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Piglet survival and pre-weaning mortality: The effect of breed, stability, and plasticity under varying housing and feeding conditions

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Abstract. The paper presents the results of a comparative analysis of the adaptive properties of Welsh and Landrace pigs based on three key economically useful traits: the number of piglets in the litter at weaning, piglet pre-weaning mortality during the suckling period, and piglet survival during the suckling period. The purpose of the study was to determine the level of stability and plasticity of the analysed economically useful traits in changing conditions of housing and feeding. In this case, the values of the studied traits in these six generations of piglets were used as environmental indices. The research was based on data on 822 litters of suckling piglets

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obtained in 2015-2024 from six generations of pigs. The animals were kept under traditional feeding and breeding conditions at Shubske Farming Enterprise LLC. The variability of the environment was formed under the influence of changes in feeding, technological, and organisational factors in the farm. To estimate the adaptive parameters, the Eberhart-Russell method was used, which determined the plasticity coefficient (b_i) and the stability index (S^2d_i) of the studied traits. Statistical processing was performed using the SPSS Statistics-22 package. The results obtained showed significant breed differences. Thus, Landrace pigs showed the best average values of all the indicators considered, in particular, a significantly higher survival rate of piglets ($p < 0.001$). However, Welsh pigs showed significantly greater plasticity in terms of survival ($b_i = 1.36$), indicating their increased sensitivity to changes in housing and feeding conditions, while in Landrace pigs this indicator was only $b_i = 0.57$. In terms of survival stability, Welsh pigs were also inferior, characterised by a higher residual variance ($S^2d_i = 58.48$ vs. 34.03 in Landrace). Based on the obtained data, a statistically significant regression model for assessing the survival of Welsh piglets was constructed ($p = 0.005$). The results of the study can be used to optimise breeding programmes and select breeds for specific production conditions

Keywords: suckling piglets; Landrace breed; Welsh breed; environment index; milk feed; regression

INTRODUCTION

The effectiveness of pig breeding is largely determined by a balanced selection of breeds that optimally meet specific production conditions and consumer market requirements. For the correct assessment of reproductive, productive, and adaptive traits of pigs from different genetic groups, it is also advisable to control a number of environmental conditions, in particular housing and feeding, including the state of technology at the farm level or external socio-economic factors in the country. This approach allows correctly assessing and predicting the effectiveness of using genetic groups in specific environmental conditions. This approach has been emphasized by several researchers. According to M. Aparicio *et al*. (2024), feeding sows during gestation and lactation, and primarily the balance of energy and nutrients in their diet, affects birth weight, milk production and colostrum quality, and consequently piglet survival. There is also evidence to support the effectiveness of measures that increase and stabilise early intake of feed other than mother's milk by piglets (e.g., the use of starter mixtures before and after weaning). In addition, according to M. Wensley *et al*. (2021), early introduction to starter feed is also important. Simultaneously, O. Korzh (2025) argued that along with the feeding system, the housing conditions also significantly affect the realisation of the genetic potential of pigs, which is expressed in their productivity. Deviations from recommended management practices, husbandry, feeding regimes, microclimatic parameters, and veterinary standards usually negatively affect the economically useful characteristics of animals. In turn, A. Kramarenko *et al*. (2023) conducted empirical studies of the causes of perinatal mortality and risk factors. The influence of farrowing order, piglet weight, parity, season and breed on the risk of stillbirths has been established. In addition, R. Shvachka (2021) showed the influence of local factors, such as climate, feeding and housing conditions, and farm structure, on the piglet survival. The researchers emphasised the expediency and necessity of adapting international approaches and recommendations (for example, regarding the optimal age of weaning, perinatal management measures) to local conditions.

The study by R. Zaalberg *et al*. (2022) showed that infectious factors such as enteritis, staphylococcal and viral infections, etc., significantly increase mortality risks. But the practices of implementing appropriate veterinary measures, such as vaccination and biosafety programmes, and early diagnosis of diseases, are important components of loss prevention, and therefore confirm their high feasibility and effectiveness. In addition, B. Tucker *et al*. (2021) noted that management and environmental factors play an equally important role. In particular, farrowing and perinatal management conditions can either promote good piglet survival (with a high level of care) or lead to significant losses in livestock numbers. It was also proven that clear control of temperature, hygiene of the farrowing site, cross-fostering of piglets, and access to colostrum reduce the pre-weaning mortality of piglets. Reviews of management practices emphasised that standardised perinatal care protocols are most effective in reducing the gap between breeds and farms. The age of weaning is also an important factor.

One of the significant problems of pig breeding, according to B. Tucker *et al*. (2021) and R. Zaalberg *et al*. (2022), remains high piglet mortality: under commercial conditions, it typically ranges from 8% to 20% depending on the country, breed, feeding and housing conditions, management, genetic potential of the

animals, and other factors. This economically useful trait has a direct economic impact on the efficiency of pig farming, as it largely determines the overall productivity of the herd, and a reduction in piglet mortality results in lower production losses. Pre-weaning mortality also varies significantly between farms. Among the biological and genetic factors that more or less determine the value of the studied trait, the weight of piglets at birth, and their morphometric indicators also play an important role. Low birth weight is associated with poor thermoregulation, difficult access to colostrum, and increased mortality. However, simple morphometric indicators (chest circumference, torso length) can sometimes be more accurate predictors of viability than weight itself. Currently, in addition to birth weight, studies suggest considering complex morphometric indicators and early behavioural or physiological traits (skin temperature, behavioural responses) as more reliable predictors of survival. This helps to more accurately control the conditions for raising piglets (heat lamps, cross-fostering, supplementary feeding), identify risk groups at an earlier stage, and thus promptly intervene to provide them with appropriate care.

Thus, the study of indicators of pre-weaning piglet mortality and factors that affect it remains a relevant area of modern pig breeding. The key variables that determine the level of survival of young animals are considered to be the breed, genetic potential, feeding conditions, housing system, and biological characteristics of animals. Moreover, contemporary research in the field of pig breeding pays considerable attention not only to the analysis of average reproductive and productive traits, but also to their variability under different conditions of housing and feeding. Insufficient attention was paid to the analysis of stress resistance, plasticity, and stability of economically useful traits of pigs of different genetic groups. Therefore, the purpose of the study was to determine the level of stability and plasticity of the number of piglets in the litter at weaning, piglet mortality during the suckling period, and piglet survival during the suckling period under variable conditions of housing and feeding.

MATERIALS AND METHODS

The study used data on 822 litters of piglets from Shubske Farming Enterprise LLC, which belonged to the Welsh (444 litters) and Landrace (378 litters) breeds. The piglets were reared under conventional suckling management with their sows until two months of age, after which they were weaned. Information on the results of rearing was recorded during 2015-2024; during this time, 6 generations of pigs were studied. The conditions of housing and feeding during the controlled period changed under the influence of both on-farm (compound feed composition, state of the economy, etc.) and national (economic, military situation, etc.) factors. Concurrently, technological and organisational elements of production were improved. In the end, seasonal and climatic fluctuations also significantly affected the process of raising piglets. In order to assess the adaptive properties of sows of the compared breeds, a mathematical model was applied, which was proposed by K. Finlay & G. Wilkinson (1963). Later, this model was slightly improved and supplemented by S. Eberhart & W. Russel (1966). It was used by the authors to assess the plasticity and stability of agricultural plant varieties. Several authors have utilised this model to determine the adaptive capabilities of agricultural animal breeds. In particular, E.G. Camargo *et al.* (2020) used it to evaluate the plasticity and stability of litter size and uniformity in Landrace pigs. In general, the model defines parameters of plasticity and stability that can be used to describe the productivity of breeds, lines, families, crossbreeds, and other genetic groups of animals in a number of environments. In the final form in this paper, the Eberhart-Russell model appeared as follows:

$$Y_{ij} = \mu_i + b_i I_j + \delta_{ij}, \quad (1)$$

where Y_{ij} – average value of the economically useful trait of the *i*-th breed in the *j*-th environment; μ_i – average value of the economically useful trait of the i-th breed in all environments; b_i – regression coefficient, which measures the degree of reaction (plasticity) of the *i*-th breed to various environments; δ_{ij} – deviation from the regression of the *i*-th breed in the *j*-th environment; I_j – environment index (average value of the economically useful trait in the *j*-th environment).

Therefore, the Eberhart-Russell method was based on calculating the linear regression coefficient (b_i) of individual values of the studied trait (a dependent variable, for example, the number of piglets at weaning) on the environment index. As an index of the environment (predictor), the average indicators of the same studied trait were used, but separately for each generation of pigs (a total of 6 generations were controlled). In this case, the regression coefficient b_i indicates the level of plasticity of this feature in the analysed breed, and the residual variance S^2d_i indicates the level of stability, respectively. As effective evaluated economically useful traits in this study, "piglet mortality for the period from birth to weaning (heads)", "number of piglets at weaning (heads)", and "piglet survival rate during the suckling period (%)" were used.

The suckling period was considered as the time interval from the birth of piglets to their weaning.

Piglet survival was determined as the percentage ratio of the number of animals that survived to weaning to the number born alive. Piglet pre-weaning mortality was calculated by recording the number of dead animals for the entire suckling period. The pre-prepared data was processed using the SPSS Statistics-22 application software suite. This application used built-in regression and variance analysis procedures. For each breed, the values of the plasticity coefficients (b_i) and stability coefficients (S^2d_i) were determined, which were used for further comparison. For each calculated parameter, the standard error, t-criterion, p-level of significance, and 95% confidence intervals were determined. To this end, the values of the corresponding environment (generation) indices I_j for each economically useful trait being evaluated were first calculated and then added to the database. To do this, the SPSS procedure "Analyse → Compare Means → Means" was used, selecting the actual evaluated feature and the grouping factor of the environment – generation.

Regression assessment was performed for each breed separately by applying the "Analyse → Regression → Linear" procedure, indicating the estimated economic and useful trait as a dependent variable ("Dependent"), and the environment index – as an independent ("Independent"). The "Statistics" tab provided for activating the "Durbin-Watson", "Confidence intervals" and "R squared change" ratings. Therefore, using the SPSS application package, separate regression models were calculated for each breed, including the values of regression coefficients b_i and residual variances S^2d_i. To assess the degree of influence of factors in the analysis of variance, the η^2 indicator was used. The statistical significance levels of all indicators evaluated in the model were calculated and then checked. The results were considered statistically significant at $p < 0.05$. All animal handling procedures were fully compliant with European legislation (Council Directive 98/58/EC, 1998).

RESULTS AND DISCUSSION

Stability and plasticity of adaptive traits of piglets and their prediction

At the first stage of research, a series of analyses of variance (ANOVA) of the influence of the breed on such economically useful features as "piglet mortality for the period from birth to weaning (heads)", "number of piglets at weaning (heads)" and "piglet survival in the suckling period (%)" were conducted. The results are presented in Table 1.

Table 1. *Main statistical characteristics of the influence of breed on the economic traits of pigs of different breeds*

Breed	Statistical indicators	Economically useful traits		
		Number of piglets in the litter at weaning, heads	Survival rate of piglets during the suckling period, %	Piglet mortality for the period from birth to weaning, heads
Landrace	Number of litter	378	378	378
	Arithmetic mean	11.83	87.81	1.68
	Standard error of the arithmetic mean	0.06	0.30	0.05
	Standard deviation	1.13	5.83	0.88
Welsh	Number of litter	444	444	444
	Arithmetic mean	11.32	83.47	2.30
	Standard error of the arithmetic mean	0.06	0.36	0.06
	Standard deviation	1.20	7.66	1.18
Total	Number of litter	822	822	822
	Arithmetic mean	11.55	85.47	2.02
	Standard error of the arithmetic mean	0.04	0.25	0.04
	Standard deviation	1.19	7.21	1.10

Source: *developed by the authors based on the research presented in this paper*

It was found that the adaptive traits under study differed significantly depending on the breed. In particular, it can be stated that pigs of the Landrace breed were significantly better ($p < 0.001$) in all analysed characteristics compared to animals of the Welsh breed. However, the highest degree of influence of the breed ($\eta^2 = 9.0\%$) was recorded on the survival rate of piglets during the suckling period. Belonging to a particular breed can explain only 4.5% of the variability in the number of piglets in the litter at weaning and 8.0% of the variability in piglet mortality from birth to weaning. Notably, over time, for the most part, there was a tendency for some improvement in the analysed economically useful traits. However, a statistically significant effect of generation was found ($p = 0.014$) only in relation to the number of piglets in the litter at weaning (heads). The degree of this impact was $\eta^2 = 1.7\%$. Possible differences in the number of piglets in the litter during weaning (heads) were recorded between the maternal generation, on the one hand, and the third, fourth, or

fifth generations, on the other, and between the first and fourth and first and fifth generations.

According to the Eberhart & Russell approach (1966) and its interpretation in animal husbandry (Shablia & Shablia, 2025), the regression coefficient (b_i) is a quantitative measure of genotype plasticity, reflecting the degree of change in the economically useful trait of animals in response to changes in environmental conditions. In the case of adaptive characteristics of piglets, this indicator determines the breed's response to changes in environmental parameters, primarily maintenance and feeding. If the plasticity index b_i of a particular breed or other genetic group is close to 1, it is characterised as medium plasticity, i.e., one in which the level of the studied economically useful trait fluctuates synchronously with fluctuations in conditions. Accordingly, the specified value of plasticity of the genetic group indicates satisfactory adaptability within the standard technological parameters of production. According to the values of $b_i > 1$, the breed (or genetic group) is classified as highly plastic, which indicates a pronounced sensitivity to changes in the conditions of keeping and feeding: an improvement in the environment in this case is accompanied by a significant improvement in the evaluated economically useful trait, while deterioration of conditions can lead to a noticeable deterioration of the trait. It is advisable to breed highly plastic genotypes in farms with good technological parameters, where conditions close to optimal for the manifestation of breeding inclinations of animals are created. When $b_i < 1$, the breed is characterised by low plasticity, which means relative stability of the economically useful trait regardless of fluctuations in environmental factors. Such animals are less demanding in terms of housing and feeding conditions, and also retain a certain level of the trait under study to a greater extent, even under stressful or unfavourable production conditions. In the course of the conducted studies, the presence of pronounced interbreeding differences in the plasticity indicator of the indicator "survival of piglets in the suckling period" was established (Fig. 1). As can be seen, Welsh piglets showed a more intense response to changes in conditions of keeping and feeding, which is reflected in the value of the regression coefficient $b_i = 1.36$, while in Landrace pigs this indicator was only $b_i = 0.57$.

