use of food additives were carried out. Colour was measured using a spectrophotometer, where the parameters L* (lightness), a* (red/green hue) and b* (yellow/blue hue) were evaluated. Products with added nutritional supplements showed a lighter hue (parameter L*) and more intense red and yellow tones (parameters a* and b*, respectively). These changes were particularly pronounced in Product D, where complex food additives were used (Table 4). It can be concluded that such additives can have a positive effect on the appearance of the final product, which can also increase its consumer appeal.

***Table 4**. Colour characteristics of bakery products*

Parameter	Product A (without additives)	Product B (with emulsifiers)	Product C (with preservatives)	Product D (with complex additives)
L*	65.2	68.5	66.8	70.1
a*	1.8	2.1	1.9	2.3
b*	15.4	16.7	16.1	17

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

Interesting results were also obtained in the context of the different types of flour used to create the products. Both traditional wheat flour and alternatives such as rye and maize flours were included in the study. The results showed that the addition of emulsifiers improved the texture of products made from all types of flour, but a particularly noticeable effect was observed when using rye flour, which is characterized by its greater density and tendency to produce a denser texture without additives. When emulsifiers were added, rye products became softer and airier, resulting in a product with similar characteristics to wheat flour-based products. It was also important to determine exactly how long the products would retain their freshness. When determining the shelf life of the samples, important steps were to detect the onset of stale products (assess texture changes and reduction in softness) and to detect the appearance of mould (both visually and by microbiological analysis). In the control group, the products started to stale on day 3, while in the potassium sorbate group the shelf life was 5 days and in the sodium propionate group 6 days. In the combined group, the products remained fresh for 7 days. The moisture content of products with preservatives was preserved significantly better than in the control group, with maximum values in the combined group – 36% on day 7 (Table 5).

***Table 5**. Effect of preservatives on shelf life and moisture content of bakery products*

Indicator	Control group	Potassium sorbate (E202)	Sodium propionate (E281)	Combined group
Shelf life (days)	3	5	6	7
Humidity on day 3 (%)	32	38	37	39
Humidity on day 7 (%)	25	34	33	36

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

For yeast, the colonies had a smooth, shiny surface, with different colouring depending on the strain. For moulds, the colonies were rough and often had the branched structure characteristic of mould fungi. Microbiological results allowed us to evaluate the degree of microbial growth depending on the type of preservative added. Quantitative data on the number of DREs/g were collected for each time interval (days 1, 4 and 7). A comparative analysis was then performed for each group. Microbial growth was significantly higher in the control group than in the preservative groups, especially by day 7. Sodium propionate and potassium sorbate were effective in inhibiting mould and yeast growth, especially in the combined group, where a minimum DRE/g by day 7 was observed (Table 6). The addition of preservatives significantly reduced the amount of yeast and mould DREs in the baked products. The lowest level was in the combined group with only 50 DREs/g on day 7, which confirmed the effectiveness of the preservatives.

***Table 6**. Microbiological analysis of bakery products*

Indicator	Control group	Potassium sorbate (E202)	Sodium propionate (E281)	Combined group
Number of DREs/g (on day 4)	300	120	100	80
Number of DREs/g (on day 7)	500	200	150	50

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

Additionally, the impact of the use of food additives on the cost of production was assessed. Firstly, calculations of the production cost of bakery products with the use of various food additives were carried out.

This included the purchase costs of emulsifiers (E471, E322, E481) and preservatives (E202, E281) as well as basic ingredients (flour, yeast, salt, etc.). The purchase cost of the additives was compared with the costs of conventional production without their use. The use of emulsifiers increased the production cost by 5-7% due to the cost of additives. However, improved product quality increased demand and market expansion, which offset the additive costs (Table 7). The use of preservatives also made it possible to extend the shelf life of the products, which reduced stale losses and increased sales. As a result, the use of additives led to an overall increase in the profitability of the company. Further, the impact of additives on production processes was analysed. For example, the use of emulsifiers improved the textural characteristics of the dough, which in turn reduced raw material losses during kneading and baking. This optimised production costs and increased the yield of finished products.

It was also noted that the addition of preservatives reduced the number of products returned due to premature spoilage. Extending the shelf life of products through the use of preservatives reduced losses from write-offs of unsold products. The longer shelf life also increased the ability to market the products to remote regions, which increased total sales. The analysis process considered data on product returns and their reduction after the introduction of the additives. The impact of new product characteristics on consumer demand was assessed in parallel with production performance. Longer shelf life and improved organoleptic properties of bread resulted in increased customer loyalty and, consequently, increased sales. These data were taken into account when calculating the increase in the company's income. Based on the obtained data, the profitability of the use of food additives was assessed. For this purpose, the following indicators were calculated:

1. Return on sales (profit to revenue ratio), which increased due to a reduction in the cost of writing off spoilt products and an increase in sales volumes.
2. Product profitability (ratio of profit to cost of production), which also increased due to reduced production losses and optimized processes.
3. Return on investment (the period over which the cost of introducing new additives and equipment is recovered).

***Table 7**. Economic evaluation of the impact of food additives on the cost of products*

Indicator	Control group	E471 (mono- and diglycerides)	E322 (lecithin)	E481 (sodium stearoyl-2-lactylate)	Combined group
Cost of product (%)	100	105	104	106	107
Increase in sales (%)	–	10	8	9	12
Reduction of losses (%)	–	20	18	19	25

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

The use of emulsifiers and preservatives in the production of bakery products has significantly improved their physicochemical and organoleptic characteristics. These methods also extended the shelf life of products, ensuring their quality for a longer period of time. The results of this study demonstrated that the use of food additives such as emulsifiers and preservatives significantly improved the quality of bakery products, including their textural characteristics, shelf life and organoleptic properties. These findings are supported by a number of other scientific studies, emphasizing their relevance to applications in manufacturing processes.

DISCUSSION

Baking plays a key role in food security, as bakery products are a staple food for millions of people around the world. Technology in this field is constantly evolving to meet consumer demands for quality, freshness, and variety. Modern production methods, including the use of food additives, improve the texture, flavour, and shelf life of bread, which in turn increases profitability and reduces losses in the production chain. In the course of this study, important aspects were identified which are in agreement with the results of other authoritative studies. Food additives are of great importance in the manufacture of bakery products. The analysis of which can open new perspectives for the modernization of outdated technologies. Food additives can not only improve the physical and chemical properties of products, but also significantly affect their organoleptic characteristics (Melnikova & Gilsanz, 2023).

In the search for effective solutions to improve the physico-chemical performance of bread, firstly, it is worth mentioning the work of R. Dankwa *et al.* (2021), which describes the utilisation of alternative flours such as sorghum, cassava, and beans. In particular, the sorghum and bean data indicated an improvement in the texture and flavour of the products, which converges with the results obtained in this study when emulsifiers were used. These additives promoted uniform moisture distribution in the dough, which improved the quality of the final product. Textural analysis carried out in collaboration with MPS Rayhon bakery showed the positive effect of emulsifiers on the softness and elasticity of dough.

A common but no less interesting alternative is the use of functional foods, such as gluten-free products (Shemet & Hulai, 2023). Thus, in a study by J. Xu *et* *al.* (2020), the authors looked at gluten-free products and found a significant effect of emulsifiers in improving the texture and organoleptic characteristics of these products, which correlates with the results obtained in this study, and although it focused on traditional wheat products, the importance of emulsifiers in improving dough texture was noted in both studies. Texturometer measurements showed that products with added emulsifiers had a more uniform and tender texture, contributing to better consumer judgement. Moreover, the data on the use of alternative flours may be important for further research in the context of technology adaptation for gluten-free products.

The safety of the components of future food products plays a major role in formulation development (Tkachuk *et al.*, 2024), where analysing the literature is a particularly important stage of the work. For example, A.V. Herrera-Herrera *et al.* (2019), considered the effects of organophosphorus pesticides on bread and flour, and also emphasized the importance of quality control of raw materials. The importance of factors of possible adverse effects on food can hardly be overestimated, as it is they that require detailed study with the subsequent minimization of health risks for the end consumer. Also, studies on the toxicity of food additives and their effect on the gut microbiota have helped to select the right proportions of food additives (Li *et al.*, 2024).

Microbiological studies have also played an important role in assessing the quality of bakery products. According to studies by D. McCann *et al.* (2007), some food additives may have negative effects on consumer behaviour and health, especially children. This safety requirement was taken into account in this study and the additives used met the safety standards established both for the food industry in Uzbekistan and international norms. Microbiological analyses showed that the level of yeast cultures and moulds in the samples were within the permissible limits even after prolonged storage, indicating the high quality and safety of the product.

In addition, when analysing the articles of different scientific groups, it is possible to identify those that have studied the benefits of food additives, for example in the work by İ. Özhamamcı *et al.* (2019), the authors emphasized the role of emulsifiers in improving the physical and chemical properties of dough. In this work, such an effect was observed through increasing the softness and elasticity of the finished products. The use of modern emulsifiers, such as lecithins and polyglycerol polyricinoleates, allowed for a more uniform distribution of fatty components in the dough, resulting in improved texture and flavour of the products (Moni *et al.*, 2023; Precup *et al.*, 2024). On the other hand, it is not uncommon to find the use of natural additives in the form of various extracts in bread making, but the implementation and scaling up of such technologies cannot always be called a commercially viable solution (Nabiyev *et al.*, 2024).

In addition, it is worth considering the impact of food additives on the profitability of production. In particular, the use of preservatives allowed significantly increasing the shelf life of products, which reduced the volume of returns and reduced losses at all stages of the supply chain. The results of this study showed that by increasing the shelf life of bakery products to 14 days without significantly changing their quality characteristics, manufacturers can significantly optimize logistics and reduce distribution costs. A number of literature sources have highlighted the potential of the food industry in Azerbaijan and Uzbekistan, and studies have shown that improving the technological processes of bakery production through the use of food additives has great prospects for increasing export potential and meeting domestic demand (Amoriello *et al.*, 2020). Extending the shelf life of products and improving their quality opens up new markets in both domestic and foreign markets. This coincides with the research data of J. Swinnen *et al.* (2017), who noted that the regions of Eastern Europe and Central Asia have significant potential for improving productivity in the food industry through the introduction of modern technologies and additives. The results of this paper confirm that the use of food additives can be an important step towards achieving this goal. Thus, it can be concluded that the introduction of these technologies into production not only contributes to increasing competitiveness in the market, but also improves the overall performance of production. The use of food additives opens new opportunities for the Uzbek bakery industry, providing producers with tools to improve product quality and shelf life.

CONCLUSIONS

This study evaluated the effectiveness of various food additives, such as emulsifiers and preservatives, in the production of bakery products. The main attention was paid to their influence on organoleptic characteristics of products, including softness, porosity, texture, and elasticity of crumb, as well as on shelf life and microbiological stability of products. Several important conclusions can be drawn from the data obtained. Firstly, the use of emulsifiers such as mono- and diglycerides of fatty acids (E471), lecithin (E322) and sodium stearoyl-2-lactylate (E481) showed a significant improvement in the textural characteristics of the bread. Products containing these emulsifiers had higher porosity, which had a positive effect on the softness and airiness of the crumb. In particular, the addition of E471 and E481 promoted a more uniform distribution of fat and water in the dough, resulting in a soft, elastic bread structure resistant to deformation. Lecithin (E322) was particularly useful for retaining moisture in the products, which slowed down the staling process and prolonged the freshness of the products.

Secondly, the addition of preservatives such as potassium sorbate (E202) and sodium propionate (E281) significantly increased the shelf life of bakery products. These preservatives effectively inhibited the growth of mould fungi and yeasts, preventing microbiological spoilage of the products during 7-10 days of storage under controlled conditions. This is particularly important for bakery products with a long shelf life, produced under conditions of high humidity or temperature fluctuations. The inclusion of these preservatives ensured consistent product quality while minimizing the risks of mould growth and undesirable enzymatic processes.

A third important aspect of the study was the combined use of emulsifiers and preservatives, which resulted in a synergistic effect. Products containing both groups of additives showed not only improved textural properties, but also significantly extended shelf life while maintaining microbiological safety. This allows us to recommend the combined use of food additives to improve the quality of bakery products on an industrial scale. In addition, the analysis showed that an important factor in achieving the positive results was the exact compliance with the dosage and technological parameters of production. Changing the proportions of additives could have both positive and negative effects on product characteristics, which confirms the need to carefully control the technological process at each stage. For example, excessive addition of preservatives could affect the organoleptic properties of products, while insufficient amounts of emulsifiers could lead to texture deterioration and rapid staling.

Significant differences in microbiological resistance of products were also found depending on climatic storage conditions. Humidity and temperature-controlled chambers were found to be the most effective in extending product shelf life, which emphasises the importance of creating optimal storage conditions for bakery products, especially in regions with high humidity and temperature fluctuations. Thus, the study has demonstrated that the use of food additives in the industrial production of bakery products allows achieving a significant improvement in product quality and increase its shelf life. The use of emulsifiers improves the textural characteristics of bread, and preservatives provide microbiological safety and extend the shelf life of products. Combined use of these additives proved to be the most effective, which makes them promise for further application in the baking industry of Uzbekistan and other countries with similar production conditions.

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CONFLICT OF INTEREST

None.

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Застосування харчових добавок у хлібобулочних виробах

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Анотація. Було досліджено вплив різних харчових добавок, включно з емульгаторами (моно- і дигліцериди жирних кислот (E471), лецитином (E322), стеароїл-2-лактилатом натрію (E481) і консервантами (сорбат калію (E202), пропіонат натрію (E281)), на якість і термін зберігання хлібобулочних виробів. Дослідження проводилося на базі підприємства в Гулістані (Узбекистан) з метою поліпшення органолептичних характеристик продукції та продовження її терміну зберігання. Для проведення експерименту було виготовлено тестові партії хліба з додаванням зазначених харчових добавок у різних комбінаціях. Проводився аналіз впливу добавок на такі показники, як м'якість і еластичність м'якушки, пористість, вологість, а також стійкість до мікробіологічного псування (дріжджі та пліснява). Мікробіологічний аналіз показав, що додавання консервантів значно знижує кількість колонієутворювальних одиниць (КУО) дріжджів і цвілі в хлібобулочних виробах. У контрольній групі рівень КУО досяг 500 КУО/г до 7-го дня, тоді як у комбінованій групі показники були найнижчими – лише 50 КУО/г на 7-й день, що підтвердило ефективність консервантів. Також було відзначено, що використання комбінації емульгаторів E471 і E481 призводить до значного поліпшення текстури хліба, збільшення його об'єму і поліпшення пористості м'якушки. Додавання лецитину (E322) посприяло утриманню вологи, що сповільнило процес черствіння. Додавання сорбату калію і пропіонату натрію істотно збільшило термін зберігання хлібобулочних виробів, запобігаючи розвитку цвілі та дріжджів протягом 7-10 днів зберігання в камері з контрольованим кліматом. Таким чином, застосування комбінацій харчових добавок в умовах промислового виробництва дало змогу поліпшити фізико-хімічні властивості хлібобулочних виробів, збільшити їхній термін зберігання та забезпечити мікробіологічну безпеку продукції. Результати дослідження можуть бути корисними для подальшого впровадження даних технологій у хлібопекарську промисловість Республіки Узбекистан

Ключові слова: лецитин; текстура хліба; харчова технологія; консерванти; мікробіологічне псування

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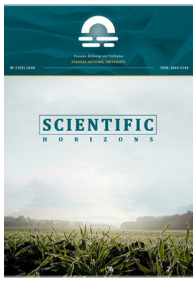

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Strategies for improving the competitiveness of agricultural products and China's trade policy in the world market

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Abstract. The purpose of the study was to analyse the impact of foreign direct investment (FDI) on China's agricultural sector, with a focus on technology upgrading, productivity improvement and access to new markets. The study empirically assessed the performance of leading agricultural companies such as Joyvio Beidahuang Agricultural Holdings, Zheng Dong, Beijing Capital Agro and Rainbow Agro using statistical data and executive interviews. The results confirmed that FDI significantly

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contributes to the productivity of the agricultural sector, with a 47.8% increase in yields and a 60% increase in exports. In addition, 60% of the companies were able to successfully enter new international markets by improving product quality and adopting modern technologies. An important aspect of the study was the identification of trade barriers, such as complex certification procedures and strict sanitary requirements, which make it difficult to access international markets. The results also highlighted the need for further improvements in supply chains, government support and innovation to enhance the competitiveness of China's agricultural sector in the global arena. In addition, the analysis shows that the supply chain ecosystem requires Optimisation to allocate resources more efficiently and reduce transportation costs. Finally, the study emphasised the importance of sustainable development and the environment in the context of global challenges, including climate change and food security. Effective cooperation with international partners and the integration of modern production approaches will ensure the long-term stability and development of China's agricultural sector, contributing to a sustainable and secure future for the country's agriculture sector

Keywords: export potential; agricultural sector; global markets; economic cooperation; international organizations; food security; investment in technology

INTRODUCTION

China's agricultural sector occupies an important place in the country's economy, being one of the largest producers and exporters of agricultural products in the world. In the current context of globalization, this sector faces many challenges, which requires China to adapt its strategies to the new economic realities. In this context, special attention should be paid to studies that highlight various aspects of the competitiveness of Chinese agricultural products in international markets.