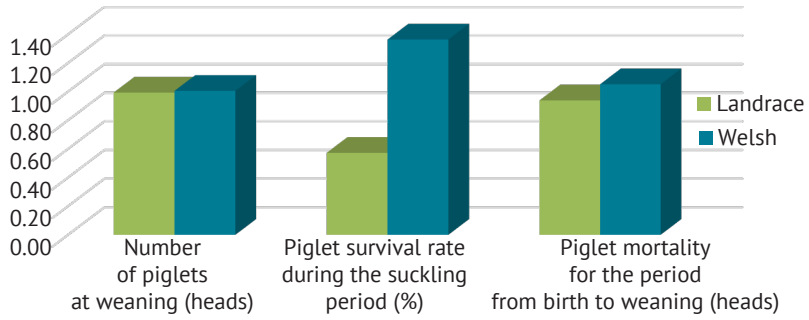

Figure 1. *Plasticity (b_i) of economically useful characteristics of Welsh and Landrace piglets*
Source: *developed by the authors based on the research presented in this paper*

The data obtained indicate that Welsh pigs can be classified as highly plastic genotypes for the analysed trait, since the regression coefficient exceeds one. This means that the survival rate of piglets of this breed is significantly improved under conditions of optimal management, balanced feeding, and proper microclimate. However, under unfavourable conditions, Welsh pigs show a noticeable decrease in the survival rate of young animals, which indicates their increased sensitivity to external factors. Unlike Welsh pigs, Landrace pigs are characterised by low plasticity in terms of piglet survival before weaning. Thus, the regression coefficient is significantly lower than one, which indicates a weaker response to changes in environmental conditions. Thus, the survival rate of Landrace suckling piglets remains more stable even with fluctuations in the level of feeding, housing or microclimate, that is, this breed reacts less with this economically useful trait to both deterioration and improvement of conditions. This allows considering the survival rate of Landrace piglets as an indicator that fluctuates little with conditions, and the Landrace breed itself in this respect – as adapted more to extensive or unstable production systems, where the advantage is given to sustainable productivity, rather than maximum potential under favourable conditions.

Stability of adaptive traits of piglets and their prediction

But the Welsh breed, as a genotype that provides a certain survival rate of piglets from birth to weaning, is an appropriate choice for intensive growing technologies

that involve a high level of feeding and care, because it is in such conditions that its genetic potential for this trait is most fully revealed. Comparative analysis of the regression lines of both breeds confirms these trends: Welsh pigs are characterised by a steeper slope of the regression line, which indicates greater reactivity to changes in the index of the environment, while Landrace pigs have a flatter line, which indicates less plasticity of the studied trait. Along with the regression coefficient (plasticity) b_i, an important element in assessing the response of genotypes to variable feeding and housing conditions (environment) is an indicator such as the stability of the trait under study. Within the Eberhart-Russell model, the stability of an economically useful trait is interpreted by the value of the residual variance of the analysed trait (S^2d_i), which characterises the degree of unpredictability of the genotype response (a certain breed of pigs in these studies) to changes in feeding and housing conditions.

The interpretation of this indicator is carried out according to the following principles: (1) low residual variance (S^2d_i) indicates a high stability of the trait, its relatively small individual deviations from the regression line, and therefore, the ability of the breed to maintain in general the relative proximity of individual values of the trait to those predicted by the regression model based on the indices of the environment. (2) High S^2d_i values, on the contrary, indicate low stability, which means increased variability in the genotype's response to external influences, more significant individual deviations of the trait from the regression line, and, accordingly, lower predictability of results under different technological conditions. Notably, the value of the residual variance S^2d_i depends on the measurement scales and the features of variation of the evaluated traits. Therefore, it is correct to conduct a comparative assessment of stability only when considering the same trait of animals of different genetic groups. That is why, within the scope of this study, comparing the stability of each of the economically useful traits separately for each breed is methodologically justified.

When it comes to estimating the stability (residual variance) of traits of different nature, it is advisable to use relative values of these traits or dimensionless coefficients to avoid distortions associated with the difference in the scale of variation. The analysis performed so far showed that Welsh suckling piglets were characterised by a higher residual survival variance (S^2d_i = 58.48) than Landrace pigs (S^2d_i = 34.03). This indicates greater individual deviations of the actual survival values of Welsh piglets from the regression line, and a lower level of predictability of this trait (Fig. 2).

Figure 2. *Stability (S^2d_i) of the survival rate (%) of suckling piglets of different breeds*
Source: *developed by the authors based on the research presented in this paper*

The data obtained indicate that the response of Welsh piglets to changes in environmental conditions is less stable. Their survival rate from birth to weaning shows wider fluctuations in response to changing feeding and housing conditions. This may indicate a more noticeable influence of uncontrolled factors on the development of the trait under study, or a lower resistance of the genotype to changing conditions. Consequently, Welsh suckling piglets are characterised by increased sensitivity and a significant amplitude of changes in the survival rate in response to changes in environmental conditions, which is accompanied by a noticeable variability of this economically useful trait. Considering the identified adaptive characteristics, a statistically reliable regression model was constructed to estimate the number of weaned piglets (heads) of the Welsh breed (Table 2). The model had a high significance (p = 0.005) and an average level of explanatory power (R^2 = 0.017).

Table 2. *Model for estimating the number of weaned piglets (heads) of the Welsh breed*

Predictor (x)	Regression coefficient			Student's t-test	Significance level p	95.0% confidence interval for b	
	Simple b (%/%)	Standard error b (%/%)	Standard β, (sy/sx)			Lower limit	Upper limit
Constant	-0.298	4.154		-0.072	0.943	-8.462	7.866
Environment index (generations), heads	1.006	0.360	0.132	2.797	0.005	0.299	1.712

Source: *developed by the authors based on the research presented in this paper*

The obtained parameters allow using this model as a tool for analysing the impact of changes in environmental conditions on the number of weaned Welsh piglets, and for predicting this trait in conditions of unstable technological factors. With regard to such an adaptive trait as "number of piglets in the litter at weaning, heads", the differences between the residual dispersions (stabilities) for the studied breeds were insignificant; they amounted to $S^2d_i = 1.41$ for Welsh pigs and $S^2d_i = 1.26$ for Landrace pigs. However, there were greater differences in terms of "piglet mortality from birth to weaning": $S^2d_i = 1.39$ for Welsh pigs and $S^2d_i = 0.77$ for Landrace pigs. Thus, it is possible to state more significant deviations of the analysed traits from the regression line for the Welsh breed compared to Landrace, which indicates their lower stability. However, it was not possible to develop reliable models for assessing characteristics such as "piglet survival during the suckling period" and "piglet mortality from birth to weaning" given the statistical parameters of the sample.

Comparison of the results obtained with data from other studies

Comparing the results with the data of other researchers, it is worth highlighting three aspects: firstly, it is the applicability and effectiveness of evaluation methods; secondly, the justification and correctness of attracting certain factors and economically useful traits to the model; thirdly, the actual results of evaluation. As for the estimation methods, it should be noted that the Eberhart-Russell model used in the study is a classic and simple way to estimate plasticity and stability on a single medium index. Modern reaction norm models (RNM) are an extension of the same idea and methodology to multidimensional environments, allowing for a deeper understanding, assessment, and prediction of the reaction of economically useful traits, taking into consideration the complex gradient of environmental factors.

According to P. Freitas *et al.* (2024), who examined the effect of a number of variables on the manifestation of the "genotype × environment" interaction in pigs, reaction norms help to better describe the variation of productive traits in genetic groups under different environmental conditions, if the interaction of the genotype with the environment is evaluated, including several traits or reaction norms in the model. According to the researchers, this may slightly improve the performance of the model, although to get an acceptable level of probability, it is usually necessary to significantly increase the sample size and improve its quality. Meanwhile, the "generations" used in these studies as environmental indices allow simultaneously assessing the complex impact of a wider range of environmental factors at the level of simpler models at an acceptable level of probability. H. Song *et al.* (2020) also showed that models of reaction norms, taking into consideration the "genotype × environment" interaction (G × E, which are conceptually equivalent to the Eberhart-Russell models), improve the prediction of genetically determined economically beneficial traits, such as the average daily gain and backfat thickness in genomic selection, demonstrating the practical implementation of the plasticity of genetic effects across environments.

In turn, H. Pham *et al.* (2025) proposed a simplified use as an environmental index of geographical and climatic conditions (with two gradations – "temperate" and "tropical humid" climate), especially for the reproductive characteristics of pigs, where the resistance of the genotype to environmental stress factors is key. Thus, these researchers use a model that is simpler than in the presented study, but emphasise its effectiveness. Therefore, it is more appropriate to use similar models with a minimum number of environmental indices to assess the plasticity and stability of genetic groups in well-defined contrasting gradations of conditions that change little over time. Testing by S.-Y. Chen *et al.* (2021) of compromise model organisation allowed the authors to conclude that it is advisable to use the so-called "quantitative environment gradient" to assess the environment. This environment index is an aggregate indicator that includes conditions of keeping, feeding, and management and, according to the researchers, allows determining how consistently genotypes of different genetic groups realise their potential under certain contrasting conditions. F. Tiezzi *et al.* (2020) suggest including directly into the models a set of several dozen environmental covariates obtained from public weather station records. This allows fully adjusting the results for the influence of a complex of climatic factors. Both of these approaches can also be used to deepen existing research, even if the volume of data is unprincipled.

Regarding the comparison of the results obtained in the presented studies of evaluating the actual indicators of plasticity and stability of various genetic groups with the conclusions of other authors, a certain similarity of the results can be stated. According to O. Tsereniuk *et al.* (2023), differences in plasticity and stability of different sows in the genetic groups of pigs of Landrace and Welsh breeds were found. In particular, significant fluctuations in the values of plasticity and stability of the indicator "number of weaned piglets" were demonstrated. According to the researchers, genetic factors and maternal effects are of great importance for pre-infant mortality in piglets. In particular, breed differences and maternal families affect the basic probability of piglet survival. Ultimately, some maternal families have higher milk production and better maternal behaviour, which

increases the chances of survival of the offspring. However, estimating the average values of plasticity of this trait for all families, it is close to those established by current studies. These statements were supported by T. Chu *et al.* (2022) and K. Will *et al.* (2024), who argued that there was a significant genetic variation in pre-weaning mortality that poses both certain risks and the potential for breeding to improve these rates. In addition, J. Dekkers (2021) noted that breeding only for prolificacy without birth weight control can increase risks, which echoes the topic of this study, which aims to evaluate the expression of prolificacy during the suckling period. The researchers proposed to use multivariate and maternal models (animal models) to identify direct and maternal genetic effects on survival, which allow separately assessing the contribution of the offspring and mother.

These approaches are basic for breeding work and individual selection, but it is more appropriate to use the methods used in this paper to assess the response of a genetic group to changing conditions. This is exactly what E. Camargo *et al.* (2020) did, assessing the plasticity and stability of the size and uniformity of piglets in Landrace breed. In contrast to current research, K.-H. Lin *et al.* (2024) applied the reaction norm model to assess the effect of "genotype × environment" on Landrace reproductive traits under heat stress (temperature and humidity index), illustrating the plasticity and variability of genetic parameters under different microclimate conditions. This allowed assessing the adaptive potential of individual genetic groups of pigs, in particular, in relation to compensatory capabilities under stress factors. As in current studies, the findings of P. Shablia *et al.* (2025) showed that methods for assessing plasticity and stability should be actively used to predict reproducible and other economically useful traits. Thus, it has been established that the use of regression models based on fertility and preservation indicators allows breeds, lines, or families with high potential for heterosis to be identified.

CONCLUSIONS

It was found that the adaptive traits under study differed significantly depending on the breed. In particular, it can be stated that in general, pigs of the Landrace breed were significantly better ($p < 0.001$) in all analysed characteristics compared to animals of the Welsh breed. The highest degree of influence of the breed ($\eta^2 = 9.0\%$) was recorded on the survival rate of piglets during the suckling period. Belonging to a particular breed can explain only 4.5% of the variability in the number of piglets in the litter at weaning and 8.0% of the variability in piglet mortality from birth to weaning**.** Significant inter-breed differences were found in terms of the plasticity of the "piglet survival rate during the suckling period" indicator. As can be seen, Welsh piglets showed a more intense response of this trait to changes in conditions of housing and feeding, which is reflected in the value of the regression coefficient $b_i = 1.36$, while in Landrace piglets this indicator was only $b_i = 0.57$.

Welsh suckling piglets were characterised by a higher residual survival variance ($S^2d_i = 58.48$) than Landrace piglets ($S^2d_i = 34.03$). This indicates greater individual deviations of the actual survival values of Welsh piglets from the regression line, and a lower level of predictability of this trait. A statistically significant regression model was developed to estimate the number of weaned piglets (heads) of the Welsh breed. The model had a high significance ($p = 0.005$) and an average level of explanatory power ($R^2 = 0.017$). In further development of the presented studies, it is planned to evaluate other breeds and genetic groups of pigs for plasticity and stability of an expanded range of economically useful traits, using other organised environmental factors such as average piglet weight, age, air temperature, and daily weight gain. This will allow assessing the adaptive potential of genetic groups, in particular, their compensatory capabilities under the influence of stressful factors.