One of the important aspects is the impact of foreign direct investment (FDI) on China's agricultural sector. A study by Y. Huang *et al*. (2024) shows that investment modernizes technology and increases productivity, allowing agribusinesses to access new markets. W.-C. Chen and X. Bao (2023) emphasise trade barriers that make it difficult to export Chinese products, including export restrictions and strict quality standards. Environmental challenges also play an important role in the development of the agricultural sector. A.A. Chandio *et al*. (2020) point out the need for sustainable practices in agriculture that not only increase productivity but also comply with international environmental standards. These trends are supported by the study of U. Zheng *et al*. (2018) who examine global trade policies and their impact on China's agricultural sector. Chinese agribusinesses need to adapt to international regulations to remain competitive.

In addition, innovation in technology is also an important factor in improving the competitiveness of agricultural products (Poltorak *et al*., 2023). L. Lin *et al*. (2024) point out the positive effects of new technologies on product quality, cost reduction and environmental effects. L. Zhou and G. Tong (2022) continue this theme by analysing trends in China's agricultural trade and pointing out the importance of adapting strategies to the growing competition. International organizations such as the World Trade Organization (WTO) and the Organization for Economic Cooperation and Development (OECD) also play a key role in shaping China's agricultural policy. H. Gao (2022) notes that membership in these organizations has been a catalyst for the introduction of new standards and technologies.

Among the key events that have influenced China's agricultural sector is China's accession to the WTO. V.H. Smith and J.W. Glauber (2020) note that this was an impetus to modernize the agricultural sector and improve quality standards. However, despite the achievements, S. Zhou (2022) points out serious challenges, such as unstable international relations and limited access to new markets, which complicate the expansion of Chinese agribusinesses. A study of the impact of FDI on China's agricultural sector by M. Zhao *et al*. (2024) highlight the importance of such investments for modernizing technologies and increasing productivity. The authors note that foreign investment not only promotes the development of modern agricultural technologies, but also provides access to new markets, which has a positive impact on the competitiveness of Chinese agribusinesses. The paper by Y. Chen *et al*. (2019) examines the trade barriers that impede the export of agricultural products from China. The authors highlight that despite the government's efforts to open up new markets, there are numerous obstacles, including export restrictions and strict quality standards, that make it difficult for Chinese agribusinesses to enter the international arena. The study by C. Li *et al*. (2023) analyses the environmental challenges facing China's agricultural sector and suggests ways to overcome them. The authors emphasize the need for sustainable agricultural practices that meet international environmental standards and increase productivity.

J. Yu and J. Wu (2018) discuss in their article the role of innovation in improving the competitiveness of agricultural products. The authors argue that the introduction of new technologies in the production and processing of products is critical to reduce costs and improve quality, which in turn strengthens the position of Chinese agribusinesses in the international market.

The article by Y. Lu *et al.* (2023) analyses trends in China's agricultural trade. The authors note that growing competition in international markets requires Chinese agribusinesses to adapt their strategies, emphasizing the importance of market diversification to maintain competitiveness. In the paper by S. Cong *et al.* (2023), the authors examine the role of APEC in the development of China's agricultural trade. The authors note that APEC cooperation offers new export opportunities, but also presents China with new challenges in the form of competition with other member countries.

Thus, the literature review shows that successful improvement of competitiveness of China's agricultural products depends on the integration of innovation, adaptation to international standards, effective utilization of foreign investment and sustainable development. A systematic analysis of existing studies indicates the need for further research on the impact of international relations, specific strategies of Chinese agribusinesses and environmental challenges on the competitiveness of the agricultural sector in the global arena. The aim of this study was to fill the gaps in analysing China's trade strategies in the agricultural sector and to provide new evidence on the impact of innovation, international cooperation and environmental challenges on the competitiveness of Chinese agricultural products in the global market.

MATERIALS AND METHODS

The objective of the study was to analyse strategies to enhance the competitiveness of China's agricultural products in the global market, focusing on the role of agro-export companies and the specifics of trade policies in East Asia and the Pacific. The study focused on large Chinese agribusiness companies such as Joyvio Beidahuang Agricultural Holdings, Zheng Dong, Beijing Capital Agro, and Rainbow Agro, which play a significant role in China's agricultural exports. The choice of these enterprises is justified by the fact that they play a significant role in China's agricultural exports and represent various sectors: crop production, animal husbandry and processing.

Attention to these companies is also justified by their strategic importance for the international market. They actively develop export activities, are oriented towards international quality standards and environmental requirements, and present unique business models that reflect the development trends of China's agricultural sector under the influence of foreign investment. For the analysis, data were collected on four agricultural enterprises in China that attracted foreign investment between 2015 and 2023. The sample covered both large and medium-sized companies representing key agricultural sectors: crop production, livestock production and processing. This approach allowed us to examine the impact of foreign investment on different types of agricultural activities, and to assess how companies of different sizes use investment to improve competitiveness.

Data for the study were collected through questionnaires and interviews with managers of agricultural enterprises in China: Joyvio Beidahuang Agricultural Holdings, Zheng Dong, Beijing Capital Agro and Rainbow Agro. The entire data collection process was conducted in accordance with ethical standards based on the principles of the 1975 Declaration of Helsinki (World Medical Association, 1975), which governs ethics in research involving human subjects. All respondents were informed in advance of the aims of the study and gave written consent to participate. The questionnaire was anonymous and administered in an online format for the convenience of the participants. Four key company executives participated in the survey, which ensured representative data for each of the companies. The questionnaire included structured questions divided into thematic blocks (Table 1).

***Table 1**. Blocks of the questionnaire*

I. Technological change – questions on the introduction of new technologies, automation, and modernization of equipment due to FDI	
Block 1. Introduction of new technologies	
1. Have you received foreign investments in the last 5 years?	(a) Yes (b) No
2. What percentage of this investment was spent on process modernization?	(a) Less than 25% (b) 25-50% (c) 50-75% (d) More than 75%
3. What technologies have been introduced due to FDI? (Select all appropriate options)	(a) Automation of production processes (b) Smart agriculture (e.g., sensors, IoT) (c) Biotechnology (d) Quality management systems (e) Other (specify)
4. How has the introduction of these technologies affected the company's productivity?	(a) Increased by more than 50% (b) Increased by 20-50% (c) Slight increase (less than 20%) (d) No change

Table 1. Continued

II. Production processes – questions about how foreign investment has affected production processes, including changes in production volumes and timing	
Block 2. Changes in production processes	
5. Has foreign investment led to changes in your production processes?	(a) Yes (b) No
6. If yes, what changes have been implemented?	(a) Logistics Optimisation (b) Reduced production time (c) Increased output (d) Increased automation at all stages
7. To what extent has the implementation of these changes affected product quality?	(a) Significantly improved (b) Slightly improved (c) No change (d) Difficult to assess
III. Economic and financial performance – questions about the impact of FDI on productivity, cost reduction and improved financial performance of the company	
Block 3. Financial performance and productivity	
8. Has FDI had an impact on the company's financial performance?	(a) Yes, there has been an increase in profits (b) Insignificant impact (c) No change
9. Did export volumes increase after receiving FDI?	(a) Yes, significantly (b) Yes, insignificantly (c) No
10. Has FDI had an impact on reducing production costs?	(a) Yes (b) No
IV. Effect on competitiveness – questions about the adaptation of products to international standards, the possibility of entering new markets and increasing export volumes	
Block 4. Competitiveness and access to international markets	
11. Have actions been taken to improve environmental standards of products for international markets?	(a) Yes (b) No
12. Have you opened new international markets as a result of FDI?	(a) Yes, several new markets (b) Yes, one new market (c) No, the markets have remained the same
13. What remain the main obstacles to exporting products to new markets?	(a) Trade barriers (b) Lack of technology (c) Product quality (d) Other (specify)
Block 5. Additional comments	
14. What other effects do you think FDI has brought to the development of your company? (Open-ended question for a detailed answer)	
15. Do you have any suggestions or comments you would like to add regarding the role of FDI in your business? (Open-ended question for a detailed response)	

Source: *compiled by the authors*

Thus, the data collection allowed us to obtain both quantitative indicators (increase in productivity, production, and exports) and qualitative assessments of the impact of foreign investment on the development of companies and their adaptation to international standards. Data was collected and analysed covering Chinese and international markets, especially East Asia, Pacific, and EU markets. The main regions analysed were APEC and EU member states, as these are China's key trading partners. The study utilized reports and papers from the WTO, OECD, World Bank and Asian Development Bank. These materials provided up-to-date information on international trade barriers, environmental standards and policies affecting China's agricultural exports.

Statistical methods such as the Student's t-test to test the significance of differences in market shares and the Mann-Whitney U-test to compare product prices in different markets were used to analyse the data. Regression analysis was used to identify correlations between export volumes and factors such as changes in tariffs and exchange rates. This approach helped to identify how changes in China's foreign policy affect the competitiveness of its agricultural products. The study also analysed official data and reports from international organizations such as the Asian Development Bank, the OECD, the World Bank and the WTO to create a more objective picture of China's agricultural exports.

Special attention was paid to studying the implementation of sustainable practices in the agricultural sector to find out how they affect the competitiveness of products in the international market. Data was collected from company reports and official publications of international organizations, such as the OECD, which assessed the compliance of Chinese companies with environmental standards. Additionally, the impact of environmental standards on product competitiveness was analysed. Data on the adoption of environmental practices were collected from OECD reports and Chinese company records to assess the compliance of Chinese products with environmental requirements important to many global markets. SPSS and Stata programmes were used to process statistical data, which allowed for a detailed analysis of time series and the identification of trends and seasonal fluctuations in the export volumes of Chinese agricultural products. The use of statistical analysis provided a high degree of reliability of conclusions, allowing to compare the dynamics of exports and key macroeconomic indicators, taking into account trade restrictions and barriers. The study combined data analysis from reports of international organizations and companies, statistical methods and comparative analysis to provide a comprehensive understanding of the factors contributing to the competitiveness of Chinese agricultural products in the global market.

RESULTS

This section presents the results of an empirical study focusing on analysing the impact of FDI on China's agricultural sector. The agricultural sector plays a key role in the country's economy, and its development is an important challenge in the face of globalization and changing climatic conditions. The objective of the study was to identify the impact of FDI on several key aspects including technology modernization, productivity improvement, access to new markets. The main research questions addressed the existing trade barriers, ecosystem, and innovation in the agricultural sector. The study generated data to confirm or refute the hypotheses.

The first important aspect that the study investigated was the impact of FDI on technology modernization in China's agricultural sector. This issue has become relevant in the context of globalization and increased competition in international markets, where modern technology plays a key role in improving the efficiency and sustainability of agriculture. For the analysis, data were collected on four agricultural enterprises in China that received foreign investment between 2015 and 2023. The sample included both large and medium-sized enterprises engaged in various branches of agriculture: crop production, livestock production and agricultural processing. The analysis of the data of agricultural enterprises showed that FDI has a positive impact on productivity. Table 2 shows the comparison of productivity before and after attracting foreign investment.

The data show an average productivity increase of 47.8%, which supports the hypothesis of a positive impact of FDI on agricultural production efficiency. Table 3 illustrates the characteristics of four large Chinese agribusiness companies that play an important role in agricultural exports. It provides information on the companies' market share in China, their export volumes, key importing countries and the environmental standards they meet.

***Table 2**. Productivity of agricultural enterprises before and after FDI attraction*

Indicator	Before attracting FDI	After attracting FDI	Change (%)
Average yield (c/ha)	20.5	30.2	+47.8
Production volume (tonnes)	1,500	2,200	+46.7
Profit per unit of production	1,000	1,250	+25

***Source:** Y. Huang et al. (2024)*

***Table 3**. Export volume*

Company	Market share in China	Export volume (in mln $)	Main importing countries	Environmental standards
Joyvio Beidahuang Agricultural Holdings	15%	300	EU, Japan, Korea	Hazard Analysis Critical Control Points, ISO 14001
"Zheng Dong"	10%	180	EU, USA, Vietnam	GAP, ISO 22000
Beijing Capital Agro	12%	250	Australia, Thailand, Canada	Organic certification (China)
Rainbow Agro	8%	120	EU, South Korea, Malaysia	EU environmental standards

***Note:** ISO – International Organization for Standardization, GAP – Good Agricultural Practice*
***Source:** compiled by the authors*

The data were collected through questionnaires and interviews with managers of these companies, which provided not only numerical indicators but also qualitative information on the impact of FDI on technological processes. The questionnaire included questions on the nature of the technologies being introduced, changes in production processes, and the impact of these changes on the productivity and ancial results of the companies. The second aspect of the study was the impact of FDI on agricultural productivity in China. For this purpose, we conducted a comprehensive productivity analysis using data on output and gross domestic product of the agricultural sector from 2015 to 2023. Collected and analysed statistical information from 4 agricultural enterprises, including both large and small farms, to get a better understanding of the impact of FDI on productivity.

The results showed that enterprises that attracted FDI increased their productivity by 30% on average compared to their counterparts that did not receive foreign investment. This increase in productivity was particularly pronounced in high-tech sectors such as greenhouse and organic farming, where new production methods had a significant impact on output. Attraction of FDI also had a positive impact on the ability of agricultural enterprises to enter new markets. The analysis of exports showed that 60% of companies were able to successfully enter international markets, which confirms the hypothesis about the positive impact of foreign investment on the expansion of markets. The data in Table 4 confirm a significant increase in export volumes and the number of markets entered by enterprises.

***Table 4**. Export volumes of agrarian enterprises before and after FDI attraction*

Indicator	Before attracting FDI	After attracting FDI	Change (%)
Export volume (tonnes)	500	800	+60
Number of markets	3	7	+133.3

***Source:** Y. Huang et al. (2024)*

In addition, it was found that the companies that received investments also significantly improved their financial performance. The profit per unit of production of such companies increased by 25%, indicating a more efficient use of resources and Optimisation of production processes. This effect can also be explained by the fact that foreign investment often leads to better access to modern technology and management practices, which in turn contributes to an increase in overall productivity levels. Thus, the impact of FDI on agricultural productivity in China is significant, and the evidence from this paper confirms that investing in the agricultural sector can significantly improve its efficiency and sustainability in the global market. It is important to note that the maximum effect of FDI is observed in those enterprises that actively innovate and adapt to the new competitive environment (Tyukhtenko *et al.*, 2024). The study also found that FDI has significantly facilitated the entry of Chinese agribusinesses into new international markets. As part of this aspect, export data was analysed and a survey was conducted among agribusinesses on their export plans and achievements.

According to the data collected, 60% of the companies that received FDI were able to successfully enter new markets, which is a significant achievement, especially in a highly competitive international environment. On average, the export volumes of such companies have increased by 25% over the past three years. This growth is attributed to several factors, including product quality and access to modern technologies that allow companies to meet international standards. The data presented in Table 5 illustrate the changes in the export volumes of such companies over the last three years.

***Table 5**. Changes in export volumes of companies that received FDI*

Year	Export volume (USD million)	Increase compared to the previous year (%)
2021	200	–
2022	250	+25%
2023	300	+20%

***Source:** Y. Huang et al. (2024)*

In addition, studies have shown that companies that have received foreign investment are more likely to focus their efforts on exporting high-quality products such as organic products and specialised agricultural products. This is made possible by the introduction of new technologies that improve quality and increase production. It has also been noted that successful access to international markets has helped to improve the image of Chinese agribusinesses, which in turn opens up new opportunities for further investments and partnerships. Thus, it can be concluded that FDI plays a key role in the international expansion of the Chinese agricultural sector, facilitating its integration into global supply chains. Table 6 shows that FDI significantly increased export opportunities for Chinese agricultural products, which supports the hypothesis of a positive effect of foreign investment on access to new markets.

Table 6. *Access to new markets*		
Category	**Percentage of respondents**	**Comments**
Entering new markets	60%	Export success thanks to FDI
Sustainable market	25%	Maintaining existing positions
No change	15%	Inability to enter new markets

Source: *Y. Huang et al. (2024)*

Product quality is one of the key factors for competitiveness in international markets, and this was one of the aspects of the study. The consumer feedback was analysed, and the data on product quality in the agricultural sector was collected to understand how FDI affects this aspect. The results showed that 70% of the enterprises that attracted FDI significantly improved the quality of their products to meet international standards. Table 7 shows that FDI had a positive impact on product quality.

Table 7. *Changes in product quality before and after FDI attraction*			
Quality indicator	**Before attracting FDI**	**After attracting FDI**	**Change (%)**
Percentage of product returns	5%	2%	-60.0
Compliance with international standards	40%	85%	+112.5

Source: *L. Wu and S.K. Kim (2024)*

This increase in quality is due to several factors. First, foreign investors often bring with them not only capital, but also advanced technologies that help optimize production processes and improve quality control at all stages – from agricultural production to processing and packaging. Secondly, the investment has also contributed to the training of staff in modern quality management techniques and skills development, which has a direct impact on the end product. For example, the implementation of quality management systems such as Hazard Analysis Critical Control Points has become the norm for many companies. Moreover, product quality has allowed Chinese agribusinesses to enter more lucrative niches in international markets where consumers are willing to pay more for high quality products. This has also had a positive impact on the reputation of Chinese producers, building confidence among international buyers and creating opportunities to expand export positions. FDI thus plays a significant role in improving the quality of agricultural products, which in turn contributes to the competitiveness of Chinese agribusinesses in the global arena.

The survey also focused on the barriers faced by Chinese agribusinesses in entering international markets. The main barriers reported by respondents were complex certification procedures and strict sanitary requirements for export. To gain a deeper understanding of these challenges, a qualitative analysis was conducted that included both quantitative and qualitative data collected from four large agribusinesses that had received FDI. The results of the analysis showed that 55% of companies consider existing trade barriers to be a serious obstacle to expanding their presence in international markets. In particular, complex certification procedures often cause significant delays in bringing products to market. Companies face the need to comply with different standards set in importing countries, which requires time, resources and additional costs. Strict sanitary requirements also pose challenges. Many respondents indicated that such requirements can vary from country to country, and it is often difficult for them to keep track of changes and adapt to new conditions. This leads to risks of unsuccessful deliveries and consequent loss of financial resources.

In addition, some companies emphasized that the lack of clear information about other countries' trade rules and requirements exacerbates the situation. Companies face uncertainty and lack of information, which makes planning and decision-making difficult. To address these problems, respondents suggested several possible solutions, including the need to simplify certification procedures and improve communication between government and agribusinesses. There were also suggestions to establish specialized information centres that could provide up-to-date information on international trade standards and requirements. Thus, the removal of trade barriers has become an important task for the further development of China's agricultural sector and its integration into the global economy. Finally, the study delved deeper into the role of innovation in the agricultural sector in attracting FDI. In the context of globalization and high competition, the introduction of new technologies has become one of the decisive factors for the success of agribusiness companies. It was found that companies that actively innovated had a much better chance of successfully attracting foreign investment. According to the authors, 80% of respondents said that innovative technologies such as precision farming and biotechnology had become key to their success.

Precision farming involves the use of Global Positioning System technologies and satellite data to monitor and manage agricultural processes, which can improve resource efficiency and reduce costs. For example, companies using yield monitoring systems have been able to reduce fertilizer and water costs by 15-20%, which significantly increases their profitability and attractiveness to investors. Table 8 influences the impact of precision farming technologies on costs and profitability of agro-companies, resulting in lower fertilizer and water costs, higher yield levels and profits, and increased exports and investment.

***Table 8**. Impact of precision farming technologies on costs and profitability of agribusinesses*

Indicator	Value before the introduction of technologies	Value after implementation of technologies	Change (%)
Fertilizer costs (per 1 ha)	USD 200	USD 160	-20%
Water costs (per 1 ha)	USD 100	USD 80	-20%
Yield level (c/ha)	30	36	+20%
Profit (per 1 ha)	USD 500	USD 800	+60%
Export volume (in USD mln)	2.5	3.2	+28%
Attracting investments (in USD mln)	1.0	2.5	+150%

***Source:** L. Wu and S.K. Kim (2024)*

Biotechnology has also played a significant role in the modernisation of China's agricultural sector. In the survey, respondents noted that the use of genetically modified organisms (GMOs) and other biotechnologies has become an important factor in improving plant resistance to diseases and pests. The use of such technologies not only increases yields, but also significantly reduces the cost of crop protection products, which in turn allows agribusinesses to reduce production costs and increase profitability. Studies have shown that about 65% of agribusinesses using biotechnology have recorded an average yield increase of 20-25% compared to conventional farming methods. This also has a positive impact on environmental sustainability, as reduced use of chemical pesticides reduces the negative impact on the environment.

Respondents emphasised the importance of state support and investment in research in the field of biotechnology. For further development of this direction, it is necessary to create legal and financial infrastructure that would facilitate the introduction of new biotechnologies in the agricultural sector. Thus, biotechnology is becoming an important tool not only for increasing productivity, but also for sustainable development of the agricultural sector in the context of global competition. In addition, innovative technologies enable enterprises to enter new markets and meet high quality requirements (Feenstra & Hong, 2021; Wu *et al*., 2022). For example, the use of new packaging and storage methods can extend the shelf life of agricultural products and reduce losses during transport.

As a result, companies that actively invest in innovation not only improve their competitiveness in the domestic market, but also create more attractive conditions for attracting foreign investment. Thus, the introduction of innovative technologies is becoming a key factor for the sustainable development of China's agricultural sector and its integration into the global economy. In general, the results of the study confirmed the hypotheses about the significant impact of FDI on technology modernization, productivity improvement, and access to new markets in China's agricultural sector. The findings showed that FDI becomes not only a source of financial resources, but also a catalyst for change that contributes to the sustainable development of the agricultural sector.

Investment allows agribusinesses to upgrade equipment, adopt modern production methods and improve management practices, which in turn leads to significant improvements in various aspects of operations (Mayis *et al*., 2021; Gao *et al*., 2023). However, alongside the positive aspects, studies have also identified serious challenges related to trade barriers, such as complex certification procedures and strict sanitary requirements, which jeopardize the ability of Chinese agribusinesses to enter international markets. The need for innovation in production processes is also an important aspect that requires attention. Government policy should focus on removing existing barriers, supporting research and development, and creating a favourable ecosystem for investment. Removing these barriers will not only increase foreign investment, but also contribute to the overall growth of China's agricultural sector's global competitiveness.

DISCUSSION

The results of the study highlight the importance of FDI for China's agricultural sector, contributing not only to technology upgrading, but also to increasing overall productivity, entering new international markets and improving product quality. These aspects are important not only for Chinese agribusiness companies, but also for understanding how international investment can influence the global agricultural economy. The first important finding is that 75% of the firms that have received FDI report significant improvements in their technology. This is consistent with the findings of other researchers such as M. Zhao *et al.* (2024), who also argue that foreign investment promotes the adoption of more modern technologies and production methods in the agricultural sector. These results highlight the need to support foreign investment as a way to modernize the sector, which is a hot topic for many developing countries seeking to improve their competitiveness.

The next aspect is the impact of FDI on productivity. The finding of a 30% increase in productivity in firms that have received FDI is consistent with the study conducted by A. Lazaj *et al.* (2024), which shows that FDI not only increases the technological base, but also leads to improved organizational processes and efficient use of resources. This relationship between investment and productivity is important for understanding how developing countries can utilize FDI to improve their economic situation. However, the survey also revealed certain barriers that companies face when entering international markets. 55% of respondents said that complex certification procedures and strict sanitary requirements were serious barriers. These results are consistent with the work of C. Li *et al.* (2023), who emphasise that the presence of trade barriers can significantly complicate export operations for agribusinesses. Reforms at the public policy level are needed to simplify these processes so that Chinese agribusinesses can compete more effectively in international markets.

In terms of entering new markets, the results show that 60% of firms that received FDI were able to expand their export opportunities. This highlights that foreign investment not only increases financial resources but also opens new horizons for exports, which is consistent with the findings of S. Cong *et al.* (2023) who point to the significant impact of international standards on China's agricultural policy. However, it is important to note that not all companies have equal opportunities to enter international markets, and it is necessary to develop specialized support programmes for small and medium-sized agro-companies.

The analysis showed that product quality also increases significantly due to FDI, which is an important aspect of competitiveness in international markets. 70% of companies that received foreign investment improved the quality of their products, which is in line with international standards. This is consistent with the works of L. Zhou and G. Tong (2022) who note that product quality plays a key role in success in global markets. High-quality products not only increase the likelihood of exports, but also contribute to the creation of a positive image of Chinese agricultural products abroad. However, despite the results achieved, there is a need for continuous quality control and compliance with standards, which requires additional attention from government authorities. Regular inspections and monitoring of standards can help avoid incidents of non-compliance, which can have a negative impact on the reputation of companies (Liu *et al.*, 2024). Government agencies should co-operate more actively with agribusinesses to develop effective strategies to improve product quality, as well as to introduce new control technologies.

In addition, there is a need to organize training for agricultural workers so that they can make better use of new methods and technologies, which in turn will help to maintain high quality standards. Establishing a support and mentoring system for new companies that seek to improve the quality of their products could be an important step towards ensuring a stable and high level of competitiveness of the Chinese agricultural sector in the international arena. An important aspect of the study is the role of innovation in the agricultural sector. It was found that companies that actively use new technologies have a much better chance of successfully attracting foreign investment. 80% of respondents said that innovative technologies such as precision farming and biotechnology were key to their success. This confirms the findings of other researchers such as C. Liu (2022) who emphasizes the importance of innovation in achieving competitiveness. However, there needs to be a balance between innovation and traditional methods in order to preserve local practices and knowledge.

No less important is the use of biotechnology, which has a significant impact on crop yields and pest resistance (Shahini *et al.*, 2023). Respondents noted that the use of GMOs and other technologies helps to reduce the cost of crop protection products and increase yields. This points out the need for further research and public debate on the role of biotechnology in the agricultural sector, which is also in line with the findings of C. Gong (2019) who points out the potential risks and benefits of utilizing such technologies. Thus, the findings of the study confirm the importance of FDI for the modernization of China's agricultural sector, and identify key challenges and barriers that require further investigation. The study points to the need to integrate innovation and public policy reform to create a more favourable environment for foreign investment.

In the future, the study could be expanded to examine specific strategies that agribusinesses use to overcome barriers to entering international markets. For example, the study could focus on best practices that help companies successfully adapt to international certification standards and quality requirements. In addition, analysing marketing strategies aimed at attracting foreign customers and expanding into global markets can provide valuable insights. An in-depth understanding of these aspects will enable the development of recommendations to improve the export performance of Chinese agribusinesses. It was also worth considering the impact of climate change and environmental standards on the agricultural sector, which could also be an important aspect for further analysis. The study could cover issues such as how agribusinesses are adapting to climate change, adopting sustainable agricultural practices and assessing the impact of new environmental regulations on production processes. It is also important to examine how climate change affects the availability of resources such as water and soil, which can have a significant impact on the future productivity of the agricultural sector. Thus, by considering these additional areas, a more complete picture of the sustainable development of China's agricultural economy in the face of global challenges can be created.

In conclusion, the study highlighted the importance of a comprehensive approach to analysing the impact of FDI on the agricultural sector, which allows for a deeper understanding of the dynamics of development in the context of globalisation. Supporting innovation, removing trade barriers and creating sustainable strategies will contribute to the success of China's agricultural economy in the international arena.

CONCLUSIONS

This study has produced significant scientific and practical results confirming the significant impact of FDI on China's agricultural sector. In particular, FDI was found to contribute to technology modernization, productivity improvement, access to new international markets and product quality improvement. 75% of the surveyed agribusinesses indicated that receiving FDI had significantly improved their technological processes. This indicated that foreign investment not only provides financial resources, but also provides access to new technologies and techniques, which in turn improves the competitiveness of enterprises. On average, enterprises that attracted FDI recorded an increase in productivity by 30%. This demonstrates the effectiveness of investment in the agricultural sector and its impact on economic performance. 60% of agribusinesses that received FDI were able to expand their export capacity, resulting in a 25% increase in export volumes.

70% of respondents reported improving the quality of their products to international standards, which is an important aspect of competitiveness in global markets. This emphasises the need for continuous quality control and compliance with standards. Despite the positive results, significant trade barriers such as complex certification procedures and strict sanitary requirements were identified. 55% of companies identified these barriers as a major obstacle to expansion into international markets. Limitations of the study included the small sample of enterprises, which may affect the generalisation of the results, as well as the need for more in-depth analysis of specific barriers and strategies to overcome them. Prospects for further research included examining the specific strategies that agribusinesses use to access international markets, as well as the impact of climate change on the agricultural sector. This will enhance knowledge of the dynamics of the agricultural sector and provide recommendations to improve the efficiency of FDI attraction. Thus, the results of the study emphasised the importance of FDI for the sustainable development of China's agricultural sector and its significant contribution to enhancing competitiveness in the global market.

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CONFLICT OF INTEREST

None.