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Виживаність та відхід поросят до відлучення: вплив породи, стабільність і пластичність за змінних умов утримання й годівлі

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Анотація. У статті представлено результати порівняльного аналізу адаптаційних властивостей свиней порід уельс і ландрас за трьома ключовими господарсько-корисними ознаками: кількістю поросят у гнізді при відлученні, відходом поросят за підсисний період та виживаністю поросят у підсисний період. Метою дослідження було визначення рівня стабільності та пластичності аналізованих господарсько-корисних ознак у змінних умовах утримання й годівлі. При цьому значення досліджених ознак у цих шести поколіннях поросят було використано в якості індексів середовища. Матеріалом для досліджень слугували дані про 822 гнізда поросят-сисунів, отриманих у 2015-2024 роках від шести поколінь свиней. Тварин утримували в умовах традиційної технології годівлі й вирощування у ТОВ «ФГ «Шубське». Варіативність середовища формувалася під впливом змінювання годівельних, технологічних і організаційних чинників у господарстві. Для оцінювання адаптаційних параметрів застосовано методику Ебергарта-Рассела, котра дозволила визначити коефіцієнт пластичності (b_i) та показник стабільності (S^2d_i) досліджуваних ознак. Статистичну обробку проведено з використанням пакета SPSS Statistics-22. Отримані результати засвідчили істотні породні відмінності. Ландраси продемонстрували кращі середні значення всіх розглянутих показників, зокрема достовірно вищу виживаність поросят ($p < 0,001$). Водночас поросята породи уельс виявили значно більшу пластичність за виживаністю ($b_i = 1,36$), що вказує на їх підвищену чутливість до змін умов утримання й годівлі, тоді як у ландрасів цей показник становив лише $b_i = 0,57$. За стабільністю виживаності уельси також поступалися, характеризуючись більшою залишковою дисперсією ($S^2d_i = 58,48$ проти 34,03 у ландрасів). На основі отриманих даних побудовано вірогідну регресійну модель оцінки виживаності поросят породи уельс ($p = 0,005$). Результати дослідження можуть бути використані для оптимізації селекційних програм та вибору порід під конкретні умови виробництва

Ключові слова: поросята-сисуни; порода ландрас; порода уельс; індекс середовища; молочні корми; регресія

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Modern biotechnological solutions in the prevention and control of coccidiosis in piglets on pig farms in Southern Ukraine

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Abstract. The aim was to theoretically substantiate and develop practical recommendations for a comprehensive biotechnological approach to disease prevention, specially adapted to the regional conditions of southern Ukraine. The materials were processed using methods of theoretical and methodological analysis, systematic and comparative analysis, analytical and synthetic generalisation, analogy and methodological design of practical recommendations. As a result of the study, the epizootic process of coccidiosis in piglets in farms in southern Ukraine was interpreted as being sustained by a combination of the environmental reservoir of Cystoisospora suis oocysts and technologically induced repeated contamination of bedding and production surfaces. The key factors determining the invasive pressure in the holding sections are the interaction of the microclimate of the premises with the modes of moistening/drying of substrates within the technological cycle, in particular during prolonged periods of high temperatures in the warm season and the presence of local areas of stable moisture. On this basis, prevention is described as managing the links "source of invasion – environment – susceptible contingent" with priority given to measures that reduce the persistence of invasive material between batches and limit the re-seeding of the environment. The limits of applicability of monochemical schemes in systems where the environmental component of transmission is preserved are justified, and the risks relevant to the microbiome, biosafety and environmental consequences of the prolonged presence of anticoccidial agents are outlined. A criteria-based intervention assessment scheme has been operationalised through a coordinated set of indicators reflecting parasitological, clinical and production outcomes. An integrated protocol has been proposed that combines sanitary and hygienic contamination control, biotechnological interventions, and standardised monitoring based on the "before/after" principle. The practical significance lies in the possibility of implementing a unified algorithm for prevention and control in farms in southern Ukraine with reproducible performance evaluation and comparability of effects between sections and production cycles

Keywords: epizootic pressure; vaccination; mucosal immunity; probiotics; antibiotic resistance

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INTRODUCTION

Coccidiosis in piglets associated with *Cystoisospora suis* is a problem of manageability in the early stages of rearing in industrial pig farming, since even short-term enteropathies quickly convert into measurable losses in productivity (weight gain, feed conversion), an increase in culling rates and higher costs for treatment and preventive measures. For the southern regions of Ukraine, the relevance is exacerbated by a combination of high temperatures during the warm season and microclimatic conditions in the housing sections (local humidity of bedding/surfaces, uneven drying between technological cycles), which contributes to the preservation of the environmental reservoir of oocysts and repeated contamination. Under such conditions, drug prophylaxis may demonstrate limited stability of effect if technological transmission routes are not controlled. In addition, the importance of biosafety and environmental justification of protocols (impact on intestinal ecology, selective resistance pressure, consequences of waste management) is increasing, which determines the need for integrated solutions with standardised monitoring of parasitological, clinical and production indicators.

In production conditions, early chemoprophylaxis of coccidiosis in piglets was considered as one of the approaches to reducing the intensity of oocyst excretion and the frequency of diarrhoeal syndromes in the suckling period. In a field study by V. Skampardonis *et al*. (2010), the effect of toltrazuril in suckling piglets with natural infection *with Isospora suis* was analysed using productive and epizootological relevant indicators, which allowed linking pharmacological intervention with the course of invasion at the group and farm levels. Clarifying the role of the environmental reservoir of invasion required tools capable of reflecting not only faecal oocyst excretion, but also the level of contamination of technological surfaces and critical areas of the machine. H. Loesing *et al*. (2025) evaluated the sponge sampling approach in combination with real-time PCR for the detection of *Cystoisospora suis* in environmental and faecal samples on piglet farms, which expanded the methodological basis for monitoring by including "environmental" samples in the epizootic surveillance system. These results were considered as a methodological basis for constructing a diagnostic contour in which the assessment of prevention effectiveness included indicators of environmental contamination along with coprological control data.

In a study by H.G. Araújo *et al*. (2020) described the diversity of enteric coccidia in pigs in the semi-arid region of Northeast Brazil, confirming the presence of several coccidian agents in the herd and emphasising the usefulness of species verification in the analysis of protozoa. In the context of controlling coccidiosis in piglets, these data were interpreted as an argument in favour of differentiated diagnosis, where the detection of oocysts in faeces was considered taking into account the potential polyetiological nature of the coccidiosis background. G. Deak *et al*. (2024) in a field study on intensive farms in south-eastern Spain simultaneously evaluated the effectiveness of prophylactic toltrazuril and the diagnostic detectability *of Cystoisospora suis* in 1-3-week-old piglets using flotation-concentration approaches for oocyst detection. It was shown that oocysts were detected in all farms, and the risk/frequency of detection was associated with age, the presence of diarrhoea and certain housing parameters (in particular, the type of pen flooring), which emphasised the importance of environmental reservoirs and management alongside pharmacological prophylaxis.

A. Jankowska-Mąkosa *et al*. (2023) analysed the level of parasitic infection in pigs as an indicator of production sustainability, linking parasitic load to farm productivity and resource costs. The study demonstrates the practical feasibility of including parasitic disease indicators in the "health-productivity-resource efficiency" assessment system, which allows for the justification of preventive programmes as an element of sustainable pig farming management. A. Shrestha *et al*. (2015) presented *Cystoisospora suis* as a model of mammalian cystoisosporosis, systematising the key links in pathogenesis and age windows of greatest susceptibility in suckling piglets. The publication summarises that early damage to enterocytes and disruption of the mucosal barrier function create the conditions for clinical diarrhoea and secondary complications, and therefore control must take into account not only the pharmacological component, but also environmental factors and husbandry techniques. E. Straberg & A. Daugschies (2007) experimentally evaluated the effectiveness of a cresol-containing agent for inactivating oocysts and reducing infectious pressure under production conditions, demonstrating the suitability of disinfection as a means of breaking the transmission cycle. The results justified the inclusion of targeted disinfection protocols in control programmes as a tool to reduce contamination of critical areas of the machine and bedding. As noted by O. Bohach *et al*. (2023) in their work, cases of mixed infections, such as isosporosis with cryptosporidiosis, require attention. Such associations of pathogens are characterised by a more severe clinical course and require the development of special comprehensive treatment and prevention protocols. The authors emphasised the importance of accurate diagnosis of each component of the infestation for the

prescription of effective therapy, as different protozoa may have different sensitivities to drugs.

The scientific reviews, including the work of J.P. Dubey & M. Santín (2025), systematise fundamental knowledge about coccidiosis. The authors stated that *Cystoisospora suis* remains the main causative agent of coccidiosis in piglets worldwide, and its life cycle and pathogenesis are well studied. In their review, the authors also discussed current trends in diagnosis, prevention and control, providing a comprehensive basis for further research and practical solutions. An understanding of the geographical distribution of pathogens is necessary for the development of regionally adapted control strategies. The study by H. Han *et al*. (2024) focuses on this aspect: the authors conducted a scoping review of coccidia species parasitising pigs of the genus *Sus* and analysed their distribution worldwide. This work emphasises that the epizootiological picture may vary from region to region, which is critical for planning effective national and local disease control programmes.

Despite the large number of publications, most studies focus on specific aspects of coccidiosis in pigs, such as the prevalence of the pathogen or the identification of risk factors, without simultaneously analysing biological, technological and regional climatic factors. Some of the studies are regionally specific or based on cross-sectional survey data, which limits the possibility of comparing results between different husbandry systems. In addition, there is a lack of systematic data in the literature on comprehensive preventive approaches combining biotechnological solutions and elements of production management, as well as a lack of studies aimed at analysing the specifics of coccidiosis control in pig farms in southern Ukraine. The aim of the work was to conduct a theoretical analysis of modern biotechnological approaches to the prevention and control of coccidiosis in piglets and to summarise scientific and production data, taking into account the climatic characteristics of southern Ukraine. To achieve this goal, three main tasks were identified: to analyse the impact of specific climatic conditions of the region on the epizootology of coccidiosis; to assess the limitations of traditional methods of chemical prevention; to systematise modern biotechnological solutions (vaccination, immunostimulation, probiotics and prebiotics) and justify their adaptation to local production realities.

MATERIALS AND METHODS

The methodological basis of the study was formed within the framework of a theoretical and empirical approach and was based on a combination of theoretical analysis of scientific sources with the generalisation of quantitative and qualitative data from previous experimental and field studies and the application of a set of complementary methods: theoretical and methodological analysis, system analysis, comparative analysis, analytical and synthetic generalisation, the analogy method, and the methodical design of practical recommendations. This approach was applied taking into account the climatic and production characteristics of pig farms in southern Ukraine, which are characterised by elevated temperatures and conditions that affect the survival and circulation of *Cystoisospora suis* oocysts. The object of the study was the process of prevention and control of coccidiosis in piglets in industrial pig farms. The subject of the study was biotechnological approaches to the control of coccidiosis, in particular the use of vaccines, probiotics and prebiotics, as well as the features of their integration into the system of preventive measures, taking into account regional climatic factors. Data collection and selection for theoretical and empirical generalisation was carried out based on publications from 2019-2025, taking into account their relevance to the topic of *Cystoisospora suis* control in pig farming and regional climatic conditions similar to those in southern Ukraine. The analysis included sources containing measurable parasitological, clinical and/or production outputs (oocyst excretion/infestation, frequency of diarrhoea/enteritis, weight gain, feed conversion, mucosal morphometry, resistance indicators), as well as describing the methods of diagnosis, prevention and management used in farms or controlled experiments. Additional criteria were full-text availability, clarity of design and the ability to compare results on a "control/intervention" or "before/after" basis within a specific study. The study employed theoretical and methodological analysis to substantiate the impact of climatic conditions in southern Ukraine on the life cycle *of Cystoisospora suis,* as well as to analyse the immune and microbiome mechanisms involved in the formation of antiparasitic protection in pigs. Within this approach, current ideas about the pathogenesis of coccidiosis, the interaction of the pathogen with the intestinal microbiome and the immune system of animals were analysed. This method was applied using regional data from the Odesa region and generalisations about risk factors and the spread of invasions (Bohach *et al.*, 2024), as well as observational data for European farms with similar climatic conditions and different levels of biosecurity/hygiene (Nunes *et al.*, 2023).

System analysis was used to integrate data on regional climatic conditions, epizootic pressure, chemoprophylaxis limitations, and the potential of biotechnological solutions into a single cause-and-effect logic for coccidiosis control. Within this approach,

production and microclimatic factors were operationalised as controllable determinants of invasive pressure, in particular the moistening/drying regime of substrates, the presence of persistent wet areas (near drinking troughs, in washing areas and areas where liquid fractions accumulate), ventilation parameters and stocking density, which determined the rate of surface drying and the duration of preservation of invasive material. The effectiveness of preventive strategies was assessed using multiple criteria: taking into account productive and clinical indicators, changes in the intestinal ecosystem (microbiome/signs of dysbiosis and barrier indicators), biosafety risks (formation/spread of antimicrobial resistance) and the environmental acceptability of use (persistence of active substances and potential environmental contamination). Within this method, sources describing the seasonal/microclimatic interaction between host and pathogen and the influence of season, age and management practices on parasitic diseases in pigs (Fay *et al.*, 2025; Senanayake *et al.*, 2025), combined with regional materials on the structure of protozoan invasions and farm typology (Bogach & Avhitova, 2019).

Comparative analysis was used according to clearly defined criteria of efficacy and safety, namely: average daily gains, feed conversion, frequency of diarrhoea syndrome in risk groups, morphometric indicators of the mucosa (height of villi in the small intestine) and indicators of non-specific resistance (in particular, the phagocytic index). The effectiveness was assessed using the "before/after" principle by comparing the specified indicators in comparable groups/conditions. This method was implemented based on data on the effectiveness of protozoal drugs in cases of associative invasions in regional conditions (Bogach & Avhitova, 2019). For the biosafety component, data on the risks of resistance selection when using ionophores (Simjee & Tice, 2023) ecological pathways and consequences of ionophore persistence in livestock systems (Alam *et al.*, 2025), and pharmacological characteristics of the drug group as a basis for biosafety/environmental criteria (Dowling & Baptiste, 2024).

Analytical and synthetic generalisation was used to convert data from selected publications into a comparable array of indicators and subsequently form generalised conclusions. At the analytical stage, the following were extracted from each source comparison design (control/intervention or "before/after"), type of intervention and measured outcomes (oocyst excretion/infestation, diarrhoea, weight gain, conversion, mucosal morphometry, resistance indicators) were extracted from each source, together with the direction and magnitude of the effect. At the synthetic stage, these data were coded according to the "target → indicator → outcome" scheme and summarised (formation of effect intervals and a minimum set of monitoring indicators), without conclusions that are not confirmed by the actual indicators presented. Analytical and synthetic generalisation was carried out on the basis of sources describing the acquired intestinal immune response to coccidiosis and the principles of vaccine prophylaxis, antigenic/immunogenic properties of gametogenic antigens of coccidia as potential vaccine targets, and features of antiparasitic immunity in pigs (Baker *et al.*, 1994; Lillehoj & Lillehoj, 2000; Wang *et al.*, 2025). Additionally, approaches to mucosal vaccines for parasitic infections and generalisations regarding coccidiosis in pigs relevant to the interpretation of age susceptibility and immune responses were taken into account (Joachim & Shrestha, 2019; Kato, 2020). Empirical data on combined regimens (vaccine + probiotic complex) were used to summarise typical indicators of the effect on productivity and microbiota under controlled infection (Cai *et al.*, 2023). To clarify the mechanisms of mucosal protection and current alternatives to antibiotics, reviews on advances in the study of immunity in coccidiosis and antibiotic replacement strategies, as well as data on the mucosal immune response in gastrointestinal helminthiasis as a comparable model of barrier resistance, were used (Lee *et al.*, 2022; Palkumbura *et al.*, 2024). For the block of immunomodulatory approaches and prevention practices, additional sources were considered that highlighted the role of vaccination in controlling infections/zoonoses in pigs and data on changes in immunological parameters when using dietary supplements in pig feed (Klikin *et al.*, 2024; Arutkumaran *et al.*, 2025). Microbiome-oriented interventions (probiotics/prebiotics) were also analysed with quantitative indicators of productivity, morphofunctional state of the mucosa and clinical indicators (Agazzi *et al.*, 2020; Begma, 2023; Kolechko *et al.*, 2023).