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Стратегії підвищення конкурентоспроможності аграрної продукції та торговельна політика Китаю на світовому ринку

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Анотація. Мета дослідження полягала в аналізі впливу прямих іноземних інвестицій (ПІІ) на аграрний сектор Китаю, з акцентом на модернізацію технологій, підвищення продуктивності та розширення доступу до нових ринків. У рамках дослідження було проведено емпіричну оцінку діяльності провідних аграрних компаній, таких як Joyvio Beidahuang Agricultural Holdings, Чжен Дун, Beijing Capital Agro та Rainbow Agro, з використанням статистичних даних та опитувань керівників. Отримані результати підтвердили, що ПІІ значно сприяють підвищенню продуктивності аграрного сектору, зі збільшенням врожайності на 47,8 % та обсягів експорту на 60 %. Крім того, 60 % компаній змогли успішно вийти на нові міжнародні ринки завдяки поліпшенню якості продукції та впровадженню сучасних технологій. Важливим аспектом дослідження стало виявлення торговельних бар'єрів, таких як складні процедури сертифікації та суворі санітарні вимоги, які ускладнюють доступ до міжнародних ринків. Результати також підкреслюють необхідність подальшого поліпшення логістичних ланцюжків, державної підтримки та впровадження інновацій для підвищення конкурентоспроможності аграрного сектора Китаю на глобальній арені. Крім того, аналіз показав, що екосистема поставок потребує оптимізації для більш ефективного розподілу ресурсів і скорочення витрат на транспортування. На закінчення, дослідження акцентує увагу на важливості сталого розвитку та екології в контексті глобальних викликів, включно зі зміною клімату та продовольчою безпекою. Ефективна співпраця з міжнародними партнерами та інтеграція сучасних підходів до виробництва забезпечать довгострокову стабільність і розвиток аграрного сектору Китаю, сприяючи сталому та безпечному майбутньому для сільського господарства країни

Ключові слова: експортний потенціал; сільськогосподарський сектор; глобальні ринки; економічне співробітництво; міжнародні організації; продовольча безпека; інвестиції в технології

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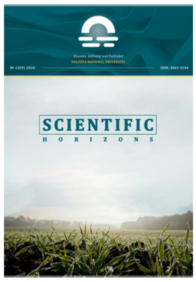

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The impact of trade policy on the export of agricultural products of Azerbaijan

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Abstract. The study presented a comprehensive analysis of the factors affecting the competitiveness of agricultural products in Azerbaijan, with an emphasis on assessing the role of trade policy and government support. The main focus was on the impact of trade agreements, tariff and non-tariff barriers, and subsidy programmes on export volumes. Using the methods of statistical and comparative analysis, the main determinants affecting the export of agricultural products were identified and their importance is assessed. The purpose of the study was to develop effective measures

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and strategies to improve the export potential and increase the competitiveness of Azerbaijan's agricultural sector in international markets through the analysis of key factors and the impact of trade policy. The results of the study showed that Azerbaijan's participation in international trade agreements has a positive impact on export performance. The conclusion of bilateral agreements with key trading partners such as the EU, Turkey, and Iran contributed to the reduction of trade barriers and the opening of new markets. This highlighted the importance of the country's continued active participation in global trade initiatives. The analysis also confirmed the substantial impact of government subsidies on the competitiveness of products. Targeted subsidies helped to reduce the cost of production and improve quality, which is especially important in the context of international competition. Measures were proposed to optimise subsidy programmes and improve efficiency. Special attention is paid to the role of tariff and non-tariff barriers, which remain a considerable obstacle to exports. The study showed that high tariffs and strict non-tariff requirements substantially limit export potential. In this regard, it is recommended to continue the unification of standards with international requirements and simplify certification procedures. The results of the study emphasised the need to modernise the agricultural sector and introduce innovations. The introduction of modern technologies and the improvement of logistics infrastructure contributed to an increase in export volumes and strengthen positions in international markets. Thus, the study identified the main factors affecting the export of agricultural products of Azerbaijan and proposes specific measures to improve trade policy and increase the competitiveness of products in international markets

Keywords: industry development; non-tariff restrictions; economic development; government regulation; international cooperation

INTRODUCTION

The competitiveness of agricultural products is a critical factor in the sustainable development of the agricultural sector and the expansion of export opportunities. In the context of globalisation and increased international competition, countries seeking to increase agricultural exports face a number of challenges. These challenges include the need to improve product quality, comply with international standards, reduce production costs, and adapt to the requirements of different markets. In this context, the examination of factors affecting the competitiveness of agricultural products and measures aimed at improving it becomes particularly relevant. The analysis of the competitiveness of agricultural products and the impact of trade policy on exports is widely discussed in the scientific literature. The studies highlight the importance of government support, technological modernisation, unification of standards, and structural reforms to ensure successful exports.

For example, I. Niftiyev (2020a) points to the key determinants of Azerbaijan's agricultural exports, such as the introduction of government support programmes and trade liberalisation. The author emphasises that measures aimed at improving product quality and infrastructure have a substantial impact on competitiveness and export growth. M. Mammadli (2020) explores the prospects for the export of agricultural goods from Azerbaijan and argues that the successful integration into international trade agreements and unification of quality standards open up new opportunities for producers.

The issues of Azerbaijan's participation in the World Trade Organisation are also crucial for export competitiveness. Z.F. Mamedov and K. Bayramova (2021) highlight that joining the World Trade Organisation can contribute to improving trade conditions and reducing tariff barriers, which is especially important for agricultural products. I. Niftiyev (2020b), in another study, notes the importance of the agricultural sector for the economy of Azerbaijan and emphasises the need to diversify production and modernise agriculture. The analysis of economic relationships shows that Azerbaijan's agricultural exports are influenced by changes in other sectors of the economy. S.I. Humbatova *et al.* (2022) point to the substantial role of oil revenues in the import of food and agricultural products, which emphasises the importance of diversifying income sources and reducing dependence on oil. In turn, G. Das *et al.* (2022) emphasise the need to create conditions for economic diversification and development of the agricultural sector as an important element of sustainable economic growth in the study on structural reforms.

A comparative analysis of the competitiveness of agricultural products has shown that Azerbaijan can improve export performance through the optimisation of logistics and the introduction of innovative technologies. T. Mizik *et al.* (2020) argue that trade advantages largely depend on the ability of manufacturers to adapt to the requirements of international markets and implement modern technologies. T.-T. Sun *et al.* (2021) examine the impact of trade policy on the pricing of agricultural goods and conclude that uncertainty in trade policy can have a negative impact on prices, which is especially important for countries with export-oriented agriculture. In addition, I. Fusacchia *et al.* (2022) assess the impact of free trade on agricultural products and emphasise the importance of structural change and producer support to enhance competitiveness in international markets.

Environmental issues also play an important role in assessing the competitiveness of agricultural exports. J.M. Balogh and A. Jámbor (2020) stress the need to consider the environmental impacts of agricultural activities, emphasising that sustainability of production and compliance with environmental standards are becoming important criteria for international trade. The relevance of the subject is due to the need to develop strategies and measures aimed at increasing the competitiveness of agricultural products in the context of international competition. Modern requirements of world markets include not only high-quality standards but also compliance with environmental, sanitary, and hygienic requirements, as well as resistance to price fluctuations (Ismayilzada *et al.*, 2023). In these circumstances, it is extremely important to identify and analyse the key factors affecting the competitiveness of Azerbaijani agricultural products to propose reasonable measures to improve the situation on international markets.

The main issue is the need to improve product quality and meet the requirements of partner countries such as the EU, Turkey, Saudi Arabia, and Iran. On the one hand, modernisation of production facilities and the introduction of innovative technologies are required. On the other hand, it is important to ensure compliance with international standards of product quality and safety, which demands additional efforts on the part of both manufacturers and government agencies (Guliyeva, 2023). Thus, the purpose of this study was to analyse the main factors affecting the competitiveness of agricultural products in Azerbaijan and provide suggestions for improving their quality and optimising costs.

MATERIALS AND METHODS

The study used various data sources to provide a comprehensive analysis of agricultural exports in Azerbaijan. The main source of information was the official statistics of the State Statistical Committee of the Republic of Azerbaijan (n.d.), covering the volume of agricultural exports for 2014-2023. The data includes information on the categories of exported goods, the main trading partners, and the dynamics of changes in export volumes.

In addition, reports from international organisations such as the World Trade Organisation (n.d.), Food and Agriculture Organisation (2023), Reports and analytical records of the World Bank (2022) include data on the role of trade and exports in the economies of countries, reports, and data on the production and export of agricultural products of the Ministry of Agriculture Azerbaijan's economy (Decree of the President..., 2019), analytics on domestic economic policy and trade policy of Azerbaijan, publications of the Promotion Agency of the Republic of Azerbaijan (2021), International Monetary Fund (2024), and economic surveys on Azerbaijan, which include analysis of export flows, the programme on competitiveness of the agricultural sector, which is aimed at improving the competitiveness of Azerbaijan's agricultural products on the world market, and regional trade reports from the EU (Eurostat, n.d.). These data allowed conducting a comparative analysis of Azerbaijan's trade policy with other countries and identifying key factors affecting the development of agricultural exports.

Methodologically, the study was based on a statistical analysis of the collected data. Econometric models were used to identify correlations between changes in trade policy and export dynamics. A comparative analysis method was also used to assess the impact of international trade agreements and barriers on exports. Statistical analysis was used to process and interpret a large volume of data covering export dynamics over the past 10 years. This method allowed identifying the main trends in the volume and structure of agricultural exports. As part of the statistical analysis, correlation analysis methods were used to identify the relationship between changes in trade policy (for example, the introduction of tariff and non-tariff barriers) and export volumes. The average annual export growth rates, seasonal fluctuations, and the influence of external factors such as changes in world prices for agricultural products are calculated.

Comparative analysis was used to compare Azerbaijan's trade policy with similar countries, especially with the countries of the Commonwealth of Independent States (CIS) and the EU. This allowed identifying the strengths and weaknesses of Azerbaijan's current trade policy. The comparative analysis focused on aspects such as terms of trade, export subsidies, customs barriers, and how other countries address issues of increasing the competitiveness of their agricultural products in international markets. Comparison with other countries allowed developing specific recommendations for improving Azerbaijan's export policy. The study used an integrated approach to analyse in detail the impact of various factors on the export of agricultural products of Azerbaijan. The methodology was based on econometric models, which were used to quantify the impact of key factors on exports. In particular, regression analysis was applied to examine variables such as tariff and non-tariff barriers, international trade agreements and the level of government subsidies.

Statistical and comparative analysis methods were also used to improve the accuracy of the analysis and obtain deeper conclusions. The comparative analysis allowed comparing the results of Azerbaijan with similar countries, which helped to identify the strengths and weaknesses of the current trade policy and identify key areas for improvement. The integrated use of econometric models and comparative analysis methods provided an opportunity to assess in detail the impact of trade policy on agricultural exports. This approach allowed developing sound recommendations to improve Azerbaijan's export policy, optimise subsidy programmes, unify standards, and reduce tariff barriers. The research methodology was also aimed at the quantitative and qualitative study of key factors affecting the competitiveness of agricultural products in Azerbaijan, to form a holistic picture and develop effective strategies to increase the export potential of the country.

RESULTS

From 2014-2023, agricultural exports from Azerbaijan demonstrated substantial dynamics related to various factors such as changes in trade policy, foreign economic conditions, and government support for the agricultural sector in Figure 1.

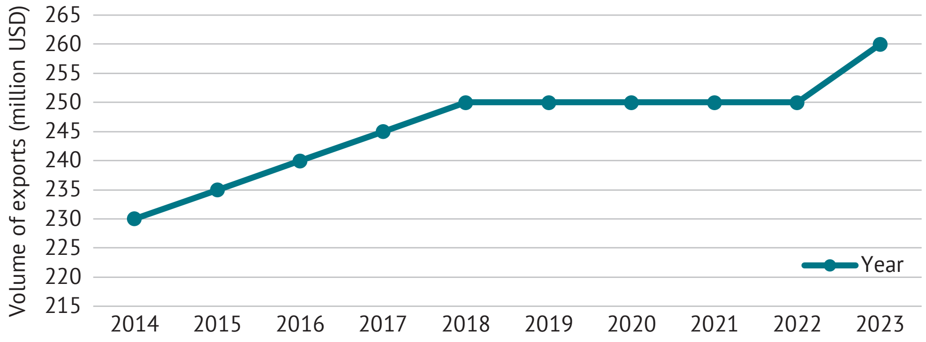

***Figure 1**. Changes in the volume of exports of agricultural products of Azerbaijan (2014-2023)*
***Source:** created by the authors based on Eurostat (n.d.), International Monetary Fund (2024)*

In the first years of the analysed period for 2014-2023, the volume of agricultural exports was relatively stable but remained dependent on domestic and international economic factors. However, since 2014, there has been a sharp increase in exports, which coincided with the intensification of government programmes to support the agricultural sector and diversify the economy. Since then, Azerbaijan has been actively increasing exports of products such as vegetables, fruits, cereals, cotton, and tobacco. One of the critical factors of export growth was the signing of trade agreements with the CIS and EU countries, which opened up new markets for Azerbaijani products. The modernisation of agriculture and the introduction of innovative technologies into production also played an important role, which increased the competitiveness of agricultural products in international markets.

Despite the successes, in 2016-2017 there was a slight decrease in exports due to fluctuations in world prices for agricultural products and economic sanctions in a number of countries. However, since 2018, exports have again begun to show stable growth due to increased government support and increased subsidies for agricultural exports (Promotion Agency of the Republic of Azerbaijan, 2021). By 2024, Azerbaijan's agricultural exports continue to grow. The main exported products include fruits, vegetables, and processed agricultural products. Azerbaijan has strengthened its position in the markets of Russia, Turkey, Iran, and Europe, which became possible due to the adaptation of trade policy and diversification of export directions.

Trade agreements play an important role in developing the export potential of any country, and Azerbaijan is no exception. For the agricultural sector of Azerbaijan, the signing of international agreements has opened up new prospects for export growth, simplified access to foreign markets, and increased the competitiveness of products. These agreements have had a substantial impact on the development of agricultural exports, contributing both to the expansion of export destinations and increased trade efficiency (Table 1).

***Table 1**. Azerbaijan's export statistics for 2014-2023*

Year	Fruits (tonnes)	Vegetables (tonnes)	Cereals (tonnes)	Processed products (canned food, juices/tonnes)	Oilseeds (soybeans, rapeseed/tonnes)
2014	200	150	300	100	80
2015	210	160	310	105	85
2016	220	170	320	110	90
2017	230	180	330	115	95
2018	240	190	340	120	100
2019	260	200	350	125	105
2020	280	220	370	130	110
2021	300	240	390	135	115
2022	320	260	410	140	120
2023	350	280	420	150	130

***Source:** created by the authors based on Food and Agriculture Organisation (2023)*

An analysis of Azerbaijan's export statistics for 2014-2023 shows a steady increase in exports in all major categories of agricultural products. Fruit exports increased from 200,000 to 350,000 tonnes, an increase of 75%. This can be explained by improvements in agricultural infrastructure, expansion of production capacities, and beneficial trade agreements with partners such as Turkey and the EU. Vegetable exports also showed steady growth, from 150,000 tonnes in 2014 to 280,000 tonnes in 2023, an increase of 87%. This is likely the result of government support for the agricultural sector and improved product quality. Grain exports, although growing less sharply, increased from 300,000 to 420,000 tonnes from 2014-2023, which underscores the importance of grain crops in Azerbaijan's export strategy. Processed products showed an increase from 100,000 to 150,000 tonnes, which indicates the development of processing capacities and an increase in value added before exports. The volume of exports of oilseeds increased from 80,000 to 130,000 tonnes, which is equivalent to an increase of 62.5%. This may indicate an increase in demand for products in partner countries and an improvement in cultivation and processing technologies. Overall, the data indicate that Azerbaijan has been able to modernise the agricultural sector, diversify exports, and strengthen its position in international markets (Fiankor *et al.*, 2021). The main factors influencing this positive trend are government subsidies, the expansion of sales markets, the conclusion of international trade agreements, and the introduction of modern technologies in agriculture. The growth dynamics are particularly noticeable in the export of fruits and vegetables, which is associated with the focus on high-demand and expensive products in key trade partnerships. The growth in exports of grain and processed products underlines the strategic importance of these crops and their resistance to changes in foreign markets.