The analogy method was used to adapt individual approaches tested in related livestock sectors, with subsequent adjustments in line with the biological and production characteristics of pig farming. As part of this method, the principles of controlling the transmission of *Cystoisospora suis* through the prophylactic use of toltrazuril were transferred to the logic of integrated prevention programmes combining management and biological interventions (Lara *et al.*, 2022). In addition, technologically proven vaccine strategies against coccidia in poultry farming and framework approaches to replacing antibiotics in pig/poultry farming were used as reference examples (Albanese *et al.*, 2018; Thong & Duc, 2022). The correctness of the transfer to pig farms was clarified taking into account

clinical and practical provisions regarding restrictions on the routine use of antibiotics and strategic arguments in favour of the development of veterinary vaccines as a long-term tool for controlling parasitic diseases (Sander *et al.*, 2020; Memon *et al.*, 2022; Burrough *et al.*, 2025). At the final stage, recommendations were developed aimed at forming a theoretically sound algorithm for the comprehensive use of biotechnological agents in the coccidiosis prevention system, taking into account regional conditions.

RESULTS

The influence of climatic conditions in Southern Ukraine on the formation of the epizootic situation of coccidiosis

The climatic conditions of southern Ukraine determine the specifics of the epizootic process of cystoisosporosis in piglets, primarily due to the dependence of the extra-organism stages of the pathogen on temperature and humidity. At elevated temperatures combined with sufficient humidity, the transition of oocysts to the invasive form (sporogony) is accelerated, and in the presence of moist substrates, the period of their viability is prolonged. Thus, for farms in the region, it is not so much the average climatic indicator that is important, but how the climate is realised within the premises – through the regime of moistening and drying of litter, surfaces and equipment between technological cycles. In production conditions, this manifests itself in the fact that even under the same external weather conditions, the invasive pressure can vary depending on ventilation, stocking density, local water sources (drinking troughs, washing, leaks), accumulation of liquid manure fractions and the frequency of sanitary treatment of sections.

The clinical and pathogenetic manifestations of coccidiosis reinforce this dependence, since damage to the small intestine in early-age piglets is accompanied by a disruption of the barrier function, changes in the architecture of the mucous membrane, and the development of diarrhoea syndrome. Diarrhoea in this system has not only clinical significance, but also epizootic significance: increased moisture content of faecal masses and increased contamination volume contribute to the formation of local wet micro-foci in the pen and increase the likelihood of invasive material remaining in substrates that do not dry out completely. Thus, maintaining moisture in the section creates conditions under which rapidly maturing oocysts are preserved long enough to ensure repeated contamination of surfaces and transmission of the invasion between groups or between successive batches of piglets. For the southern regions of Ukraine (Odesa, Kherson, Mykolaiv, Zaporizhzhia), the warm season is characterised by temperature conditions that shorten the maturation of oocysts, and in the presence of moisture in the substrates, the viability of the invasive material is maintained within a time frame sufficient to maintain circulation within the technological cycle. In practical terms, this means that the key controllable factor is not the hot season itself, but the ability of the farm to ensure complete drying of surfaces and bedding between cycles of detention and to minimise areas of chronic moisture. It is these points (wet areas of the floor, areas under drinkers, places where liquid fractions accumulate) that determine the persistence of contamination and the re-seeding of the section with invasive material.

Empirical observations for the Odesa region are consistent with this logic: the infection rate of suckling piglets *with Cystoisospora suis* at 40.3% reflects the preservation of invasive material in the environment and the presence of conditions for its maintenance in critical areas of the section (Bohach *et al.*, 2024). At the same time, data from European farms show that under similar climatic conditions, the spread of the invasion varies significantly depending on the level of biosecurity and hygiene, i.e., the climate acts as a backdrop against which management decisions are made (Nunes *et al.*, 2023). In this context, technological variables – the frequency and quality of sanitation, the organisation of animal flows, adherence to the principle of "everything is empty – all occupied" principle, and humidity control in the section – become factors that either break the chain of transmission or, conversely, stabilise repeated contamination (Fay *et al.*, 2025; Senanayake *et al.*, 2025). An additional argument in favour of the decisive role of hydrothermal conditions is that within the Northern Black Sea region, shifts in the structure of protozoan invasions are recorded depending on the humidity of the area. Under conditions of a summer decrease in the hydrothermal coefficient (0.3-0.5), the incidence of *Isospora suis* in suckling piglets was 27.6% and *Cryptosporidium spp.* 6.9%, while in more humid areas (1-1.4), the infestation rate of *Cryptosporidium spp*. was 18.5% higher (Bogach & Avhitova, 2019). These ratios indicate that the water regime of the environment (both at the level of the microclimate of the premises and at the level of local natural and climatic differences) can influence not only the intensity of protozoan load, but also the profile of dominant agents, which should be taken into account when selecting prevention priorities.

The dependence of protozoan intensity on the type of farm is also indicative: the overall infestation rate in large farms (>100 sows) was 41.5%, in medium-sized farms (25-100) – 66.1%, in small farms (<25) – 77.9%,

and the proportion of mixed infections in small farms reached 36.9%, with mono-infections predominating in large farms (74.9%). These data support the conclusion that, given the climatic conditions of the region, organisational and hygienic practices and environmental humidity management remain decisive factors in determining the frequency of re-contamination and the conditions for the transmission of invasive material. As a result, the combination of warm season temperature and humidity conditions and the maintenance of moisture in the substrates leads to the formation of constant *Cystoisospora suis* infestation pressure in farms in southern Ukraine, which persists due to repeated contamination of sections between technological cycles.

Disadvantages of traditional chemoprophylactic approaches in regional conditions

In industrial pig farming, chemoprophylaxis of coccidiosis is often perceived as a quick tool for reducing clinical manifestations in risk groups. however, in farms in southern Ukraine, its effectiveness and acceptability are determined not only by antiparasitic activity, but also by systemic consequences that manifest themselves at the level of intestinal ecology, biosafety and environmental safety of production. In a region where temperature loads increase during the warm season and stable microclimate control in sections becomes more difficult, any preventive intervention actually works in conditions of increased sensitivity of piglets to enteropathies and dysbiotic shifts. That is why traditional schemes, which boil down to the routine use of chemoprophylactic agents without reference to stress periods, the structure of invasions and sanitary and hygienic restrictions of a particular farm, have a predictably narrow window of effectiveness and can create secondary problems that negate the expected preventive result.

One of the key reasons for limited effectiveness in southern Ukraine is the overlap of pharmacological intervention with heat stress factors. High temperatures in summer and transitional periods with significant daily temperature fluctuations are usually accompanied by changes in feed and water consumption, fluctuations in intestinal motility, increased microbiota lability, and changes in the barrier function of the mucosa. Under such conditions, reducing the invasive load with medication alone does not guarantee clinical stabilisation, since diarrhoea syndrome in piglets in real production conditions is a multifactorial phenomenon and is maintained by a chain of stress → barrier disruption → dysbiosis → inflammation, which can persist even with partial control of the protozoan component. As a result, prophylaxis formally directed against coccidia during the warm season should often be evaluated not only by the fact of its use, but also by whether it is possible to prevent the destabilisation of the intestinal ecosystem and secondary complications that increase the severity of enteropathies.

The second systemic aspect is the effect of chemoprophylaxis, in particular ionophore coccidiostats, on the intestinal microbiome and, accordingly, on microbiome-dependent resistance mechanisms. In prophylactic (subtherapeutic) regimens, such agents can shift the composition of the microbiota, which is critical in the context of early age, since during this period the microbiome is not yet stabilised and easily transitions to a dysbiotic state under the influence of stressors, changes in feeding and technological manipulations. The practical consequence is that even with a decrease in the protozoan component, colonisation resistance may deteriorate, the production of metabolites that support the epithelial barrier may change, and the susceptibility to diarrhoeal syndromes or their prolongation may increase. In southern farms, these risks are further exacerbated by the fact that heat stress and microclimatic factors often increase the frequency of wet areas in sections, which maintains the background pressure of enteropathogens and increases sensitivity to any microbiome shifts. In other words, chemoprophylaxis can create a paradoxical situation here: antiparasitic intervention is carried out, but the functional prerequisites for diarrhoea are not eliminated and are sometimes even exacerbated by undesirable effects on the microbiota.

The third set of limitations is related to biosafety and antimicrobial resistance. Sources warn that the use of ionophores creates selective pressure on enterococcus populations and may be associated with mobile genetic elements capable of transferring resistance determinants between bacterial species (Simjee & Tice, 2023). For farms, this means that a preventive strategy that does not take into account the biosafety cost potentially contributes to the formation of a reservoir of resistant strains in the intestinal ecosystem of animals and in housing substrates. In the regional conditions of southern Ukraine, this risk has an additional practical dimension: during the warm season, increased humidity in certain areas, intensive washing cycles, manure removal and contact with technological surfaces increase the likelihood of microorganisms circulating between sections and through contaminated objects. In this logic, antimicrobial resistance ceases to be a distant problem and becomes a parameter that must be taken into account when choosing prevention as an element of risk management in the production system.

The fourth aspect is the environmental component, which is increasingly being considered as part of the

requirements for the safety of animal husbandry technologies. According to sources, certain coccidiostats can persist in the environment after being excreted, enter water bodies and have toxic effects on aquatic organisms even at low concentrations, while traditional treatment systems do not always ensure complete removal of such substances (Alam *et al.*, 2025). For southern Ukraine, where the practice of applying organic waste as fertiliser is widespread, this means an increased likelihood of chronic low-dose exposure in soil and water systems and a potential impact on microbial communities in the environment, the ecological trail of chemoprophylaxis should be considered not as a secondary ethical argument, but as a real component of limiting its routine use in the region.

The practical disadvantage of traditional schemes in southern farms is that they often do not take into account the structure of protozoan associations and the pattern of infestation in a particular farm. Empirical data from monitoring mixed infestations have shown that effectiveness can vary significantly depending on the pathogen: for "Brovitacocid", 66.7% extensive effectiveness was reported for balantidiasis and 88.9% for cryptosporidiosis, with simultaneously high indicators for other protozoa, while for "Amprolev-plus", 100% effectiveness was reported for the protozoa studied. In regional conditions, such differences have direct practical significance: if a farm is characterised by a stable association of protozoan agents, monodirectional prophylaxis for one typical pathogen naturally leaves room for the preservation of diarrhoeal syndromes and repeated contamination pressure, especially under conditions of heat stress and microclimate fluctuations. That is why sources describing the pharmacological characteristics of drug groups and approaches to their use emphasise the need for the rational, time-limited use of chemoprophylactic agents and the correct choice of regimen depending on farm conditions (Dowling & Baptiste, 2024). Therefore, for southern Ukraine, it is crucial that traditional chemoprophylaxis cannot be considered a self-sufficient universal strategy: its microbiome consequences, biosafety risks, environmental constraints, and variability in effectiveness against associative invasions become significant precisely in conditions of heat stress, when the stability of intestinal resistance is most vulnerable, and preventive solutions require maximum alignment with production realities and controlled indicators.

Immunological mechanisms of adapted biotechnological control of coccidiosis

Biotechnological approaches to coccidiosis control are considered through two complementary levels: specific (antigen-dependent) immunity and non-specific resistance (innate effector mechanisms and mucosal barrier) (Lillehoj & Lillehoj, 2000). The specific level is most often operationalised by markers of intestinal immunity and morphofunctional characteristics of the mucosa, while the applied significance is assessed by functional outputs, primarily by the dynamics of oocyst excretion and/or clinical manifestations of enteropathy (Baker *et al.*, 1994; Wang *et al.*, 2025). At the level of evidence, it is not the isolated increase in a single indicator (e.g., IgA or cytokines) that is decisive, but the consistency of the chain immune indicator → parasitological/clinical outcome, i.e., the correlation of changes in markers with changes in oocyst excretion and the severity of diarrhoea.

Vaccine strategies for coccidiosis in related animal systems are described as approaches aimed at developing local (intestinal) immunity and reducing the manifestations of invasion through immunological control of mucosal damage (Joachim & Shrestha, 2019; Kato, 2020). The role of secretory IgA, gut-associated lymphoid tissue and cytokine profile as mechanistic elements of the response is also emphasised, however, the applied significance for the control of coccidiosis is confirmed precisely by functional indicators (oocyst excretion/clinical manifestations/morphological markers of damage). The statement about "reproduction control" is correct only when it is linked to a measurable outcome, i.e., a reduction in oocyst excretion or a decrease in the severity of enteropathy under conditions of controlled infection or production observation (Cai *et al.*, 2023).

Non-specific resistance in the context of biotechnological control of coccidiosis is considered a resource for supporting barrier and effector mechanisms during periods of physiological and technological vulnerability (early age, weaning, heat stress) when the risk of enteropathy and microbiota imbalance increases. Immunostimulatory agents (β-glucans, nucleotides, and other agents with an immunotraining effect) are modifiers of phagocytosis and cytokine responses; accordingly, the phagocytic index and cytokine response indicators in sources are the most direct indicators of this level, while the frequency of diarrhoea is used as a clinically oriented indicator of the total effect at the intestinal level. According to this logic, immunostimulation is not a substitute for specific prophylaxis, but rather a tool whose effect should be correctly assessed through changes in indicators of non-specific resistance and clinical manifestations, rather than through assumptions about a direct impact on parasitological outcomes without relevant data.