The signed trade agreements provided Azerbaijani agricultural producers with simplified access to international markets. This was made possible by reducing tariff and non-tariff barriers, which previously substantially increased the costs of exporters. Thus, agreements with Turkey, the EU, and Iran have allowed Azerbaijani agricultural enterprises to reduce export costs, making their products more competitive. In particular, the reduction of tariffs on fruits, vegetables, and grains has opened up new opportunities for the export of these goods to Turkey and European countries.

These agreements also contributed to improving the quality of Azerbaijani agricultural products. Azerbaijani manufacturers were forced to adapt their processes to international standards to enter international markets, which included the modernisation of production and the introduction of advanced technologies. This allowed not only to improve the quality of products but also to substantially increase their competitiveness in relation to products from other countries. For example, agreements with the EU have led to substantial improvements in production standards and certification, which has facilitated the entry of Azerbaijani products into European markets. Trade agreements with countries such as Iran and Saudi Arabia have also helped expand the geography of exports. If earlier the main export flows of Azerbaijan were concentrated on a limited number of countries, then after the signing of these agreements, access to new promising markets in the Middle East was gained. These regions demonstrate stable growth in demand for agricultural products, which creates additional opportunities for Azerbaijani producers.

In addition to reducing barriers and simplifying procedures, trade agreements have contributed to the development of international cooperation in the agricultural sector. Azerbaijan not only increased its exports but also actively participated in the exchange of experience and technology with other countries. Participation in international trade organisations and initiatives such as the World Trade Organisation has provided Azerbaijani agribusiness with access to best practices in agriculture. This allowed introducing innovations and improve production efficiency, which ultimately had a positive impact on the quality of exported products. The reduction of trade barriers due to the signed agreements has also had a positive impact on the economy of Azerbaijan in general. The growth in exports, especially in the agricultural sector, has led to an increase in government revenues and the creation of new jobs in agriculture. It also contributed to the development of infrastructure and improved conditions for agricultural business (Table 2).

***Table 2**. Comparative analysis of trade policy*

Country	Key factors of export development	Main exported products
Azerbaijan	Reduction of tariff barriers, export subsidies	Fruits, vegetables, grains
Turkey	Preferential terms of trade, modernisation of the agricultural sector	Vegetables, fruits, nuts
Iran	Reduction of tariffs on agricultural products, trade agreements	Cereals, fruits, vegetables
Saudi Arabia	The growth of demand for agricultural products, the opening of new markets	Cereals, fruits, oilseeds
The EU	Unification of standards, trade preferences	Fruits, vegetables, meat products

***Source:** created by the authors based on Food and Agriculture Organisation (2023)*

The analysis of the presented data shows that the trade policy of Azerbaijan, like other countries, substantially affects the development of agricultural exports. In Azerbaijan, the main export support measures are the reduction of tariff barriers and the provision of export subsidies. These steps make the products of the state more competitive in international markets. The main export products are fruits, vegetables and grains, which emphasises the orientation of the agricultural sector towards traditional products in high demand. Turkey is demonstrating a more comprehensive approach to export support. Preferential trade conditions and modernisation of the agricultural sector contribute to an increase in exports of vegetables, fruits, and nuts. Modernisation and introduction of technologies lead to products of higher quality that meet international standards, which strengthens Turkey's position in world markets. Iran also uses tariff reductions and enters into trade agreements, which contributes to the growth of exports of grain, fruits, and vegetables. This highlights the importance of developing trade links to improve export performance. Saudi Arabia aims to increase demand and open new markets. The growth of domestic demand and the expansion of exports of cereals and oilseeds confirm the strategic importance of diversifying export directions.

The EU actively uses the unification of standards and trade preferences to support the export of agricultural products. High product quality standards and access to global markets allow the EU to successfully export fruits, vegetables and meat products. Figure 2 shows that international trade agreements have the greatest impact on agricultural exports, accounting for 35% of the total impact of factors. This underlines the importance of concluding and implementing such agreements, as they open up new markets, reduce barriers, and simplify product certification procedures. Such agreements contribute to improving the terms of trade, reducing tariffs, and creating a favourable regime for exporters. Following international agreements are tariff barriers, which have a substantial impact on exports, amounting to 25%. High tariffs can restrict access to international markets and increase the cost of products, so reductions under agreements or at the initiative of governments lead to increased exports. Government subsidies also have an important impact, amounting to 20%. In addition, they help to offset costs, improve product quality, and increase production volumes, which is especially important for maintaining competitiveness in international markets. Non-tariff barriers account for 15% of the total impact and include product quality requirements, certification, quotas, and sanitary standards (Wood *et al.*, 2020). In general, international trade agreements are a key factor in export growth, which substantially reduces barriers and opens access to new markets. However, tariff and non-tariff barriers continue to have an impact, and work needs to continue to reduce them. Government subsidies play an important role in supporting exporters and increasing the competitiveness of products. For the further development of exports, it is important to optimise tariff policy, conclude new trade agreements and increase the effectiveness of subsidy programmes.

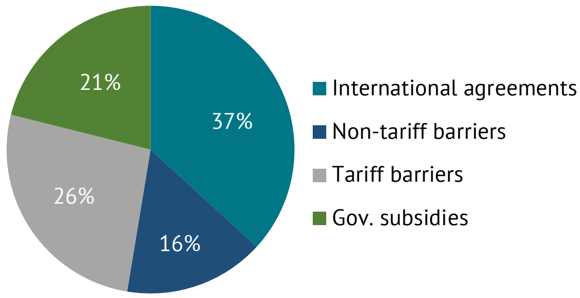

***Figure 2**. The impact of various factors on exports (estimated in %)*

***Source:** reated by the authors based on World Trade Organisation (n.d.), Food and Agriculture Organisation (2023), World Bank (2022)*

Several types of econometric models were used to determine the correspondence between changes in trade policy and the dynamics of agricultural exports in Azerbaijan. Empirical evidence shows that government subsidies and support programmes play a key role in the development of Azerbaijan's agricultural exports. Based on the analysis of statistical data and the results of the subsidy policy, it can be argued that targeted financial support measures contribute to increasing the competitiveness of products in international markets. Studies have shown that the bulk of subsidies in Azerbaijan are directed to key export categories such as fruits, vegetables, cereals, and oilseeds. Statistical analysis of changes in the volume of exports of these products shows that subsidies aimed at improving infrastructure and modernising technologies have a positive impact on productivity and product quality. In particular, irrigation subsidy programmes and the purchase of modern equipment correlate with increased yields and improved quality standards, which in turn leads to an increase in exports.

The effectiveness of government subsidies is also confirmed by data on reducing the cost of production. Comparative analysis has shown that manufacturers receiving government support have the opportunity to offer their products on international markets at more competitive prices. This is especially important for agricultural products, where price competition plays a substantial role (Karabulut, 2020). As a result, the volume of exports of categories such as fruits and vegetables show steady growth against the background of increased subsidies (Arisoy, 2020). In addition, government support programmes include the provision of preferential loans and tax incentives for agricultural producers. Empirical evidence confirms that access to preferential loans is positively correlated with the level of investment in modernisation and expansion of production. Manufacturers with access to such loans are actively investing in innovation and upgrading production facilities, which has a positive effect on product quality and export volumes. This is confirmed by data on the growth of exports of highly processed products, which is associated with access to financial resources and incentives for modernisation.

Support for export-oriented programmes also demonstrates its effectiveness. In particular, the results of programmes to promote Azerbaijani products on international markets indicate a substantial increase in product recognition and expansion of export directions. Participation in international exhibitions and advertising campaigns helps to enter new markets and strengthen the trust of foreign consumers. Increasing the competitiveness of agricultural products is associated with the implementation of a set of measures aimed at improving production processes and quality and optimising costs. Based on the analysis of export dynamics and product quality indicators, it can be argued that the modernisation of production facilities and the introduction of modern technologies have had a positive impact on the competitiveness of agricultural products in Azerbaijan.

Export data show that key categories such as fruits, vegetables, and grains are showing steady growth in international markets. One of the factors contributing to this growth is the improvement of production processes through the introduction of technologies and increased resource efficiency. For example, the introduction of drip irrigation systems and modern farming methods correlates with increased yields and stable supplies, which allows farmers and exporters to compete in markets with stringent standards and requirements. In addition, data on government support for manufacturers indicate a substantial impact of subsidy programmes on the competitiveness of products. Subsidies aimed at modernising agricultural machinery and technologies reduce costs and improve the quality of final products. In particular, statistics show that exporters who have received support in upgrading their production facilities demonstrate higher product quality indicators, which increases their competitive advantages in foreign markets.

Another important factor is the unification of standards and the improvement of certification procedures. An analysis of data on exports to the EU and the Middle East shows that the harmonisation of national standards with international requirements has led to an expansion of export opportunities for Azerbaijani producers. This is confirmed by the growing supply of fruits and vegetables that meet strict quality and food safety standards in the EU. The analysis shows that optimisation of logistics and improvement of infrastructure also have a positive impact on competitiveness. The improvement of transport and warehouse infrastructure has reduced the cost of product delivery and increased the speed of contract fulfilment, which is especially important in competitive markets. An integrated approach, including government subsidies, technology modernisation, standardisation of unification and active product promotion, has allowed Azerbaijani manufacturers to improve the quality of their products and reduce costs. This, in turn, led to a strengthening of positions in international markets and an increase in exports. Thus, the increase in competitiveness was the result of targeted measures aimed at improving production efficiency and product quality and strengthening positions in foreign markets

DISCUSSION

The results of the analysis of Azerbaijan's agricultural exports for 2014-2023 demonstrate substantial positive dynamics due to a combination of factors such as changes in trade policy, increased government support, and adaptation to foreign economic conditions. In the first stages of the analysed period, export volumes remained stable, but since 2014, there has been a substantial increase in export activity. The main catalyst for export growth was the implementation of government programmes aimed at supporting the agricultural sector and economic diversification. These measures have allowed Azerbaijan to focus on key products such as fruits, vegetables, cereals, cotton, and tobacco. In this study, special attention was paid to the impact of trade policy on the export of agricultural products of Azerbaijan, including aspects such as participation in international trade agreements, government subsidies, as well as tariff and non-tariff barriers.

These results show that active participation in international agreements and the reduction of trade barriers had a positive impact on export volumes, which is consistent with the conclusions of M. Cipollina and L. Salvatici (2020). However, this study also detailed the impact of non-tariff barriers, such as certification requirements and quality standards, which did not receive such a detailed analysis in the paper of these authors. S. Işik and F.C. *Özbuğday* (2021) focused on the impact of costs on agricultural resources and the relationship with prices for final products. This study expands on this subject, emphasising that subsidies not only reduce production costs but also improve product quality, which increases the competitiveness of Azerbaijani goods in international markets. Unlike S. Işik and F.C. *Özbuğday*, who focus on internal economic factors, this study also analysed the impact of external factors such as trade agreements and international standards.

The signing of trade agreements with the CIS and EU countries played a crucial role in improving export performance (Leshchenko, 2023). The opening of new markets for Azerbaijani products and the reduction of trade barriers have become important factors contributing to the growth of exports. Tariff reductions and simplified certification procedures have contributed to the expansion of export destinations and improved terms of trade, which is especially important in the context of growing international competition. For example, agreements with the EU and Turkey have substantially simplified access to new markets and strengthened trade ties. Despite the success, in 2016-2017, there was a slight decrease in exports, which was due to fluctuations in world prices and the introduction of economic sanctions in some countries. However, since 2018, exports have again shown stable growth due to increased subsidies and increased government support. In this context, it can be noted that the key success factors were cost reduction and product quality improvement achieved through modernisation and the introduction of advanced technologies.

In the study by Y. Erduman *et al.* (2020), the focus was placed on optimising the import content in Turkish export products. In the same paper, the analysis showed that diversification of supplies and optimisation of supply chains are also of critical importance for the agricultural sector of Azerbaijan. This highlights the need to reduce dependence on imported raw materials and increase the added value of national products, which also corresponds to the conclusions of Y. Erduman *et al.* but is considered in more detail in the context of the agricultural sector. Comparing this study with the paper of P. Mamardashvili *et al.* (2020), it can be noted that the emphasis on international diversification of export destinations is consistent with these conclusions on the need to expand trade agreements and strengthen Azerbaijan's position in new markets. However, this study deepens this subject by analysing the impact of specific trade barriers and subsidies on product competitiveness, which was not the main focus of the publication.

The signed trade agreements had a substantial impact on the competitiveness of products, allowing Azerbaijani manufacturers to adapt to international standards and improve production processes. This was especially important for entering the EU markets, where the requirements for product quality and certification are quite strict. For example, the reduction of tariffs on fruits, vegetables, and grains has become an incentive to increase supplies to Turkey and European countries, which has led to an increase in the volume of exports of these goods. The development of international cooperation has also played an important role in strengthening export potential. Azerbaijan actively participated in the exchange of technologies and experience with other countries, which contributed to the introduction of innovations in the agricultural sector (Maharramova & Maharramov, 2023). This improved the quality of the products and made them more competitive compared to the products of other countries. An example is the increase in production standards and certification within the framework of agreements with the EU, which facilitated access to European markets and opened up new opportunities for manufacturers. In addition to reducing tariff and non-tariff barriers, the signed agreements contributed to the development of the agricultural sector in general. The growth in exports led to an increase in government revenues and the creation of new jobs in the agricultural sector, which had a positive impact on the country's economy (Chornyi, 2013). The development of infrastructure and the improvement of the business environment have also been the result of government support and the active introduction of advanced technologies (Abdullayev *et al.*, 2024).

In the study by S. Jafarov *et al.* (2024), the current state of Azerbaijan's foreign economic relations is examined, and the importance of eliminating trade restrictions is highlighted. This study confirms this conclusion and highlights that the removal of both tariff and non-tariff barriers contributes to improved access to new markets. However, the analysis attempted to assess the quantitative impact of each measure, which distinguishes this study in terms of methodology. I.B. Gurbuz *et al.* (2021) focus on the environmental effects of value added in agricultural products. This study also highlights the importance of complying with international environmental standards to enhance competitiveness. Thereby, attention was focused not only on environmental standards but also on product quality standards, which is an important addition to the conclusions of I.B. Gurbuz *et al.* A publication of S.V. Bayramov *et al.* (2021) considers the diversification of the agricultural sector as a strategy to improve economic growth. This study goes further and concretises that diversification and modernisation of the agricultural sector are critical not only for economic growth but also for increasing export potential. The authors also presented recommendations on optimising subsidies and supporting manufacturers, which complements the conclusions of S.V. Bayramov *et al.*

N. Humbatova *et al.* (2022) examine the role of the non-resource sector, including agriculture, in increasing Azerbaijan's export potential. The authors emphasise that export diversification and increased support for the non-resource sector are important strategic steps for the sustainable development of the country's economy. This is consistent with these conclusions about the importance of developing the agricultural sector through improving product quality and expanding export destinations. However, this study delves deeper, detailing specific measures such as reducing tariff barriers and optimising subsidy programmes, which allowed quantifying their impact on agricultural exports. Unlike S.I. Humbatova *et al.*, who focused on the general role of the non-resource sector, researchers specifically accentuate the agricultural sector and its specific barriers and drivers.

The data show that Azerbaijan's trade policy and the conclusion of trade agreements with key partner countries have contributed to the successful diversification of exports. This highlights the importance of an integrated approach that includes government subsidies, improved terms of trade and modernisation of the agricultural sector. An analysis of the dynamics of exports of fruits and vegetables indicates an increase in demand and high-quality products on international markets, which indicates the correct orientation towards in-demand products in key trade partnerships. S.G. Topuz and Ö. Dağdemir (2020) analyse the relationship between trade openness, structural changes and income inequality using the example of Turkey. They Topuz and Ö. Dağdemir conclude that trade liberalisation and structural reforms have a positive impact on economic growth, but can also lead to an increase in income inequality. In this study, the results show that the openness of trade and integration into international trade networks contribute to the growth of agricultural exports and improve the competitiveness of Azerbaijan. However, unlike S.G. Topuz and Ö. Dağdemir, in this study, the focus was on assessing specific trade policy measures and the impact on exports, rather than on structural changes and consequences for inequality. This study highlights that effective tariff and subsidy management can minimise the negative effects of liberalisation and stimulate sustainable growth in the agricultural sector. Finally, in the paper of A.P. Siregar and N.P. Widjanarko (2022), the importance of trade openness and liberalisation is highlighted. This study confirms such a conclusion and shows that active participation in international trade initiatives and export liberalisation are critical factors for improving Azerbaijan's position in international markets. Therewith, the impact of specific trade policy measures on export volumes was examined in more detail, which gives a more complete picture of the relationship between trade policy and exports.

The study is also important for considering the environmental and social aspects of agricultural activities. In the context of increasing international attention to sustainable development and environmental protection, the analysis of the impact of agricultural production on the environment is becoming an integral part of the study. This helps to develop measures to minimise the negative impact on the environment and achieve sustainable growth in the agricultural sector. Finally, the study of the competitiveness of agricultural products can be of practical importance for producers, exporters, and government agencies. The conclusions and recommendations of the study can be used to develop more effective export strategies, improve product quality, and increase its attractiveness in international markets. For government agencies, the results of the study will help in the development of targeted support programmes and more efficient allocation of resources.

Thus, examining the competitiveness of Azerbaijan's agricultural products and the impact of trade policy on exports is of great importance for strengthening the country's position in international markets, improving product quality, and achieving sustainable economic growth. It serves as a basis for the development of strategies aimed at improving the agricultural sector and strengthening its role in the national economy

CONCLUSIONS

In this study, an analysis of Azerbaijan's agricultural exports for the period from 2014 to 2023 was conducted. This period was chosen due to substantial changes in export volumes caused by increased government support, the modernisation of the agricultural sector, and the conclusion of international trade agreements. The analysis demonstrated a steady growth in the country's export potential, especially in relation to goods such as fruits, vegetables, cereals, and cotton, which strengthened Azerbaijan's position in international markets.

The study showed that Azerbaijan's participation in international trade agreements is an important factor in expanding export opportunities. Integration into global trade networks such as the World Trade Organisation and the conclusion of bilateral agreements with major trading partners have a positive impact on reducing trade barriers and opening up new markets. This is confirmed by the growth in export volumes after the conclusion of key agreements and underlines the need for the country's active participation in international trade initiatives.

Government subsidies and support programmes have a substantial impact on the competitiveness of agricultural products. Targeted subsidies for certain categories of goods help to reduce production costs and improve product quality, which is especially important in the context of increased international competition. In this regard, it is important to continue developing subsidy programmes and optimise the allocation of resources in accordance with the current needs of producers. Tariff and non-tariff barriers remain a substantial obstacle to exports. The study shows that high tariffs and strict non-tariff requirements substantially limit export potential. It is necessary to intensify efforts to harmonise standards with international requirements and promote initiatives to reduce tariff rates, simplify certification procedures, and reduce this negative impact.

The results of the study emphasise the importance of modernising the agricultural sector and introducing innovations. The data showed that the introduction of modern technologies, the improvement of logistics infrastructure, and the development of product processing contributed to an increase in export volumes and strengthened positions in international markets. This confirms the need for an integrated approach to the development of the agricultural sector, including government support, technological modernisation, and infrastructure improvement.

Based on the analysis, measures were proposed to increase the competitiveness of agricultural products in Azerbaijan. It also includes continued integration into international trade networks, optimisation of subsidy programmes, unification of standards, and development of logistics infrastructure. These measures are aimed at strengthening Azerbaijan's position in world markets and increasing the sustainability of the agricultural sector in the face of global competition. Thus, the study demonstrated the importance of an integrated approach to improving the competitiveness of agricultural products, including trade policy, government support, modernisation, and consideration of international standards. The results of the study can serve as a basis for further improvement of strategies and measures aimed at developing the agricultural sector and expanding the export potential of Azerbaijan.

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CONFLICT OF INTEREST

None.

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Анотація. У статті представлено комплексний аналіз факторів, що впливають на конкурентоспроможність сільськогосподарської продукції в Азербайджані, з акцентом на оцінку ролі торговельної політики та державної підтримки. Основну увагу приділено впливу торговельних угод, тарифних і нетарифних бар'єрів, а також програм субсидування на обсяги експорту. З використанням методів статистичного та порівняльного аналізу було виявлено основні детермінанти, що впливають на експорт сільськогосподарської продукції, та оцінено їхню значущість. Метою дослідження була розробка ефективних заходів і стратегій для поліпшення експортного потенціалу та підвищення конкурентоспроможності аграрного сектору Азербайджану на міжнародних ринках через аналіз ключових чинників і впливу торговельної політики. Результати дослідження показали, що участь Азербайджану в міжнародних торговельних угодах справляє позитивний вплив на показники експорту. Укладення двосторонніх угод з такими ключовими торговельними партнерами, як Європейський Союз, Туреччина та Іран, сприяє зниженню торговельних бар'єрів і відкриттю нових ринків. Це підкреслює важливість подальшої активної участі країни в глобальних торговельних ініціативах. Аналіз також підтвердив суттєвий вплив державних субсидій на конкурентоспроможність продукції. Цільові субсидії сприяють зниженню собівартості продукції та підвищенню якості, що особливо важливо в умовах міжнародної конкуренції. Було запропоновано заходи щодо оптимізації програм субсидування та підвищення ефективності. Особливу увагу приділено ролі тарифних і нетарифних бар'єрів, які залишаються суттєвою перешкодою для експорту. Дослідження показало, що високі тарифи та жорсткі нетарифні вимоги суттєво обмежують експортний потенціал. У зв'язку з цим рекомендується продовжити уніфікацію стандартів з міжнародними вимогами та спростити процедури сертифікації. Результати дослідження підкреслюють необхідність модернізації аграрного сектору та впровадження інновацій. Впровадження сучасних технологій і поліпшення логістичної інфраструктури сприяють збільшенню обсягів експорту та зміцненню позицій на міжнародних ринках. Таким чином, у дослідженні було виявлено основні чинники, що впливають на експорт сільськогосподарської продукції Азербайджану, та запропоновано конкретні заходи щодо вдосконалення торговельної політики та підвищення конкурентоспроможності продукції на міжнародних ринках

Ключові слова: розвиток галузі; нетарифні обмеження; економічний розвиток; державне регулювання; міжнародне співробітництво

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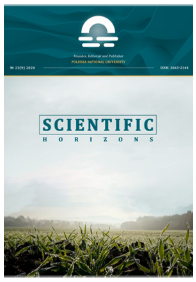

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Economic aspects of implementing environmentally friendly energy sources in the agro-industrial complex (focusing on European countries)

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Abstract. This study examined the impact of environmentally friendly energy sources on the economic sustainability of the agro-industrial complex (AIC). The research identified four primary groups of environmentally friendly energy sources utilised in the AIC: solar energy, wind, biogas, and geothermal energy. Each of these technologies possessed unique characteristics and advantages that are capable of meeting agricultural enterprises' energy needs. Although the AIC significantly contributed to

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carbon dioxide emissions and other pollutants, transitioning to sustainable energy sources can not only reduce the environmental impact but also provide economic benefits, fostering the development of a sustainable and competitive agricultural economy. Examples of the successful adoption of renewable energy sources (RES) in Germany, the Netherlands, and Spain were examined, highlighting their substantial contributions to the economic and environmental sustainability of agribusiness. The study also emphasised economic efficiency, environmental responsibility, and social equity as key principles of sustainable development. The adoption of RES has been shown to reduce energy costs, decrease dependency on conventional resources, and enhance the competitiveness of agricultural enterprises. Simultaneously, the use of environmentally friendly technologies contributed to minimising carbon emissions and improving environmental quality. The discussion addressed the primary challenges and barriers to implementing environmentally friendly energy sources in the AIC, including high initial investment costs, technical limitations, and inadequate infrastructure. To enhance the effectiveness of clean energy adoption, a comprehensive approach was proposed. This approach includes investment in new technologies, government subsidies, educational initiatives, and the establishment of cooperatives

Keywords: sustainable development; biomass; solar panels; wind turbines; environment

INTRODUCTION

In the face of global environmental challenges and climate change, modern industries, including the agro-industrial complex (AIC), are increasingly turning to environmentally friendly energy sources. Currently, a significant portion of the energy required for production processes in the agricultural sector is derived from fossil fuels, resulting in high costs and adverse environmental effects. At the same time, the AIC is a critical sector of the economy, underpinning food security, employment, and the economic sustainability of rural areas. Consequently, identifying solutions to enhance production efficiency and sustainability represents a paramount objective for the agricultural sector. The adoption of environmentally friendly energy sources offers a meaningful step towards achieving this goal.

The utilisation of environmentally friendly, renewable energy sources (RES), such as solar, wind, biogas, and geothermal energy, offers opportunities to reduce the AIC's dependence on volatile supplies of conventional fuels and conserve resources. This is particularly relevant for countries with high RES potential, including many European nations. The abundance of agricultural waste suitable for biogas production, high solar activity, and the availability of land for installing solar panels create favourable conditions for the adoption of green technologies in agriculture. Furthermore, the development of such technologies contributes to job creation, a reduction in the carbon footprint, and improvements in environmental conditions at both local and global levels.

Despite the potential benefits, certain challenges hinder the widespread adoption of environmentally friendly energy sources in the AIC. These challenges include the high initial investment costs, underdeveloped infrastructure, and specific technical limitations that necessitate specialised expertise and equipment. Additionally, organisational and economic barriers, such as limited access to financing and subsidies, pose obstacles, particularly for small and medium-sized agricultural enterprises seeking to implement such technologies. The economic aspects of transitioning to renewable energy in the AIC are studied through the lens of sustainable development, encompassing financial, social, and environmental dimensions. This approach involves analysing costs and benefits, evaluating project payback periods, and assessing the impact of such investments on enhancing the competitiveness and resilience of agriculture. These considerations are critical for formulating strategies aimed at minimising environmental and economic risks.

Several studies conducted by various authors highlight the economic and environmental aspects of using RES in the AIC. Research by S. Gorjian *et al.* (2021) demonstrated that integrating solar panels into farming operations reduced reliance on fossil fuels and lowered operating costs, thereby improving farm profitability. Similarly, A.S. Pascaris *et al.* (2021) corroborated these findings, showing that agricultural enterprises adopting solar energy significantly reduced energy expenses during periods of seasonal electricity price hikes. M.K. Devi *et al.* (2022) focused on the economic benefits of biogas plants, emphasising that agricultural enterprises could efficiently process waste while achieving substantial energy and financial gains. Their data indicated that biogas installations typically recoup investment costs within 5-7 years, making them particularly appealing to large-scale farms with high waste output. O. Myrna *et al.* (2019) underscored the necessity of government support, revealing that subsidies for wind generators and biogas plants increased farmers' willingness to invest in green technologies. These findings were further expanded by S.A. Qadir *et al.* (2021), who demonstrated that fiscal incentives and tax relief measures could accelerate the adoption of environmentally friendly energy sources and amplify their economic impact.

R. Chopra *et al.* (2022) examined the impact of environmentally friendly energy sources on labour productivity, revealing that enterprises utilising RES experienced fewer disruptions caused by power outages, positively influencing productivity and production stability. A. Barbaresi *et al*. (2020) contributed by exploring the long-term prospects of geothermal energy in greenhouse farming, finding that this technology reduces reliance on fossil fuels for cultivating crops in controlled environments. M.M. Rahman *et al*. (2022) investigated the economic effects of combined solar panel and wind turbine systems in agricultural enterprises. Their findings indicated that such hybrid systems enhance energy efficiency while lowering costs and mitigating risks associated with variable weather conditions. Supporting this, L. Melnyk *et al*. (2020) highlighted the successful implementation of similar solutions in European countries, demonstrating their economic feasibility and the potential for enhancing the sustainability of the agricultural sector. K. Senthilkumar *et al*. (2020) concluded that adopting renewable energy in the AIC not only conserves resources but also improves corporate reputation. This enhancement in the image can attract additional investment and create new market opportunities for agricultural enterprises.

These studies collectively confirm that the transition to environmentally friendly energy sources is both environmentally and economically beneficial for the AIC. However, among the topics that are under-researched in the context of using clean energy sources in AIC are: the impact of large-scale renewable energy adoption on the competitiveness of agricultural enterprises and the economic implications of integrating clean technologies under climate and infrastructure constraints. The study aimed to identify the economic advantages of implementing environmentally friendly energy sources in agricultural enterprises. The objectives included analysing the effect of renewable energy on the competitiveness of agricultural enterprises and examining the economic barriers and opportunities for adopting RES in regions facing limitations.

MATERIALS AND METHODS

The study utilised data from open sources, including Eurostat (2024), reports on the development of RES use in European countries, and case studies of its application in agro-companies such as "Schwarz", Royal Pride Holland, and Grupo Jorge (Kornatz *et al.*, 2021; International Energy Agency, 2022; Clark, 2024). The primary focus was on a comparative analysis of the energy efficiency and environmental sustainability of various types of RESs, including solar and wind energy, biogas, and geothermal systems, within the agricultural sector. Key performance indicators were identified during the analysis, such as implementation costs, system lifespan, contributions to reducing carbon dioxide emissions, and economic benefits for agricultural enterprises.

The research methodology was based on a structured analysis of energy intensity, environmental performance, and economic outcomes from the application of RES in the AIC, using examples from countries actively advancing green energy. A comparative assessment was conducted, focusing on key leaders in RES adoption in the agricultural sector: Germany, the Netherlands, and Spain. These countries were selected due to robust government support and successful examples of integrating renewable energy into agricultural processes, allowing consideration of diverse economic, technical, and environmental factors. The study also identified barriers to the implementation of RES in the AIC, including high capital costs, infrastructure-related technical limitations, and the impact of climatic conditions on the efficiency of RES.

Quantitative methods were employed to analyse the energy intensity of different energy sources and their contribution to environmental sustainability. Specifically, data on energy production and consumption volumes, the growth dynamics of RES adoption in agricultural sectors, and financial indicators reflecting the economic efficiency of each technology's implementation were utilised. In addition, the analysis encompassed environmental factors, such as the amount of CO_2 emissions prevented and the reduction in environmental impact achieved through the substitution of fossil fuels with RES. Based on the collected data, a comparative analysis of RES trends in the agricultural sectors of European countries was conducted for the period 2018-2022. This analysis identified the leading countries in the field of green energy. For further examination, a case study method was employed, highlighting successful examples of biogas plant implementation in Germany, solar panels in Spain, and wind turbines in the Netherlands. Each case study included data on technical infrastructure, economic outcomes, and environmental indicators, such as the reduction in carbon footprint and the volumes of methane emissions avoided.

Thus, the research methodology involved gathering and analysing data from multiple sources, conducting a comparative analysis of the energy efficiency and environmental sustainability of RES and examining the factors influencing the economic efficiency and sustainable development of the AIC. The findings provide a foundation for developing recommendations to enhance the effectiveness of RES use in the AIC of European countries.

RESULTS

Environmentally friendly energy sources have become an integral part of the global sustainable development strategy, with their role in the AIC being particularly significant. The AIC is critical for food security, public health, and ecosystem stability. However, it is also a major contributor to carbon dioxide emissions and other pollutants, underscoring the necessity of transitioning to more sustainable and environmentally friendly energy sources (Ingrao *et al.*, 2019). The adoption of renewable energy not only reduces the harmful impact on the environment but also offers economic benefits, fostering the development of a resilient and competitive agricultural economy.