Data on combined approaches (combining immunoprophylaxis with microbiome-oriented interventions) are heterogeneous in design and animal species,

so such associations are presented as potential and limited by the scope of the relevant sources. Non-specific resistance in this context is interpreted as a resource for supporting barrier and effector mechanisms during periods of physiological and technological vulnerability. Immunostimulatory agents are described as modifiers of phagocytosis and cytokine responses, with the phagocytic index and cytokine response markers being the most direct indicators, while the frequency of diarrhoea is used as a clinically relevant summary indicator. At the same time, immunostimulation is more often presented as a component of combined programmes, and that is why its effect should be correctly assessed through changes in indicators of non-specific resistance and clinical dynamics, rather than through assumptions about direct parasitological mechanisms without appropriate measurements. The generalisation is a comparison of mechanistic indicators and functional outcomes, and the formulation of cause-and-effect mechanisms is only acceptable within designs where the relevant baseline indicators (oocyst excretion/clinical signs/productivity) are available (Table 1).

Table 1. *Generalisation of the immunological effects of vaccination and immunostimulants in the adapted coccidiosis control system*

Component of biotechnological control	Level of immunity	Main immune targets/ mechanisms (summarised)	Indicators used in sources	Type of data on which the summary was based
Vaccination (live attenuated/ antigenic approaches; principles described for coccidiosis)	Specific (mainly mucosal)	Induction of local intestinal immunity; involvement of humoral and cellular links; participation of intestinal lymphoid tissue	Secretory IgA; cell populations in the mucosa; cytokine markers; dynamics of oocyst excretion	Mechanistic and applied data on coccidiosis; transferability of principles to other species, taking into account the biology of mucosal immunity
Immunostimulants (β-glucans, nucleotides, other immunotraining agents)	Non-specific (innate; maintenance of the mucosal barrier)	Activation of innate immune receptor systems; modulation of phagocytosis and cytokine responses; support of effector mechanisms during periods of stress	Phagocytic index; markers of cytokine response; indicators of non-specific resistance; frequency of diarrhoeal syndromes as a clinical indicator	Mechanistic and experimental data on immunostimulation; interpretation for pig farming, taking into account stress factors
Combined protocols (vaccination + immunostimulation/ microbiome-oriented interventions)	Specific + non-specific	Simultaneous influence on the formation of antigen-specific response and increased readiness of effector mechanisms; potential synchronisation of immune and microbiome factors	Oocyst excretion; clinical signs of enteritis; resistance/ productivity indicators (depending on study design)	Data from related/ model studies of combined interventions used for mechanistic interpretation

Source: *compiled by the authors based on D. Baker et al. (1994), H. Lillehoj & E. Lillehoj (2000), A. Joachim & A. Shrestha (2019), H. Kato (2020), F. Wang et al. (2025)*

Table 1 correlates the levels of immune response and the type of indicators: mechanistic markers (secretory IgA, mucosal cell populations, cytokine profiles, phagocytic index) show the direction of immune modulation, while applied significance is confirmed only by functional outputs (primarily oocyst excretion dynamics, frequency of clinical manifestations of enteritis/diarrhoea and, if available, productive metrics). This division sets limits: statements about a potential reduction in the risk of transmission or "epizootic load" are linked to changes in oocyst excretion as a parasitological outcome, while changes in IgA/cytokines/phagocytosis reflect the involvement of the corresponding links of immunity without direct automatic transfer to the level of field efficacy. For combined protocols, the simultaneous presence of indicators of different nature (oocyst excretion, clinical manifestations, resistance/productivity) is recorded, but the statement about the synchronisation of immune and microbiome factors remains a mechanistic interpretation of related data.

Microbiome-oriented prevention strategies and their impact on piglet health

Within the framework of systems analysis, the intestinal microbiome was considered as a functional level through which the barrier properties of the epithelium and the immune effects of the mucous membrane were realised. Accordingly, probiotics and prebiotics were interpreted as interventions that could alter the microbial environment of the intestine (colonisation resistance, metabolite production, local pH changes, synthesis of antimicrobial peptides) and associated with changes in the frequency of diarrhoeal syndromes and productivity indicators in risk groups. Microbiome-oriented

interventions were operationalised through a set of control indicators that simultaneously reflected barrier function, clinical manifestation and production effect. Accordingly, the effectiveness assessment was structured as a "before/after" comparison based on morphometric markers of the mucosa (villus height), frequency of diarrhoeal syndromes, and productivity metrics (average daily gain, feed conversion), which allowed the impact of microbiome correction to be interpreted not only mechanistically but also practically.

The logic of "before/after" the implementation of microbiome-oriented strategies was formalised by comparing conditions described in the sources as typical for technologically vulnerable periods (weaning, diet change, stress loads). In the "before" state, attention was focused on the combination of two processes: an increase in the frequency of diarrhoeal syndromes in risk groups and changes in the morphofunctional indicators of the mucous membrane, which were used as proxy indicators of barrier function. In particular, for prebiotics (MOS/FOS), morphometric data were considered as one of the operational indicators of the condition of the mucosa: the addition of MOS to weaned piglets was associated with an increase in villus height in the small intestine from 450 ± 35 μm to 520 ± 40 μm (a change of +15.6%, $p < 0.05$) (Agazzi *et al.*, 2020). This result was interpreted as a change in a parameter reflecting the absorption surface and the condition of the epithelial barrier.

In the "after" state of probiotic and/or prebiotic administration, the generalisation was based on quantitative indicators of productivity and feeding efficiency and on data on the frequency of diarrhoeal syndromes in risk groups. For *Bacillus subtilis*-based probiotics in the feeding of fattening pigs, data were reported on a 12.3% increase in average daily gains in the experimental group compared to the control (Begma, 2023). Other studies reported an increase of 8-10% and a change in feed efficiency of 5-7% when using probiotic complexes (Kolechko *et al.*, 2023). Microbiome-oriented interventions could be reflected in productivity indicators through the enzymatic activity of probiotic strains and changes in the proportion of opportunistic microorganisms in the intestinal microbial profile. Information on combined interventions (immunoprophylaxis + probiotic) in model/related studies, where changes in oocyst excretion and productivity metrics were recorded, was considered separately and used as a mechanistic basis for explaining the potential synchronisation of immune and microbiome factors in control protocols (Table 2).

Table 2. *Predicted changes in piglet health and productivity indicators with the introduction of probiotics and prebiotics*

Indicator	"Before" status (control/no intervention)	"After" status (introduction of probiotics/prebiotics)	Effect interval according to sources (estimate)
Average daily gain, g/day	Baseline (according to the design of a specific study)	Increase relative to control	+8-12% (depending on the protocol/complex)
Feed conversion (kg of feed/kg of gain)	Baseline	Decrease relative to control	-5-7% (change in feed efficiency)
Frequency of diarrhoea syndromes in risk groups	Baseline in the risk group	Decrease in frequency after correction of the microbiome/resistance	-15-20% (as a clinical indicator in the protocols used)
Height of villi in the small intestine, μm	450 ± 35	520 ± 40	+15.6% ($p < 0.05$)
Indicators of non-specific resistance (e.g., phagocytic index)	Baseline	Increase after implementation of comprehensive programmes (where data available)	+20-30% (according to the ranges given in the sources)

Note: *predicted changes were formed as an interpretation of quantitative effects and reflected a "control/experimental" or "before/after" comparison within specific studies; actual values may vary depending on the age of the animals, diet composition, husbandry technology, and background epizootic pressure*

Source: *compiled by the authors based on A. Agazzi et al. (2020), N. Begma (2023), A. Kolechko et al. (2023), I. Klikin et al. (2024)*

The data in Table 2 summarised the effects of probiotics/prebiotics in the format "functional link – expected indicator – magnitude of change" and showed that the most consistently reproducible outcomes in different protocols were productivity metrics and feeding efficiency (an increase in average daily gains within +8-12% and a decrease in feed conversion by 5-7%). The morphometric indicator of the mucosa (villous height in the small intestine) in the protocol increased from 450 ± 35 to 520 ± 40 μm (+15.6%; $p < 0.05$), reflecting a statistically significant change in the morphometric indicator. A decrease in the frequency of diarrhoeal syndromes in risk groups was considered a clinical outcome reflecting the cumulative effect of colonisation resistance correction and metabolic activity of the microbiome. At the same time, indicators of non-specific

resistance (in particular, the phagocytic index) were interpreted as contextually dependent indicators: their increase was more often described as part of complex programmes (a combination of immunoprophylaxis and probiotic interventions).

Practical recommendations for implementation in farms in Southern Ukraine

The recommendations are formulated as an applied protocol for the prevention and control of coccidiosis, combining risk-oriented diagnostics, biotechnological interventions (vaccination, immunostimulation, probiotics and prebiotics) and veterinary and sanitary measures with quantitative assessment of effectiveness. Implementation of the protocol is advisable provided that the epizootic situation on the farm is standardised, critical periods for piglets (farrowing, weaning, episodes of high temperatures) are planned, and "before/after" indicators are compared to monitor the effectiveness of the measures taken. For monitoring purposes, it is recommended to determine baseline and control values for infestation and/or oocyst excretion intensity, frequency of diarrhoea syndromes in piglets, average daily weight gain and feed conversion.

Control points should be coordinated with the production cycle: baseline indicators should be recorded before the protocol is launched, and repeat indicators should be recorded after the initial implementation cycle and subsequently at intervals that allow for comparison of batches under comparable technological conditions. To confirm the pathogen, coprological methods and/or molecular genetic tests can be used, depending on the availability of laboratory facilities, and the results should be used to adjust the frequency of control and identify priority risk groups. Specific immunoprophylaxis, subject to the availability of appropriate preparations and approved internal regulations, should be integrated into the standard early rearing protocol, ensuring coverage of the entire litter and attachment to the first days of life of piglets in accordance with the manufacturer's instructions. The effectiveness of immunoprophylaxis should be assessed based on the dynamics of oocyst excretion and/or infestation, the frequency of clinical manifestations of enteritis or diarrhoeal syndromes, and indirect production indicators, including average daily gains and feed conversion, which allows changes associated with intestinal health to be distinguished from fluctuations in feeding and management.

Preventive correction of non-specific resistance should be planned taking into account periods of increased risk, which are determined by the technological calendar and temperature conditions in the premises. Immunostimulants should be used in sows during the pre-farrowing period, in piglets during weaning, and during periods of high temperatures when there is a tendency for an increase in the incidence of diarrhoea or a deterioration in productivity in risk groups. It is recommended to evaluate the effect based on the frequency of diarrhoeal syndromes, survival and culling rates, and, if possible, laboratory indicators of non-specific resistance in accordance with the internal control programme. Microbiome-oriented measures should be implemented as a permanent element of prevention for risk groups, with an emphasis on weaning, regrouping and transition to a different diet. It is recommended to introduce probiotics (in particular, based on spore-forming bacteria compatible with feed production technology) and prebiotics (e.g., mannan-oligosaccharides) into the feed in accordance with the feeding schedule, feed form, and manufacturer's instructions. It is advisable to evaluate effectiveness on a "before/after" basis at the batch or section level in terms of average daily gains, feed conversion and diarrhoea frequency, and, if possible, to additionally take into account indicators of the condition of the mucous membrane or markers of resistance used in the relevant control protocols.

Veterinary and sanitary measures should be considered a mandatory component of control, with increased emphasis during the warm season and during periods of intensive turnover of batches. It is advisable to ensure mechanical cleaning, washing and disinfection, control of litter and technological surfaces humidity, as well as adherence to the "all empty – all occupied" principle to reduce the persistence of invasive material between batches. It is separately recommended to organise systematic control of rodents as a possible mechanical factor of re-contamination of the environment, and it is advisable to monitor the effectiveness of the sanitary unit through changes in infestation and/or oocyst excretion and the frequency of diarrhoeal syndromes in subsequent batches under comparable technological conditions.

It is advisable to implement the protocol in stages, starting with a basic assessment of the epizootic situation and preparation of organisational conditions, including coordination of the sampling scheme and ensuring the temperature conditions for storage of biological preparations. After recording the baseline values, it is recommended to launch the key elements of the programme, combining immunoprophylactic measures for piglets with probiotic-prebiotic feeding support, as well as planning immunostimulation in accordance with technological events and temperature conditions. Further monitoring of effectiveness is recommended 2-3 months after the start, comparing "before/after" indicators for oocyst excretion or infestation, frequency

of diarrhoea, average daily gains and feed conversion, after which it is advisable to adjust the intensity of individual measures based on the data obtained.

DISCUSSION

In this study, the control of coccidiosis caused by *Cystoisospora suis* for the conditions of southern Ukraine is interpreted as a multi-component task, where the clinical effect is determined not only by the action on the parasite in the body, but also by the intensity of repeated entry of invasive material from the environment and the state of the intestinal barrier during technologically vulnerable periods. The limited self-sufficiency of chemoprophylaxis is consistent with the empirical observations of A.A. Lara *et al*. (2022), where *C. suis* circulation in the farm persisted despite the prophylactic use of toltrazuril. In this study, this was interpreted as a manifestation of the fact that the pharmacological component mainly affects the endogenous phase of the parasite, while the exogenous phase (oocysts in substrates) can maintain invasive pressure during repeated contamination. The results of A.A. Lara *et al*. (2022) supported the conclusion that prophylactic regimens limited to chemoprophylaxis do not always ensure transmission interruption in intensive housing conditions, especially in the presence of moisture retention areas, high animal density, and fluctuations in hygiene discipline. Biotechnological tools in this study were considered not as a replacement for chemoprophylaxis, but as means that can influence other links in the process.

The summary by G.A. Albanese *et al*. (2018), based on poultry farming data, demonstrated the technological feasibility of vaccine strategies against coccidia as a group of parasites and showed that the targeted formation of a local intestinal immune response can be achieved with the appropriate drugs and administration protocols. For pig farming, direct transfer is limited, but a comparable source correlates with the conclusion of this study regarding the fundamental achievability of mucosal immunity management as a tool for the prevention of coccidial infections, provided that it is adapted to the biology *of C. suis* and production contexts. This study shows that under conditions of technological stress and temperature load, the stability of the intestinal barrier can modify the severity of diarrhoeal syndromes and, therefore, influence the clinical manifestation of coccidiosis. The systematisation of alternatives to antibiotics by H.T. Thong & H.V. Duc (2022) is relevant because it describes the mechanisms of competitive exclusion, immune modulation and barrier function support associated with enteropathologies. Unlike the authors' general framework, this study focuses on the operationalisation of such mechanisms through measurable outputs (frequency of diarrhoea, productivity metrics, mucosal morphometric indicators), which increases the applied certainty of the criteria for monitoring and evaluating effectiveness.