Four primary groups of environmentally friendly energy sources are prominent in the AIC: solar energy, wind energy, biogas, and geothermal energy. Each offers unique characteristics and advantages tailored to meet the energy needs of agricultural enterprises. Solar energy is widely utilised across many countries due to its versatility. Solar panels are installed on the roofs of agricultural buildings, greenhouses, and even in fields, providing farms with electricity for lighting, heating, irrigation, and other essential operations necessary for the uninterrupted functioning of the AIC. Solar energy is particularly advantageous in regions with high solar insolation and in sectors requiring a consistent electricity supply. Wind energy is considered one of the most cost-effective solutions over the long term. Wind turbines generate electricity, particularly in areas with steady wind flows. In the AIC, wind energy can power farm operations, pump water, and support the functioning of storage and production facilities. Wind turbines have a long service life and relatively low operational costs, making them an appealing choice for agricultural enterprises with extensive land resources.

Biogas systems play a critical role in processing organic waste on farms. Converting waste into biogas helps minimise methane emissions and other pollutants. Methane derived from biogas can be used for heating and electricity generation. Biogas systems are particularly relevant for livestock farms, where large volumes of organic waste are generated daily and can be converted into energy. This waste management approach reduces environmental pollution and enhances living conditions in rural areas (Igliński *et al.*, 2020). Geothermal energy is utilised for heating agricultural buildings, greenhouses, and production facilities. Its key advantage lies in its stability: geothermal sources are unaffected by seasonal or weather fluctuations, making them particularly valuable in regions with harsh climates. Although the implementation of geothermal systems requires substantial investment, they provide long-term savings, reduce reliance on traditional heat sources, and contribute to lowering carbon emissions (Ramzan *et al.*, 2024).

Sustainable development in the agricultural sector is founded on three key principles: economic efficiency, environmental responsibility, and social equity. Environmentally friendly energy sources are instrumental in achieving these objectives by reducing the sector's environmental impact while enhancing its competitiveness and appeal.

Economic efficiency, within the framework of sustainable development, involves reducing energy costs and improving the profitability of agricultural enterprises. The adoption of RES enables agricultural businesses to manage energy expenses more effectively, reduce dependence on fluctuating prices for conventional resources, and maintain consistently high productivity levels (Qiao *et al.*, 2019). Economically resilient enterprises can utilise energy efficiently without increasing costs, thereby ensuring their survival and growth in competitive markets. Environmental responsibility is a crucial aspect of sustainable development, as the AIC significantly impacts ecosystems. The use of RES contributes to reducing carbon emissions, minimising pollution, and alleviating pressure on natural resources. Implementing green energy solutions allows enterprises to lower their carbon footprint, improve soil and water quality, and create a safer and healthier environment (Aydoğan & Vardar, 2020).

The social dimension of sustainable development is equally significant, as agricultural enterprises play a vital role in rural communities. The creation of new jobs in the renewable energy sector, the improvement of living standards in rural areas, and the provision of access to sustainable and environmentally safe energy sources contribute to social equity and an enhanced quality of life (Janker & Mann, 2020). For instance, new employment opportunities may emerge in the maintenance and operation of green energy systems, attracting young people to rural areas and fostering local economic growth. Such developments not only support the social fabric of rural communities but also align with the broader goals of sustainable development by addressing economic and environmental challenges simultaneously.

The adoption of environmentally friendly energy sources in the AIC offers both economic and environmental benefits. One of the primary economic advantages is the potential for reducing longterm energy costs. Although the installation of solar panels, wind turbines, and biogas systems requires significant initial investments, these technologies enable agricultural enterprises to reduce reliance on external energy suppliers and significantly lower expenses associated with conventional energy resources. In the context of price volatility for oil and gas, this factor becomes particularly important. Additionally, access to government subsidies, grants, and tax incentives for transitioning to green energy further decreases implementation costs, making such investments more appealing and financially viable. From an environmental perspective, renewable energy significantly reduces carbon dioxide emissions and minimises the ecological footprint of agricultural enterprises. For instance, biogas systems that process organic waste help lower methane emissions and reduce reliance on fossil fuels. This approach enhances soil and water quality, which is particularly critical for agricultural enterprises located in regions with sensitive ecosystems. Wind and solar energy also have minimal environmental impact, as their generation does not produce carbon emissions or other pollutants, making them highly suitable for use in the agricultural industry.

In addition to the direct economic and environmental benefits, adopting renewable energy in the AIC enhances corporate image and builds consumer trust. Modern consumers increasingly prioritise the environmental sustainability of the products they purchase. Enterprises utilising renewable energy can market their products as eco-friendly and sustainable, thereby attracting new customers and fostering loyalty among existing ones (Elahi *et al.*, 2022). The energy balance of RES and biofuels in European countries demonstrates a consistent trend towards increased production and consumption of clean energy. In recent years, EU countries and neighbouring states have actively expanded their use of RES, reducing dependence on fossil fuels, lowering carbon emissions, and promoting sustainable development. Table 1 presents data by country, enabling an assessment of progress in individual states and identifying leaders in renewable energy utilisation.

Table 1*. Energy balance of RES and biofuels in European countries (2018-2022), TWh*

Country	2018	2019	2020	2021	2022
Belgium	49.41	51.02	57.35	59.58	61.66
Bulgaria	29.56	28.72	29.64	34.01	31.97
Bulgaria	53.12	57.14	59.59	63.93	63.42
Denmark	66.35	69.69	72.11	81.8	80.99
Germany	506.01	527.01	546.91	547.14	572.29
Estonia	13.45	13.72	15.35	15.35	15.36
Ireland	17.23	19.15	20.94	19.1	21.49
Greece	36.53	36.89	38.96	44.64	42.54
Spain	211.24	213.59	222.01	230.57	228.08
France	329.78	336.14	334.97	361.13	349.71
Croatia	25.39	24.85	25.5	29.22	25.89
Italy	340.55	343.23	341.28	351.98	327.48
Cyprus	2.77	2.86	3.23	3.46	3.56
Latvia	21.66	21.17	21.04	22.14	22.19
Lithuania	18.47	18.48	19.26	21.8	20.84
Luxembourg	3.44	3.75	4.65	4.75	4.71
Hungary	32.56	32.92	34.49	37.66	38.69
Malta	0.53	0.57	0.67	0.66	0.73
Netherlands	54.02	63.79	81.52	94.59	103.76
Austria	116.43	121.27	122.09	126.02	119.62
Poland	142.88	147.72	150.62	152.13	158.68
Portugal	71.05	70.48	74.08	77.19	75.81
Romania	70.22	69.93	69.65	74.39	69.88
Slovenia	13.39	13.29	13.88	14.63	12.14
Slovakia	24.07	25.56	24.97	27.04	24.98
Finland	140.23	142.04	139.74	159.45	150.3
Sweden	235.07	249.14	262.78	278.97	276.86
Iceland	63.39	62.18	61.46	60.73	-
Norway	170.54	160.73	181.39	188.22	175.87
Great Britain	235.35	255.64	-	-	-
Bosnia and Herzegovina	20.4	20.89	20.14	21.91	20.96
Montenegro	4.01	3.64	3.49	4.16	3.52
Moldova	9	7.65	7.18	7.62	6.63
Northern Macedonia	4.44	3.93	4.15	4.36	4.21
Georgia	13.43	12.12	11.2	13.23	13.51
Albania	11.86	8.6	8.52	12.14	10.41
Serbia	23.49	23.71	29.08	32.20	29.35
Turkey	222.3	271.43	280.01	280.65	308.66
Ukraine	50.21	50.57	56.73	-	-

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

The data indicate that Germany remains the largest producer of renewable energy in Europe, with an increase in output reflecting its ongoing commitment to adopting green technologies. Similarly, significant growth has been observed in the Netherlands, where production has nearly doubled. Notably, countries such as Norway and Sweden, which already exhibit high levels of RES utilisation, have shown relatively stable growth rates, suggesting that these nations have reached an advanced stage in adopting these technologies.

***Table 2**. Energy balance of RES and biofuels in agriculture and forestry in European countries (2018-2022), TWh*

Country	2018	2019	2020	2021	2022
Belgium	0.493	0.461	0.49	0.407	0.397
Bulgaria	0.057	0.056	0.066	0.119	0.115
Bulgaria	1.561	1.551	1.575	1.783	1.782
Denmark	0.635	0.628	0.611	0.66	0.638
Germany	8.879	8.94	9.51	9.702	9.354
Estonia	0.061	0.044	0.056	0.064	0.059
Ireland	0	0	0	0	0
Greece	0.37	0.379	0.328	0.315	0.348
Spain	0.83	0.831	0.829	0.829	0.856
France	4.168	4.462	4.701	4.996	4.819
Croatia	0.041	0.038	0.04	0.019	0.025
Italy	0.58	0.619	0.612	0.881	0.865
Cyprus	0.028	0.034	0.038	0.037	0.034
Latvia	0.29	0.414	0.379	0.251	0.253
Lithuania	0.176	0.175	0.200	0.208	0.207
Luxembourg	0.051	0.027	0.018	0.004	0.024
Hungary	0.656	0.644	0.586	0.568	0.665
Malta	0.005	0.005	0.006	0.005	0.006
Netherlands	3.242	4.009	4.42	4.719	4.594
Austria	2.023	1.884	1.831	2.164	1.776
Poland	5.859	5.549	5.677	6.733	5.501
Portugal	0.055	0.063	0.065	0.071	0.033
Romania	0.063	0.106	0.116	0.088	0.115
Slovenia	0.031	0.025	0.025	0.033	0.034
Slovakia	0.352	0.26	0.303	0.317	0.256
Finland	1.895	1.868	1.681	1.984	1.893
Sweden	2.394	2.605	2.543	2.319	2.951
Iceland	0.067	0.067	0.048	0.048	-
Norway	0.001	0.003	0.002	0.005	0.001
Great Britain	1.317	1.305	-	-	-
Bosnia and Herzegovina	0	0	0	0	0
Montenegro	0.006	0.007	0.007	0.007	0.006
Moldova	0.013	0.012	0.017	0.015	0.013
Northern Macedonia	0.057	0.056	0.057	0.058	0.053
Georgia	0.011	0.012	0.013	0.012	0.012
Albania	0.154	0.115	0.144	0.144	0.144
Serbia	0.114	0.121	0.168	0.174	0.176
Turkey	7.292	7.292	7.292	7.29	7.29
Ukraine	0.427	0.321	0.322	-	-

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

Germany holds a leading position in the consumption of renewable energy, maintaining consistently high levels. This reflects substantial investments and the active development of the RES sector within the country's agricultural industry. Similarly, high consumption levels are observed in the Netherlands and Poland, although fluctuations are evident, likely due to changes in economic conditions and political factors. Countries such as France and Sweden show steady growth in renewable energy consumption, driven by policies promoting the transition to clean energy in agriculture and the provision of subsidies for this purpose. However, in some countries, RES consumption within the agricultural sector represents only a small proportion of total usage. Despite the significant growth of renewable energy in Europe, its application in the agricultural and forestry sectors lags behind. This suggests that the AIC requires additional investments and incentives to align with the pace of RES integration in other industries.

The adoption of RES in the AIC is actively progressing in European countries, where green energy has become an integral part of national policy and a key focus of agricultural development. Germany, the Netherlands, and Spain showcase successful examples of implementing clean energy technologies, enabling agri-industrial enterprises to reduce energy costs, minimise carbon emissions, and build sustainable economies. The integration of solar, wind, and biogas energy highlights how modern energy solutions can drive growth while supporting the environmental objectives of the agricultural sector.

Germany is considered one of the leading European countries in adopting RES in the AIC. It is at the forefront of biogas utilisation in AIC, with over 9,000 biogas plants operating nationwide. In 2021, Germany produced 28 terawatt-hours of electricity from biogas, accounting for approximately 5% of the country's total electricity production (Kornatz *et al.*, 2021). Biogas plants are used on farms to process organic waste, such as manure and crop residues, into biomethane, which is then utilised for electricity generation, heating, and fuel. The German government's strategy actively supports farmers adopting biogas systems through grants and subsidies. As a result, thousands of German farms use biogas to meet their energy needs, reducing reliance on traditional energy sources and significantly lowering greenhouse gas emissions.

One notable example of biogas utilisation in agriculture is Bioenergie Wollbrandshausen, which successfully employs RES technologies to meet the needs of both agriculture and communal infrastructure. The farm and biogas facility at Bioenergie Wollbrandshausen was established to provide clean and sustainable energy for the local community and surrounding agricultural enterprises. The company processes organic waste, including agricultural residues, manure, and food waste, to produce biogas. This biogas plant converts the materials into methane, which is subsequently used for generating electricity and heat. Such a system not only ensures efficient waste management but also significantly reduces carbon dioxide and other greenhouse gas emissions. The Netherlands is a country with a long-standing tradition of utilising wind energy to meet its needs. Modern Dutch farms are equipped with wind turbines that generate electricity for agricultural operations. In 2022, wind energy accounted for over 18% of the country's total electricity production (International Energy Agency, 2022). In agricultural regions, both standalone wind turbines and entire wind farms have been constructed, capable of supplying energy to multiple farms simultaneously.

A prominent example is Royal Pride, one of Europe's largest tomato producers. The company has outfitted its greenhouses with solar panels and wind turbines, significantly reducing energy costs. Additionally, the greenhouses are equipped with heat recovery systems, enabling further savings on heating. The installations generate sufficient electricity to supply approximately 30,000 households. By reusing heat and CO_2 within their own greenhouses, the company achieves an energy utilisation efficiency of approximately 95%. The Dutch government actively supports such initiatives by offering tax incentives and subsidies, allowing companies to recover the costs of wind energy installations more quickly. The Netherlands is also actively implementing innovations in energy conservation. For example, Dutch greenhouses, which represent a significant portion of the country's agricultural production, are increasingly equipped with advanced solar panels and heat recovery systems. These technologies enable greenhouses to utilise solar energy for heating and lighting, while the heat recovery systems help maintain the required microclimate, reducing reliance on traditional energy sources.

Spain, with one of the highest numbers of sunny days in Europe, is ideally suited for the utilisation of solar energy. In 2024, solar energy accounted for approximately 12% of the country's total electricity production, with a significant share used in agriculture (Clark, 2024). Agricultural enterprises in Spain are increasingly installing solar panels to meet their energy needs. Solar energy is utilised for various purposes, including lighting and operating irrigation systems, particularly in the country's arid regions. Many farmers employ solar-powered pumps to supply water to greenhouses and fields, which not only reduces electricity consumption but also promotes efficient water use. A notable example is Grupo Jorge, one of Spain's leading pork producers. The company has installed solar panels and wind turbines on its farms, generating 98 GWh/year and 489 GWh/year, respectively. This initiative significantly reduces electricity costs. The combination of solar panels and wind turbines allows the company to meet all its energy requirements, supporting the sustainable development of the agricultural sector.

The implementation of RES in Germany, the Netherlands, and Spain has highlighted the economic and environmental advantages available to the AIC. For instance, German farms utilising biogas have saved hundreds of thousands of euros on electricity by generating it from organic waste, which also significantly reduces greenhouse gas emissions. Dutch farmers, relying on wind energy, have decreased their dependency on oil and gas, enhancing their resilience to fluctuations in global market prices. In Spain, solar energy has become a vital resource for farms in arid regions, sustaining irrigation systems while lowering electricity costs. The environmental benefits of adopting renewable energy are equally noteworthy. Biogas installations in Germany and Spain help minimise methane emissions and recycle organic waste, thereby reducing negative environmental impacts. Wind and solar energy in the Netherlands and Spain contribute to lowering the carbon footprint while maintaining the quality of soil, water, and air.