Clinical and practical generalisations by E.R. Burrough *et al*. (2025) highlighted the limitations of routine antibiotic use due to the risks of dysbiosis and antimicrobial resistance and emphasised the priority of strategies to support gut health and the animals' own immune response. In this study, these findings are specified for coccidiosis in piglets: while maintaining invasive pressure from the intervention environment, which exacerbates dysbiotic shifts or reduces colonisation resistance, may exacerbate diarrhoeal syndromes such as the leading clinical phenotype. Thus, the data of E.R Burrough *et al*. (2025) are consistent with the conclusion of this study on the advisability of shifting the preventive strategy towards stabilising the barrier function and resistance, rather than towards long-term medication in the diet. The strategic advisability of vaccine prophylaxis as a long-term tool for controlling parasitic diseases is substantiated by V.A. Sander *et al*. (2020), who emphasised the potential for reducing the overall burden of infections without constant pharmacological treatment. In this study, the authors' position is used to argue that the vaccine component (if technologically feasible) logically fits into control programmes aimed at reducing parasitological and clinical indicators in combination with hygiene and management.

Mechanistic data from F.U. Memon *et al*. (2022) (bird model) demonstrated the ability of *Bacillus subtilis* to modulate the microbiome under conditions of active *Eimeria* invasion, indicating the potential of probiotic interventions to maintain microbial balance during periods of parasitic load. In this study, these data were compared with the conclusion that productivity metrics and feeding efficiency may be integral indicators of the effectiveness of microbiome-oriented interventions in pig farming, although interspecies extrapolation requires caution. Applied evidence for *Bacillus* spp.-based alternatives to antibiotics is provided by Y. Cheng *et al*. (2021), who described the positive effects of fermented products on productivity and digestive health indicators. The generalisations obtained in this study about productive outputs as stable indicators of the effect of microbiome-oriented interventions are consistent with the data from Y. Cheng *et al*. (2021) on the evaluation of such interventions through quantitative production and clinical indicators.

The work of C. Zifan *et al*. (2023) demonstrated an approach using recombinant *Bacillus subtilis* expressing the coccidian antigen (SAG22). In this study, such solutions were interpreted as a promising technological

direction for combining the probiotic component and antigenic stimulus; at the same time, the mechanistic effect of simultaneous modulation of the immune and microbiome links for pig farming requires separate confirmation in designs that include parallel direct measurements of the relevant indicators. In the prebiotics section, I.M. Youssef *et al*. (2024) described the positive effects of MOS on intestinal morphology and resistance indicators in model systems. In this study, these data were correlated with the use of mucosal morphometric indicators as operational indicators of barrier status and with the conclusion that nutritional interventions can increase mucosal resistance during periods of stress. For pigs, A. Lee *et al*. (2025) demonstrated the effectiveness of galacto- and xylooligosaccharides in manipulating the microbiota and improving intestinal architecture. This is consistent with the conclusion of this study on the relevance of prebiotics as a component capable of influencing the barrier and thereby indirectly modifying the course of enteropathies in risk groups.

For integrated systems in pig farming, L.M. Gómez-Osorio *et al*. (2025) (using proliferative enteropathy as an example) demonstrated the effectiveness of approaches combining vaccination, feed additives and management measures. The conclusions of this study are consistent with the authors' position on the practical feasibility of protocols, where different tools address different risk mechanisms: immune resistance, intestinal ecology, technological factors, and environmental contamination. Data from M. Delsart *et al*. (2022) showed that on alternative farms, hygiene and management can minimise the parasite load without intensive medication. For this study, this supports the conclusion that a veterinary and sanitary unit is a prerequisite, especially in regions with a risk of persistent invasive material in wet substrates. Additionally, E. Labussière *et al*. (2022) demonstrated a modification of the faecal microbiota and associated physiological/behavioural changes when *Saccharomyces cerevisiae* var. *boulardii* was used during heat stress. In this study, these data were considered relevant to the conditions of southern Ukraine, as they supported the thesis that temperature stress can be accompanied by changes in intestinal ecology, and that microbiome-oriented interventions may have practical significance during periods of high temperatures. Thus, the results of this study specified the above international observations for the conditions of southern Ukraine, where climatic factors and the microclimate of the sections create the preconditions for repeated invasive pressure and increase the relevance of integrated preventive solutions.

CONCLUSIONS

The study found that the climatic and microclimatic conditions of pig farms in southern Ukraine, in particular prolonged periods of high temperatures during the warm season combined with local moisture in the substrates, create conditions for accelerated sporogony and prolonged preservation of *Cystoisospora suis* oocysts in the environment. Under such conditions, repeated contamination of bedding and technological surfaces is maintained, and the invasive pressure in piglet housing sections increases due to insufficient drying between technological cycles. This justifies the need for a systematic, rather than episodic, approach to prevention, focused on managing the links "source of invasion – environment – susceptible contingent".

It has been shown that routine chemoprophylaxis in subtherapeutic regimens has fundamental limitations, as it does not eliminate the environmental reservoir of invasion and does not control re-seeding of the environment. Additionally, it has been taken into account that the prolonged presence of chemical anticoccidials may be accompanied by undesirable consequences for intestinal ecology and biosafety, in particular due to the modulation of the microbiome and microbiome-dependent components of resistance, selective pressure on antimicrobial resistance, and environmental aspects of the persistence of active substances in the manure-soil-water system. The combination of these factors makes it advisable to move from monostrategies to integrated control protocols.

A comprehensive biotechnological approach to the prevention and control of coccidiosis has been substantiated, combining immunoprophylactic, immunostimulatory and microbiome-oriented interventions with enhanced veterinary and sanitary measures aimed at reducing contamination and ensuring substrate drying. Vaccine strategies are interpreted as a tool for reducing invasive pressure through the formation of mucosal antigen-specific protection and potential limitation of oocyst excretion, immunostimulation – as support for non-specific resistance during critical periods of technological and thermal stress, and probiotics and prebiotics as means of stabilising intestinal ecology and barrier function. A limitation remains the lack of comparable field data on the effectiveness of individual commercial biotechnological products specifically against *C. suis* in pigs, which determines the need for further controlled trials of the protocol with parallel assessment of parasitological, clinical and productive indicators and economic feasibility. Prospects for further research lie in conducting controlled field trials of an integrated protocol for the prevention of *Cystoisospora suis* in farms in southern Ukraine with simultaneous

assessment of parasitological, clinical, productive, microbiome, and ecological safety indicators.

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Сучасні біотехнологічні рішення у профілактиці й контролі кокцидіозу поросят у свинарських господарствах Півдня України

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Анотація. Метою дослідження було теоретичне обґрунтування та розробка практичних рекомендацій щодо комплексного біотехнологічного підходу до профілактики захворювання, спеціально адаптованого до регіональних умов Півдня України. Матеріали опрацьовано методами теоретико-методологічного аналізу, системного та порівняльного аналізу, аналітико-синтетичного узагальнення, методу аналогії та методичного проєктування практичних рекомендацій. У результаті проведеного дослідження епізоотичний процес кокцидіозу поросят у господарствах Півдня України інтерпретовано як такий, що підтримується поєднанням довкіллєвого резервуару ооцист Cystoisospora suis та технологічно зумовленої повторної контамінації підстилки й виробничих поверхонь. Ключовими чинниками, що визначають інвазійний тиск у секціях утримання, визначено взаємодію мікроклімату приміщень із режимами зволоження/висихання субстратів у межах технологічного циклу, зокрема за тривалих періодів високих температур у теплий сезон і наявності локальних зон стабільної вологи. На цій основі профілактику описано як керування ланками «джерело інвазії – середовище – сприйнятливий контингент» із пріоритетом заходів, що зменшують персистенцію інвазійного матеріалу між партіями та обмежують повторне засівання середовища. Обґрунтовано межі застосовності монохімічних схем у системах, де зберігається довкіллєвий компонент передачі, а також окреслено ризики, релевантні для мікробіому, біобезпеки та екологічних наслідків тривалої присутності антикокцидійних засобів. Операціоналізовано критеріальну схему оцінювання втручань через узгоджений набір індикаторів, що відображають паразитологічний, клінічний та виробничий виходи. Запропоновано інтегрований протокол, що поєднує санітарно-гігієнічне керування контамінацією, біотехнологічні інтервенції і стандартизований моніторинг за принципом «до/після». Практичне значення полягає у можливості впровадження у господарствах Півдня України уніфікованого алгоритму профілактики та контролю з відтворюваним оцінюванням результативності й зіставністю ефектів між секціями та виробничими циклами

Ключові слова: епізоотичний тиск; вакцинація; мукозальний імунітет; пробіотики; антибіотикорезистентність

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Influence of clonex and indole-3-butyric acid on the rhizogenesis of *Picea pungens* f. *glauca* cuttings

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Abstract. The study aimed to provide a quantitative assessment of the effects of different concentrations of indole-3-butyric acid (IBA) and gel-based formulations on the intensity of rhizogenesis in semi-hardwood cuttings of *Picea pungens* f. *glauca*, with the objective of identifying the most effective treatment options. Over a three-year period (2023-2025), the efficacy of Clonex Green, Clonex Purple, and Clonex Red, as well as aqueous IBA solutions at concentrations of 1,000, 3,000, and 5,000 mg L^{-1}, was evaluated in the propagation of semi-hardwood cuttings of *Picea pungens* f. *glauca*. Cuttings 8-12 cm in length were collected from stock plants up to 10 years of age and established in a substrate composed of a 1:1 mixture of river sand and highmoor peat. The results demonstrated that the application of Clonex formulations and IBA significantly increased the rooting percentage compared with the control treatment, where the mean value was only 5.6%. The highest efficacy was achieved with the gel formulation Clonex Purple, which resulted in a rooting percentage of 37.8%. High effectiveness (28.9%) was also observed with Clonex Green and with the aqueous IBA solution at a concentration of 1,000 mg L^{-1}. It was found that a further increase in the concentration of pure IBA to 3,000 mg L^{-1} led to a decrease in rooting to 24.4%, while the application of 5,000 mg L^{-1} caused a pronounced inhibition of rhizogenesis (11.1%), indicating a phytotoxic effect. Gel-based stimulants (Clonex) were shown to outperform aqueous solutions, which can be attributed to prolonged contact of the active substance with the base of the cutting, its gradual release, and protection against leaching from the substrate. Statistical analysis using analysis of variance confirmed the significance of the observed differences (LSD0.05 = 1.71-1.83). The findings provide a basis for recommending optimal concentrations of growth stimulants to improve the production of high-quality planting material of ornamental coniferous species

Keywords: vegetative propagation; plant rooting; auxins; adventitious roots; rooting stimulators

INTRODUCTION

Efficient propagation of ornamental coniferous species remains a key objective in modern ornamental horticulture and forestry. Particular attention is given to blue spruce (*Picea pungens* f. *glauca*), which is widely used in urban landscaping due to its high ornamental value and tolerance to adverse environmental conditions. However, generative propagation does not ensure the preservation of its morphological traits, thereby necessitating the use of vegetative methods. Among these, stem cuttings represent one of the most promising approaches for producing uniform planting material, although rooting efficiency in conifers remains relatively low, which highlights the need to develop effective strategies for stimulating rhizogenesis and improving rooting technologies.

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A critical role in the propagation of woody plants by cuttings is played by phytohormones, particularly auxins, as demonstrated in study analysing the physiological and molecular mechanisms of adventitious root formation, where S. Liu *et al*. (2025) showed that indole-3-butyric acid (IBA) promotes rhizogenesis by activating cell division in vascular tissues and initiating the formation of root primordia. This mechanism contributes to increased rooting percentages and improved root system morphology, confirming the relevance of IBA application in vegetative propagation systems. The stimulatory effect of IBA on adventitious root formation has also been confirmed in experimental study on woody species, where M.A. Ibrahim *et al*. (2025), investigating rhizogenesis in *Zanthoxylum beecheyanum*, demonstrated that exogenous auxin application enhances cell division in the cambial zone and initiates root primordia development, resulting in higher rooting rates and improved root system architecture compared with untreated controls. These findings further substantiated the pivotal role of auxins in regulating rhizogenic processes.

A synthesis of contemporary research indicated that growth regulators substantially improve the efficiency of vegetative propagation in woody plants, with S.J. Trueman *et al*. (2021) demonstrating, through an extensive analysis of auxin-mediated adventitious root induction, that exogenous application of IBA increases rooting success, promotes the formation of a greater number of roots, and enhances their subsequent development, while its effectiveness is strongly dependent on concentration, physiological status of donor plants, cutting type, and environmental conditions. This highlighted the complex regulatory role of IBA in rhizogenesis. Further evidence of the effectiveness of IBA has been reported in studies on *Ficus benjamina*, where Y.P. Zala & M.M. Masu (2025) established that concentrations of 1,000-2,000 mg L^{-1} significantly stimulate root formation, increasing root number, length, and total biomass, with the highest morphological parameters observed at 2,000 mg L^{-1}, indicating a pronounced dose-dependent stimulatory effect.

In contemporary research, considerable attention is devoted to the use of commercial auxin-based formulations to enhance the rooting of woody plant cuttings. Among these, *Clonex Rooting Gel*, containing indole-3-butyric acid at a concentration of 0.31%, has been widely investigated. In a study on the clonal propagation of coniferous species, it was demonstrated by J.B. Silva Filho *et al*. (2026), working with *Pinus lambertiana* and *Pinus ponderosa*, that the application of Clonex led to a marked increase in rooting percentage alongside an improvement in overall root system development. The treatment was further associated with the formation of a greater number of first-order roots, which positively influenced the subsequent performance of planting stock. Importantly, the gel-based formulation was found to minimise the leaching of the active compound, thereby ensuring more consistent conditions for the induction of adventitious roots. It was also emphasised within the study that the effectiveness of rooting stimulants is strongly contingent upon their integration with an optimal substrate and appropriate environmental conditions, particularly temperature regime, air humidity, and the physical properties of the rooting medium.

The effectiveness of auxin-containing formulations has also been confirmed in ex vitro systems, where A.D. Oakes *et al*. (2020), analysing rooting in *Castanea dentata*, demonstrated that treatment of shoot bases with Clonex Rooting Gel stimulates adventitious root formation and improves subsequent acclimatisation success, indicating its suitability for enhancing both rhizogenesis and planting material quality. Despite the substantial body of research on the use of growth regulators in the rooting of woody plant cuttings, the effectiveness of rhizogenesis stimulators in the vegetative propagation of *Picea pungens* f. *glauca* remains insufficiently explored. The aim of this study was to evaluate the effectiveness of rhizogenesis stimulators in the rooting of semi-hardwood cuttings of *Picea pungens* f. *glauca*.