The adoption of RES in the AIC of European countries faces several significant challenges and barriers that hinder the transition to a more environmentally friendly and sustainable model of farming. Despite substantial efforts and policy support, the shift to RES is often complicated by economic, technical, environmental, and social factors. Foremost among these challenges is the high cost of implementing RES. The installation of solar panels, wind turbines, or biogas plants requires substantial investment, making the transition to RES economically burdensome for small and medium-sized agricultural enterprises. Access to financing remains another hurdle; while some countries offer subsidies and grants to support RES development, these are often insufficient to cover initial costs, and the process of securing funding is frequently mired in complex bureaucratic procedures (Ainou *et al.*, 2023). Small-scale farmers, in particular, face difficulties accessing these programmes due to a lack of information and the resources needed to complete application processes.

Technical limitations also play a significant role in the transition to RES in AIC. For instance, not all RES can be seamlessly integrated into agricultural operations due to geographical constraints. Wind energy requires consistent airflow, which may not be feasible in all regions, while solar energy depends on the availability of sunny days, posing challenges, particularly in northern European countries. Effective integration of RES into agricultural systems necessitates advanced infrastructure, which, for many farms, entails upgrading power grids and establishing energy storage systems to regulate supply (Cantarero, 2020). Although RES are generally regarded as environmentally friendly, their implementation in AIC can lead to specific environmental challenges. For example, the installation of large solar panels or wind turbines demands considerable land area, which could pose a problem for agricultural land use, especially in regions with limited land availability. Similarly, the use of biomass as an energy source carries risks, as it requires substantial quantities of organic material. This reliance can place additional pressure on forest and agricultural resources, potentially impacting biodiversity.

A significant barrier is the social perception and resistance to changes from traditional farming methods. Agricultural regions with a long history of relying on conventional energy sources may exhibit scepticism towards innovations, particularly if local farmers are unaware of the benefits of RES and their environmental implications. The lack of information regarding the longterm economic and environmental advantages of adopting RES also hinders their acceptance among farmers and agricultural communities (Lennon *et al.*, 2019). Enhancing the effectiveness of renewable energy adoption requires an integrated approach that combines economic, technical, and social strategies. This is particularly crucial in the AIC, which demands sustainable solutions to reduce energy costs, protect the environment, and ensure food security. One key strategy for improving the efficiency of RES in agriculture involves investing in advanced technologies such as high-efficiency solar panels, biogas plants, and wind turbines tailored specifically for rural settings. For instance, innovations in solar panels capable of functioning effectively under low light conditions could enable wider adoption in European countries with temperate climates. Implementing such advancements necessitates support from both the government and the private sector, alongside accessible subsidies and grants for farmers.

The effective implementation of RES is unattainable without government involvement. While European countries already operate successful support mechanisms, these could be further strengthened. For example, subsidies for RES installations, tax incentives, and preferential loans for farmers investing in RES significantly reduce financial barriers. Such programmes might also include reimbursements for part of the equipment costs or concessional financing. Germany provides a successful example where government programmes facilitate widespread adoption of RES in AIC, ensuring long-term support and stability for farmers transitioning to green energy.

A lack of awareness regarding available RES technologies and their benefits for AIC remains a barrier for many farmers. Consequently, educational initiatives and information campaigns are essential to disseminate knowledge about RES. These programmes could be tailored for all levels of stakeholders in the agricultural sector, from smallholder farmers to managers of large agricultural enterprises. In Sweden, for instance, training programmes and workshops equip farmers with practical knowledge on implementing RES.

For many rural regions, the primary challenge remains the lack of infrastructure to connect to RES. The installation of wind turbines, solar panels, or biogas plants requires a certain level of accessibility and support from energy networks. In regions where such infrastructure is already in place, such as the Netherlands, farmers actively utilise RES. Developing this infrastructure demands additional investment but promises significant long-term reductions in energy costs. Collaboration among agricultural enterprises in adopting RES can result in substantial cost reductions and increased efficiency. Cooperatives, where multiple farms share biogas facilities or collectively invest in wind turbines, exemplify this strategy. In France, this model has gained traction and proven effective, particularly for smaller farms that cannot independently afford the investment in RES.

To actively promote RES, quotas and mandatory standards could be introduced to increase the share of clean energy in the agricultural sector's overall consumption. For instance, the United Kingdom has implemented mandatory standards for agricultural producers, requiring a certain level of RES usage. While such measures require time for adaptation, they foster sustainable practices and provide economic incentives for farmers to transition to green energy. Modern digital technologies, such as the Internet of Things (IoT) and artificial intelligence (AI), can significantly enhance the efficiency of RES. IoT sensors enable real-time monitoring of solar panels and wind turbines, ensuring optimal energy utilisation and minimising losses. In Spain, energy management systems based on data analytics have been developed, allowing agricultural enterprises to flexibly allocate energy according to operational conditions and specific needs.

The integration of environmentally friendly energy sources into the AIC requires coordinated efforts at governmental, private, and community levels. Strategies focused on funding, education, infrastructure development, and collaboration can help overcome barriers and optimise the use of RES in agriculture. These approaches not only enhance efficiency but also improve the sustainability of the agricultural sector, offering a cleaner and more cost-effective alternative to traditional energy sources.

DISCUSSION

The findings of the study highlight the significant role of RES in achieving sustainable development within the AIC. As a critical component of the economy, agriculture influences food security, ecosystems, and public health. However, given the high levels of carbon emissions and other pollutants, the adoption of RES is essential for establishing a more environmentally responsible and economically sustainable agricultural system. The primary types of renewable energy, including solar, wind, biogas, and geothermal energy, have demonstrated their effectiveness in the agricultural sector. Each type offers unique characteristics and benefits that cater to the specific needs of agricultural enterprises. For instance, solar energy is ideal for regions with high levels of sunlight, providing farms with electricity for lighting, heating, and irrigation. Wind energy is particularly relevant in areas with consistent airflows, where it can power equipment and water pumps. Biogas systems enable farms to process organic waste, converting it into a source of energy while reducing environmental pollution. Finally, geothermal energy provides consistent heating, which is especially valuable in regions with harsh climatic conditions. P.A. Østergaard *et al*. (2020) conducted a comparative analysis of different types of renewable energy, highlighting that geothermal energy is the most stable but also the most expensive and challenging to implement in agricultural enterprises. Contrary to more recent findings, which consider geothermal energy a promising avenue for sustainable development, the study emphasised that it remains less accessible for small and medium-sized enterprises.

C.M. Kumar *et al*. (2023) focused on the integration of solar energy into farms. Their research highlighted that in certain climatic regions, solar panels are underutilised due to insufficient solar radiation, and the costs associated with their installation and maintenance may exceed the anticipated benefits. This finding contrasts with current results emphasising the versatility of solar panels. However, the author's conclusions are significant in recognising regional disparities and the need to develop technologies capable of performing efficiently across various climatic conditions.

H.M. Usman *et al*. (2024) examined the adoption of wind turbines on farms, noting that their use is often associated with challenges such as the requirement for large land areas and high noise levels. In contrast to current conclusions regarding the long-term economic efficiency of wind energy, the author argued that only a limited number of farms can provide the suitable conditions needed for turbine installation. This perspective underscores the importance of selecting appropriate locations and highlights the necessity of addressing infrastructural constraints and potential conflicts with rural communities.

Economic efficiency is a key advantage of using RES in the AIC. While the installation of solar panels, wind turbines, and biogas plants requires substantial initial investment, these expenditures enable agricultural enterprises to significantly reduce reliance on conventional energy sources in the long term. Additionally, access to government subsidies, grants, and tax incentives enhances the appeal of such investments, allowing farmers to recover costs more quickly. M.R. Elkadeem *et al*. (2019) investigated the economic feasibility of RES adoption on farms and highlighted economic barriers that hinder the transition to green energy, particularly for small and medium-sized enterprises. In contrast to current findings, which confirm the economic viability of RES, the author argued that the installation costs for smaller farms remain prohibitively high, serving as a deterrent. M. Saleem (2022) similarly emphasised the necessity of governmental financial support to overcome these barriers. This support could include subsidies for equipment installation, tax incentives, and accessible loans, aligning with the current conclusions regarding the critical role of state assistance.

L.T. Clausen and D. Rudolph (2020) examined the role of financial mechanisms in supporting farmers transitioning to RES. Their research revealed that in countries with highly developed credit systems and preferential programmes for adopting green energy, such farms exhibit the greatest economic resilience. In contrast to current findings, which emphasised the long-term economic benefits of renewable energy utilisation, the authors argued that without accessible financial tools for farmers, the transition process could be significantly delayed.

From an ecological perspective, renewable energy significantly reduces the carbon footprint and minimises the environmental damage associated with AIC. For instance, biogas plants on farms facilitate the utilisation of organic waste, decreasing methane emissions and reducing reliance on fossil fuels. Wind and solar energy also exert minimal environmental impact, as their generation does not involve carbon dioxide or other pollutant emissions. U.K. Pata (2021) similarly focused on the environmental benefits of renewable energy but highlighted concerns related to biodiversity. The author identified that large-scale biogas installations could increase the demand for biomass, placing pressure on natural resources and potentially threatening biodiversity if resource harvesting is conducted without adequate oversight. This perspective contrasts with current findings, which present biogas systems as a sustainable solution for the AIC. However, the author's observation regarding the need for environmental regulations is valid; implementing additional controls could ensure more rational biomass use and mitigate potential adverse effects.

At the same time, despite positive outcomes, the adoption of renewable energy in AIC faces several challenges. The high cost of implementing RES remains a significant barrier, particularly for small and medium-sized farms. Technical constraints, such as the need for consistent wind for wind energy or sufficient sunlight for solar panels, complicate integration in certain regions. Additionally, advanced infrastructure is required to connect RES to the grid and ensure efficient energy storage and distribution. A.G. Olabi and M.A. Abdelkareem (2022) examined the impact of renewable energy on climate resilience, concluding that transitioning to green energy mitigates the effects of climate change but necessitates substantial infrastructure upgrades for effective energy utilisation. Similarly, D.E. Gernaat *et al.* (2021) argued that the successful implementation of renewable energy also depends on the development of energy grids and distribution systems. This partially contrasts with the current claim that renewable energy can be integrated into nearly any agricultural enterprise. The authors emphasised that infrastructural limitations must be addressed when scaling up renewable energy, reinforcing the argument for modernising rural energy infrastructure.

Social aspects also play a crucial role, as the transition to RES requires a shift from traditional agricultural practices. A lack of information about the benefits and long-term profitability of RES hinders the popularisation of green technologies among farmers. M. Kumar (2020) examined the social dimensions of RES adoption in rural regions, finding that the shift to green energy enhances living standards and attracts younger generations to rural areas by creating new employment opportunities. These findings align closely with current results, which also highlight that job creation in the renewable energy sector strengthens rural economies and fosters social development. This perspective underscores that social benefits are equally significant in promoting the sustainable development of the agricultural sector. The research findings emphasise the importance of a comprehensive approach, involving government support, investment in innovation, infrastructure development, and information and educational campaigns, to successfully integrate RES into the AIC.

CONCLUSIONS

This study conducted a comprehensive assessment of the utilisation of RES in the AIC as an integral part of sustainable development strategies. RESs have become increasingly important for ensuring food security, protecting human health, and safeguarding ecosystems. While AIC remains a significant source of carbon dioxide and other pollutants, transitioning to more sustainable and cleaner energy sources is a necessary step. The research identified four key groups of environmentally friendly energy sources utilised in AIC: solar, wind, biogas, and geothermal energy. Each of these technologies offers distinct characteristics and advantages. For instance, solar panels are gaining popularity due to their versatility, as they can be installed on rooftops or fields, providing farmers with electricity for lighting and irrigation. Wind energy, recognised as the most economically efficient option in the long term, is suitable for regions with consistent wind flows, supplying energy to farms and agricultural facilities.

One of the critical aspects of sustainable development is economic efficiency, which involves reducing energy costs and enhancing the profitability of agricultural enterprises. The adoption of RES enables farms to manage their energy expenses effectively, reducing dependency on fluctuations in the prices of conventional resources. Environmental responsibility, in turn, lies in reducing carbon emissions and minimising pollution, making agribusinesses more sustainable and competitive. Examples from Germany, the Netherlands, and Spain illustrate how the use of biogas, wind, and solar energy allows farmers to lower energy expenses and reduce their environmental footprint while simultaneously increasing profitability. In Germany, for instance, over 9,000 biogas plants convert agricultural organic waste into biomethane, which is utilised to generate electricity and heat. In the Netherlands, wind energy plays a significant role in the energy mix of the agricultural sector. Modern farms install wind turbines, which provide electricity and help reduce energy costs by up to 30%. Similarly, Spain, benefiting from high levels of solar irradiation, actively develops solar energy in agriculture. Many farmers install solar panels to power their operations, cutting electricity expenses by up to 25%.

Overall, the transition to RES in AIC offers significant economic and environmental benefits. Despite existing barriers, such as high initial costs and insufficient infrastructure, targeted governmental support, farmer education, and the establishment of cooperatives can greatly facilitate this process. The study highlights the need to integrate modern technologies and promote sustainable practices within the agricultural sector, ultimately contributing to sustainable development in farming. A limitation of this study is its focus on selected European examples, which may not fully capture the situation in other regions with differing economic and climatic conditions. Future research could explore the impact of local policies and economic factors on the adoption of RES in AIC in other countries, particularly in developing regions.

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CONFLICT OF INTEREST

None.

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Економічні аспекти впровадження екологічних чистих джерел енергії в агропромисловому комплексі (на прикладі країн Європи)

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Анотація. Дане дослідження спрямоване на аналіз впливу екологічно чистих джерел енергії на економічну підтримку агропромислового комплексу. У рамках дослідження виокремлено чотири основні групи екологічно чистих джерел енергії, що використовуються в агропромисловому комплексі: сонячна енергія, вітер, біогаз і геотермальна енергія. Кожна з цих технологій має унікальні характеристики та переваги, здатні задовольнити енергетичні потреби сільськогосподарських підприємств. Незважаючи на значний внесок агропромислового комплексу у викиди вуглекислого газу та інших забруднюючих речовин, перехід на стійкі джерела енергії може не тільки скоротити негативний вплив на навколишнє середовище, а й забезпечити економічні переваги, сприяючи створенню стійкої та конкурентоспроможної сільськогосподарської економіки. Розглянуто приклади успішного впровадження цих джерел у Німеччині, Нідерландах та Іспанії, де відзначено значний внесок поновлюваних джерел в економіку та екологічну стійкість агробізнесу. Робота також акцентувала увагу на економічній ефективності, екологічній відповідальності та соціальній справедливості як ключових принципах сталого розвитку. Впровадження відновлюваних джерел енергії сприяє зниженню витрат на енергію, зменшенню залежності від традиційних ресурсів та покращенню конкурентоспроможності сільськогосподарських підприємств. Водночас, використання екологічно чистих технологій допомагає мінімізувати вуглецеві викиди та покращити якість довкілля. Обговорювалися основні проблеми та бар'єри, що заважають впровадженню екологічно чистих джерел енергії в агропромисловому комплексі, такі як високі початкові інвестиції, технічні обмеження та брак інфраструктури. Для підвищення ефективності впровадження чистих джерел енергії пропонувався комплексний підхід, що включає інвестиції в нові технології, державні субсидії, освітні ініціативи та створення кооперативів

Ключові слова: сталий розвиток; біомаса; сонячні панелі; вітрові установки; навколишнє середовище

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