MATERIALS AND METHODS

The study was conducted during 2023-2025 to determine the effect of different rooting stimulators on the rooting of semi-hardwood cuttings of *Picea pungens* Engelm. f. *glauca*. The experimental methodology was based on a comparative design incorporating both control and treatment variants, with the latter involving the application of different growth regulators.

The experimental design comprised a control treatment without the application of rooting stimulants, in which cuttings were treated with water prior to planting, and a series of experimental variants involving the use of commercial formulations, namely *Clonex Green*, *Clonex Purple*, and *Clonex Red*. The active ingredient in these preparations is IBA, present at concentrations of 1, mg L^{-1} in Clonex Green, 3,000 mg L^{-1} in Clonex Purple, and 8,000 mg L^{-1} in Clonex Red. In addition, aqueous solutions of IBA at concentrations of 1,000, 3,000, and 5,000 mg L^{-1} were included as separate treatments. The selection of these products was informed by an analysis of recent scientific literature, which highlighted the high efficacy of auxin-based growth regulators in stimulating adventitious root formation in woody plant cuttings (Abshahi *et al.*, 2022; Swathi *et al.*, 2025; Silva Filho *et al.*, 2026). The specific concentrations and formulation types were chosen with due consideration of

the biological characteristics of the study species and the experimental conditions.

Cuttings were collected from stock plants up to 10 years of age. The selection of donor plant age was guided by methodological considerations, as reported by M. Younessi-Hamzekhanlu *et al.* (2026). Cuttings were taken from the upper part of the crown. Shoots of medium thickness were selected for propagation, while both excessively thin and overly thick shoots were excluded, as the morphometric characteristics of cuttings have a significant influence on the intensity of rhizogenesis. In the present study, cuttings measured 8-12 cm in length, with a basal diameter of 0.3-0.5 cm. Cuttings were excised using secateurs without the formation of a "heel". Collection was carried out in spring, in early April, prior to the onset of active shoot growth. The cuttings measured 8-12 cm in length. Following selection, the cuttings were transported to the greenhouse in a moist environment to prevent desiccation.

Prior to planting, needles were removed from the basal 2-3 cm of each cutting in order to reduce the risk of tissue decay and to improve contact between the cutting base and the substrate. The basal ends were then briefly treated with Clonex and aqueous solutions of IBA for 3-5 seconds. Cuttings were inserted into the substrate to a depth of 2-3 cm. The rooting medium consisted of a 1:1 mixture of river sand and high-moor peat. The selection of this substrate was determined by its high aeration capacity, adequate moisture retention, and overall suitability for root system development. Prior to the establishment of the experiment, the substrate was pre-treated to eliminate pathogenic microorganisms and weed seeds. The sand component was thoroughly washed under running water to remove fine dust and silt particles. After thorough mixing, the sand-peat substrate was subjected to thermal treatment by steaming. This procedure was carried out at a temperature of approximately 90-95°C for 30-40 minutes.

The study was conducted under protected ground conditions in a greenhouse, allowing for controlled microclimatic parameters. Air temperature during the rooting period was maintained within the range of 25-30°C, which is considered optimal for the induction of rhizogenesis in semi-hardwood cuttings of coniferous species. To prevent overheating during the summer period, shading was applied using a polymer shade net, which reduced solar radiation intensity and helped to stabilise the temperature regime. Optimal air and substrate moisture levels were maintained using a fine mist irrigation system. Watering was carried out at 30-minute intervals with a duration of 15 seconds. This regime ensured a consistently high relative humidity of 85-95%, thereby reducing transpiration, preventing cutting desiccation, and creating favourable conditions for the formation of adventitious roots.

The experiment was established using a replicated design. Each treatment comprised 30 cuttings with four replicates, providing a sufficient sample size for subsequent statistical analysis. The total number of cuttings per treatment therefore amounted to 120. Rooting efficiency was assessed by recording the number of cuttings that had formed a root system by the end of the rooting period. Evaluation was conducted 120 days after planting. The study was conducted in accordance with ethical standards for work involving biological materials (Convention on Biological Diversity, n.d.). Statistical analysis of the results was performed using Microsoft Excel, with the data processed as both absolute values and percentages relative to the total number of cuttings in each treatment. The reliability of the obtained data was assessed using analysis of variance (ANOVA), which enabled the determination of the effects of the studied factors on the rooting process of cuttings.

RESULTS AND DISCUSSION

An investigation was conducted to evaluate the effects of different formulations and concentrations of auxin-based treatments on the rooting of semi-hardwood cuttings of *Picea pungens* f. *glauca*. While a graphical representation of the obtained results expressed as percentages is shown in Figure 1.

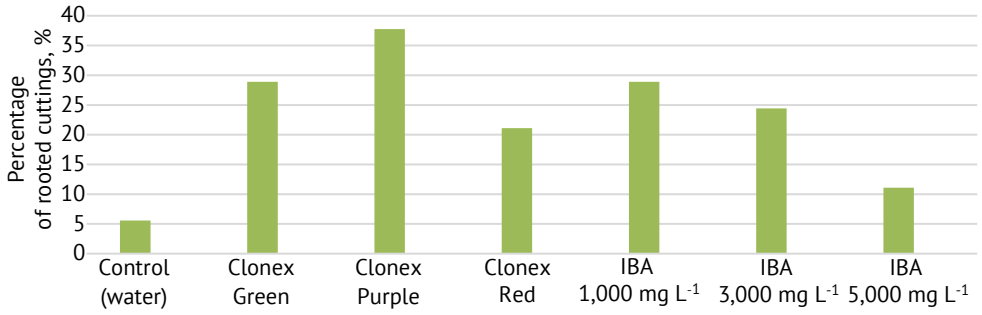

Figure 1. *Comparative effectiveness of Clonex preparations and IBA concentrations on the rooting of Picea pungens f. glauca cuttings (average for 2023-2025)*

Source: *developed by the author*

The control treatment, in which the cuttings had been planted without the application of growth stimulators, showed the lowest rooting level throughout the entire study period: in 2023 only one cutting rooted, while in 2024 and 2025 two cuttings rooted each year. On average over the three-year period, only 1.67 cuttings rooted out of the total number established per treatment, which corresponds to 5.6%. This confirmed the low natural ability of *Picea pungens* f. *glauca* cuttings to form roots without the use of rhizogenesis stimulators. In the treatment with Clonex Green, 9 cuttings rooted in 2023, 10 cuttings rooted in 2024, and 9 cuttings rooted in 2025. For comparison, in the control treatment only 1, 2, and 2 cuttings rooted during the same years. Thus, even with a minimal exposure time of the preparation (3-5 s), the use of Clonex Green ensured a 4-5-fold higher rooting level compared with the control. The average number of rooted cuttings over the three-year period was 8.67, which corresponded to 28.9%, which indicates the consistently high effectiveness of this preparation.

The highest rooting values were obtained with the application of Clonex Purple. In 2023, 12 cuttings rooted; in 2024, 11 cuttings rooted; and in 2025, 11 cuttings rooted. In comparison with the control treatment, where only 1-2 cuttings rooted, this preparation ensured a substantially higher rooting level. The average number of rooted cuttings during the study period was 11.3, corresponding to 37.8%, which allowed Clonex Purple to be considered the most effective among the tested preparations. The high efficacy of Clonex Purple was attributed to both its composition and physical form. The gel-based formulation ensured uniform coverage of the cutting base and prolonged contact between the active substance and plant tissues. This facilitated the gradual penetration of the growth regulator into cambial and parenchymal tissues, thereby stimulating the initiation of root primordia. The combination of an IBA (optimal auxin) concentration and sustained contact with the cutting surface resulted in the highest rooting percentage (37.8%) being recorded in the treatment involving Clonex Purple. The application of Clonex Red proved to be less effective. In 2023, 6 cuttings rooted; in 2024, 7 cuttings rooted; and in 2025, 6 cuttings rooted. Although these values significantly exceeded those of the control treatment, they were lower than the results obtained with the other Clonex preparations. On average over the three years, 6.3 cuttings rooted, corresponding to 21.1%.

The analysis of treatments involving the application of IBA showed that the most effective among the tested concentrations was 1,000 mg L^{-1}. In 2023 and 2024, 9 cuttings rooted in this treatment each year, while in 2025, 8 cuttings rooted, which was significantly higher than the control. The average result over the three-year period was 8.67 rooted cuttings, corresponding to 28.9%.

In the treatment with an IBA concentration of 3,000 mg L^{-1}, 8 cuttings rooted in 2023, 7 cuttings in 2024, and 7 cuttings in 2025. Compared with the control, these values were also considerably higher; however, they were somewhat lower than those obtained with the concentration of 1,000 mg L^{-1}. The average number of rooted cuttings in this treatment was 7.3, corresponding to 24.4%.

The lowest results among the IBA treatments were recorded at the concentration of 5,000 mg L^{-1}. In 2023, 3 cuttings rooted; in 2024, 3 cuttings rooted; and in 2025, 4 cuttings rooted. Although these values still exceeded those of the control treatment, they were substantially lower compared with the other IBA concentrations, indicating an inhibitory effect of the excessive auxin concentration on root formation processes. The average rooting value in this treatment was only 3.3 cuttings, corresponding to 11.1%. The summarised quantitative indicators of cutting rooting over the three-year study period are presented in Table 1.

Table 1. *Rooting percentage of Picea pungens f. glauca cuttings as influenced by Clonex formulations and IBA concentration (2023-2025)*

Treatment variant	Concentration mg L^{-1}	Number of cuttings in the treatment, pcs.	Rooted cuttings, pcs. (2023)	Rooted cuttings, pcs. (2024)	Rooted cuttings, pcs. (2025)	Average number of rooted cuttings in 2023-2025, pcs.
Control (water)	water	30	1	2	2	1.67
Clonex Green	1,500	30	9	8	9	8.67
Clonex Purple	3,000	30	12	11	11	11.33
Clonex Red	8,000	30	6	7	6	6.33
IBA	1,000	30	9	9	8	8.67
IBA	3,000	30	8	7	7	7.33
IBA	5,000	30	3	3	4	3.33
$LSD_{0.05}$			1.71	1.83	1.76	

Source: *developed by the author*

Despite the higher concentration of the active substance in Clonex Red (8,000 mg L^{-1}), its application proved to be more effective than the aqueous IBA solution at a concentration of 5,000 mg L^{-1}. This was attributed to the sustained release of auxin from the gel-based formulation, which ensured a more gradual and controlled effect on cutting tissues, whereas high concentrations of IBA in aqueous solution tended to induce phytotoxic effects and inhibit root formation processes. The decline in rooting efficiency observed at increased IBA concentrations of 3,000 and 5,000 mg L^{-1} was associated with the phytotoxic effects of excessive auxin doses. An overabundance of growth regulators might disrupt the normal course of physiological processes within cutting tissues, leading to the inhibition of cell division and differentiation. At high concentrations, auxins could also induce the formation of necrotic zones in the basal region and disrupt the balance of endogenous phytohormones. As a result, instead of stimulating rhizogenesis, a partial suppression of root system formation occurred, as evidenced in the treatments with 3,000 and 5,000 mg L^{-1}.

Using the analysis of variance (ANOVA) method, mathematical processing of the experimental data confirmed the statistical significance of the effect of the studied growth stimulators (Clonex preparations and different concentrations of IBA) on the intensity of root system formation in *Picea pungens* f. *glauca*. The calculated least significant difference ($LSD_{0.05}$) values were 1.71 in 2023, 1.83 in 2024, and 1.76 in 2025, which clearly demonstrated a significant increase in rooting rates in the treatments with Clonex Purple, Clonex Green, and the IBA solution at a concentration of 1,000 mg L^{-1} compared with the control, thus excluding the influence of random experimental error. A significant improvement over the control was observed with the application of Clonex Green, Clonex Purple, and Clonex Red, as well as with aqueous IBA solutions at concentrations of 1,000, 3,000, and 5,000 mg L^{-1} over the three-year study period. An exception was recorded in 2024, when the application of IBA at 5000 mg L^{-1} did not result in a statistically significant advantage over the control.

Overall, the results obtained indicate the expediency of using auxin-containing formulations in the vegetative propagation of *Picea pungens* f. *glauca*, as their application substantially enhances the rooting efficiency of cuttings. Among the treatments studied, Clonex Purple demonstrated the highest effectiveness. The use of gel-based stimulants may therefore be recommended for ornamental horticulture practice, as they provide more stable conditions for the action of growth regulators and contribute to higher rooting percentages.

It should also be noted that the rooting efficiency of cuttings may have been influenced by environmental conditions, particularly temperature, air humidity, and light intensity within the greenhouse. Optimal temperature and elevated humidity levels contribute to reduced transpiration and prevent desiccation of cuttings during the period of root system formation. At the same time, an adequate level of diffused light supports photosynthetic activity in the tissues, promoting the accumulation of assimilates required for the development of adventitious roots. Thus, the combination of optimal microclimatic conditions with the use of effective rhizogenesis stimulants creates favourable prerequisites for increasing the rooting percentage of *Picea pungens* f. *glauca* cuttings.

The results of the present study were consistent with the findings reported by M.F. El-Banna *et al*. (2023), who investigated the influence of IBA on the formation of adventitious roots in cuttings of *Zanthoxylum beecheyanum*. In that study, it was established that the application of exogenous auxin stimulated the rhizogenesis process, resulting in an increase in rooting percentage, as well as in the number and length of roots. In particular, rooting in the control treatments ranged from approximately 20-25%, whereas treatment with IBA at a concentration of 500 mg kg^{-1} increased this value to 40-45%. The application of a concentration of 1,000 mg kg^{-1} increased the rooting percentage to 55-60%, while concentrations of 1,500-2,000 mg kg^{-1} resulted in 70-80% of rooted cuttings. However, a further increase in concentration to 2,500 mg kg^{-1} was accompanied by a decline in rooting efficiency. The results obtained in the study likewise confirmed the pronounced stimulating effect of auxin-containing preparations on the formation of adventitious roots, demonstrating optimal efficiency at lower concentrations and a decline at higher concentrations.

Comparable findings regarding the stimulatory effect of auxin-based formulations on the rooting of coniferous cuttings have been reported by J.B. Silva Filho *et al*. (2026), who, in the course of clonal propagation of *Pinus lambertiana* and *Pinus ponderosa*, applied a gel-based Clonex preparation containing IBA at a concentration of approximately 0.31%. It was established that the use of this formulation resulted in high rooting performance: in *Pinus lambertiana*, the proportion of rooted cuttings reached 80%, whereas in *Pinus ponderosa* it was approximately 40%, significantly exceeding the control treatments, where rooting ranged from 10% to 30%. The results were consistent with this trend, confirming that the gel-based formulation (Clonex Purple) provides superior rooting performance compared to the control and aqueous solutions.

The difference in absolute values can be attributed to species-specific characteristics.

Important results regarding the role of stimulators have also been obtained in studies on the rooting of *Cupressus macrocarpa* cuttings. In the study by Y.A. Abdulraahman & M.Z. Ayoub (2023), it was established that the application of auxin-based growth regulators significantly improved the rooting of semi-hardwood cuttings of this species. The maximum rooting percentage in their experiment reached 51.11%, whereas the control treatment ranged from 26% to 28%, depending on the experimental conditions. The present findings similarly confirmed the positive influence of auxin-based preparations on the formation of adventitious roots. As observed in experiment, the maximum rooting efficiency was achieved at lower IBA concentrations and with the Clonex Purple, while higher doses led to a decline.

The lower rooting level observed in comparison with the results reported for *Cupressus macrocarpa* might be explained by interspecific differences among the studied plants. Species of the genus *Picea* are generally characterised by a lower capacity for adventitious root formation compared with many other conifer species. This is associated with the anatomical characteristics of their shoots, a higher degree of tissue lignification, and lower activity of cambial cells involved in the formation of root primordia. In the study by M. Sanz Gallego *et al*. (2025), it was found that the application of IBA at a concentration of 4,000 ppm significantly increased the efficiency of rhizogenesis in cuttings of *Juniperus communis*. The maximum rooting percentage reached 45.6%, whereas in the control treatment it was 23.5%. These results confirmed the important role of exogenous auxins in stimulating the formation of adventitious roots in conifer species. A comparable positive response to the application of IBA and the commercial preparation Clonex was observed in the present study. These differences in results may be attributed to interspecific characteristics of the studied plants.

The obtained results were appropriately compared with the data reported by G.E. Oğuztürk *et al*. (2025), who investigated the effects of different auxin types (IBA, NAA, IAA) at concentrations of 1,000; 3,000; 5,000; and 8,000 ppm on the rooting of semi-hardwood cuttings of *Photinia* × *fraseri*. In that study, rhizogenesis exhibited a clearly defined concentration optimum, with the highest rooting percentage (93.33 ± 8.16%) achieved at an IBA concentration of 5,000 ppm, significantly exceeding the control (58.33 ± 7.53%). At the same time, a reduction in concentration to 1,000 ppm resulted in decreased rooting (48.33 ± 11.69%), whereas an increase to 8,000 ppm led to inhibition of the rooting process.

The present findings demonstrated a comparable concentration-dependent pattern, characterised by the presence of an optimal level and the suppression of rhizogenesis when this threshold is exceeded. At the same time, it should be noted that the effective auxin concentrations reported in the cited study were substantially higher than those observed in the present work. This discrepancy is attributable to species-specific characteristics and differences in physiological sensitivity to auxins. This was further illustrated by the control treatments, where the rooting percentage in the present study was 5.6%. Coniferous species, including *Picea pungens* f. *glauca*, are generally characterised by a higher sensitivity to exogenous growth regulators, which consequently narrows the effective range of their application.

The effects of indole-3-butyric acid (IBA) concentrations (4,000; 6,000; and 8,000 mg L^{-1}) and substrate composition on the rooting of semi-hardwood cuttings of *Photinia* × *fraseri* were investigated by N.S. Hasan & Y.H. Hammo (2021). The study demonstrated that the application of IBA significantly enhanced rooting performance: at a concentration of 4,000 mg L^{-1}, the rooting percentage reached 43.33%, while at 6,000 and 8,000 mg L^{-1} it increased to 50.56% and 51.78%, respectively, compared with substantially lower values in the untreated control. Moreover, when peat was used as the substrate in combination with 6,000 mg L^{-1} IBA, rooting increased to 73.33%, highlighting the critical role of interactions between environmental factors and growth regulators in the rhizogenesis process. The present results were consistent with these findings, confirming the stimulatory effect of IBA on cutting rooting, albeit with a decline at higher concentrations. This discrepancy was attributed to species-specific characteristics, as well as differences in the physiological status of the cuttings and their sensitivity to exogenous auxins. In addition, the higher rooting performance observed with Clonex formulations compared with aqueous IBA solutions underscored the importance of the preparative form, which ensured a prolonged release of auxin and a more effective realisation of its physiological action.

The influence of different concentrations of indole-3-butyric acid (0-6,000 ppm) on the rooting of *Corylus colurna* cuttings under controlled greenhouse conditions was investigated by S. Çolak *et al*. (2025). The study demonstrated that the highest rooting percentage (25%) was achieved at an IBA concentration of 5,000 ppm, whereas at 1,000; 2,000; and 6,000 ppm rooting remained at approximately 15%. The lowest value (8.3%) was recorded at 4,000 ppm. In addition, the greatest number of roots per cutting (on average 8) was observed at 1,000 ppm, compared with only 0.6 in

the control, indicating a pronounced stimulatory effect of auxin on root system morphogenesis. The present results partially corresponded to these findings, as they also confirmed the existence of an optimal concentration range of IBA for the stimulation of rhizogenesis. However, in contrast to the cited study, where the optimum was shifted towards higher concentrations (5,000 ppm), lower auxin concentrations proved to be more effective for *Picea pungens* f. *glauca*. This difference was attributable to species-specific characteristics and an increased sensitivity of this taxon to exogenous growth regulators.

Furthermore, the use of Clonex formulations resulted in higher rooting performance compared with aqueous IBA solutions, which highlighted the important role of the preparative form in enhancing auxin effectiveness. Overall, the findings supported the species-specific nature of optimal auxin concentrations and emphasised the need to consider both concentration and formulation when stimulating rhizogenesis. The application of indole-3-butyric acid at concentrations of 0; 1,000; 2,000; and 3,000 mg L^{-1} in combination with substrate composition during the rooting of hardwood cuttings of *Cydonia oblonga* was examined by R.R. Aziz *et al*. (2024). The study revealed that IBA application did not enhance rhizogenesis efficiency: rooting percentages under auxin treatment ranged from 46% to 47%, and in some cases decreased to 7-8% depending on the substrate. In contrast, the control treatment, involving cultivation in pure river sand without auxin application, achieved a rooting percentage of 70.83%. These findings indicated the absence of a positive effect of IBA for this species within the tested concentration range.

The present results differed markedly from these observations, as a clear stimulatory effect of both aqueous IBA and Clonex preparations on the rooting of *Picea pungens* f. *glauca* was established, significantly exceeding the control. The observed discrepancies can be attributed to both species-specific characteristics and differences in rooting conditions. Unlike studies in which the highest rooting performance was achieved in pure river sand without auxin application, the present experiment utilised a substrate composed of a 1:1 mixture of river sand and peat, characterised by improved moisture retention and aeration properties. These conditions likely enhanced the effectiveness of exogenous auxin and promoted the formation of adventitious roots. Thus, the efficiency of IBA application was determined not only by species-specific traits but also by the complex of rooting conditions, particularly substrate composition.

The results can be appropriately compared with those reported by K. Harika *et al*. (2024), who investigated the effects of different concentrations of indole-3-butyric acid (0; 1,000; 1,500; and 2,000 ppm) on the rooting of semi-hardwood cuttings of *Punica granatum*. In that study, the highest rooting percentage (58.89%) was achieved at an IBA concentration of 2,000 ppm, while the control treatment showed substantially lower values. Moreover, this concentration resulted in the greatest number of roots per cutting (12.02) and the maximum root length (14.14 cm), indicating a pronounced stimulatory effect of auxin on rhizogenesis.

The obtained results were consistent with those reported in the cited study and confirmed the positive effect of IBA on cutting rooting. At the same time, it was established that the optimal concentration for *Picea pungens* f. *glauca* is lower than that reported in the referenced work, indicating a greater sensitivity of this taxon to exogenous auxins. However, in contrast to the cited study, where the optimum was observed at a higher concentration (2,000 ppm), increasing the IBA concentration to 3,000 and 5,000 mg L^{-1} in *Picea pungens* f. *glauca* resulted in a decline in rooting efficiency (to 24.4% and 11.1%, respectively), indicating a greater sensitivity of this species to excessive auxin levels. This was attributed to species-specific characteristics of coniferous plants and a more pronounced manifestation of phytotoxic effects when the optimal concentration of the growth regulator is exceeded. Thus, the results confirmed that the effectiveness of IBA is determined not only by its presence but also by the precise selection of concentration and the preparative form of application.

The effects of indole-3-butyric acid (IBA) at concentrations of 0; 1,000; 2,000; and 3,000 mg L^{-1} in combination with substrate composition on the rooting of *Bougainvillea* spp. cuttings were investigated by A.T. Rasul *et al*. (2025). The study demonstrated that the untreated control consistently exhibited the lowest rooting performance regardless of substrate type. Application of IBA at 1,000 mg L^{-1} increased rooting percentage and stimulated shoot development, although it did not produce maximum values. The highest rooting level (up to 80.49% in *Bougainvillea glabra*) was achieved at 2,000 mg L^{-1}, which was identified as the optimal concentration for the induction of adventitious roots. Further increasing the concentration to 3,000 mg L^{-1} did not enhance rooting percentage but promoted the development of a more robust root system, including greater root number and length. In addition, peat as a substrate provided the most favourable conditions for rooting compared with other media.

The present findings partially corresponded to these results, confirming the stimulatory effect of IBA on rhizogenesis. However, in contrast to the cited study, the optimal concentration range appeared to be narrower for *Picea pungens* f. *glauca*. Furthermore, whereas

substrate composition played a significant role in the cited study, the present results indicated a more pronounced effect of auxin concentration and formulation. In particular, the use of Clonex preparations ensured higher rooting performance compared with aqueous IBA solutions. Overall, the findings confirmed that rhizogenesis efficiency is governed by a complex interaction of factors, among which both the concentration of the growth regulator and the rooting conditions are of primary importance.

The obtained results can be compared with those reported by F.E.F. de Felice *et al*. (2024), who investigated the effect of different concentrations of indole-3-butyric acid (0; 1,000; 2,000; and 4,000 mg L^{-1}) on the rooting of mini-cuttings of *Eucalyptus camaldulensis* collected under arid conditions. The study demonstrated that the application of IBA significantly enhanced rhizogenesis: rooting in the control reached 55%, whereas treatment with 2,000 mg L^{-1} IBA increased this value to 80%, representing the optimal response. In contrast, concentrations of 1,000 and 4,000 mg L^{-1} did not result in further improvement and were inferior to the optimal treatment, indicating a clearly defined auxin optimum.

The present findings were generally consistent with these data, as they likewise confirmed the dependence of rooting efficiency on IBA concentration. Similar to the cited study, the existence of an optimal concentration range was identified, beyond which rhizogenesis efficiency decreases. At the same time, although the presence of an auxin optimum was confirmed, the absolute values of rooting differ substantially, being markedly lower for *Picea pungens* f. *glauca*. This discrepancy was attributable to biological characteristics of coniferous species, which generally exhibit a lower capacity for adventitious root formation compared with representatives of the genus *Eucalyptus*.

A comparative analysis of the obtained results with the data reported by I.S. Negri *et al*. (2025) indicated that their study examined the effects of indole-3-butyric acid concentration and the age of donor plants on the rooting of *Fraxinus excelsior* cuttings. It was established that cuttings collected from juvenile plants exhibited a rooting percentage of 39.44% without the application of stimulants, whereas material derived from mature trees failed to form roots. In treatments involving IBA at concentrations of 1-2%, rooting of juvenile cuttings ranged from 44.82% to 58.62% after 6 months of cultivation, increasing further to 58.62-75.86% after 9 months, demonstrating the enhanced effectiveness of auxin when physiologically young material is used.

The present findings partially corresponded to these results, as a stimulatory effect of IBA on the rooting of *Picea pungens* f. *glauca* cuttings was likewise observed, although the overall level of rhizogenesis was substantially lower. This discrepancy appeared to be systematic and could primarily be explained by interspecific differences, as representatives of the genus *Picea* are characterised by a considerably lower morphogenetic potential for adventitious root formation compared with deciduous species such as *Fraxinus excelsior*. In addition, the cited study highlighted the critical role of donor plant age, whereas in the present work cuttings were obtained from plants up to 10 years old, which partially mitigates this factor but does not allow similarly high rooting performance to be achieved. Furthermore, the application of Clonex Purple increased rooting to 37.8%. However, even this value remained lower than those reported for *Fraxinus excelsior*. Overall, these findings indicated that the effectiveness of auxin-based treatments was determined not solely by concentration but by a complex interplay of species-specific traits, physiological status of the source material, and rooting conditions, which may lead to substantial variation among studies.

Important findings on the effect of indole-3-butyric acid on rhizogenesis in coniferous cuttings were reported by M. Abshahi *et al*. (2022), who investigated the influence of IBA concentration, substrate type, and cutting season on the rooting of *Juniperus sabina*. The study employed a wide range of IBA concentrations (0, 1,000, 2,000, 4,000, and 8,000 ppm) in combination with different substrates and seasonal timings of cutting collection. It was demonstrated that IBA treatment significantly increased the rooting percentage, root biomass, and morphological characteristics compared with the control. The maximum rooting rate reached 62% at a concentration of 1,000 ppm. The results obtained are broadly consistent with these findings, as both studies revealed a clearly expressed stimulatory effect of IBA on adventitious root formation. In particular, the increase in rooting percentage under the influence of exogenous auxin, relative to the control, confirmed the key role of IBA as a regulator of cellular differentiation and the initiation of root primordia.

At the same time, notable differences were identified in both the level of effectiveness and the optimal concentrations. In the cited study, rooting percentages exceeded 60%, whereas in the case of *Picea pungens* f. *glauca*, the maximum value reached 37.8% with Clonex Purple and 28.9% with an aqueous IBA solution (1,000 mg L^{-1}). Moreover, in *Juniperus sabina*, the effective IBA concentration range was broader (1,000-4,000 ppm), while in the present study, increasing the concentration to 3,000-5,000 mg L^{-1} resulted in reduced rooting, indicating a narrower optimum and

a higher sensitivity of this taxon to auxin. These differences can be attributed to species-specific biological characteristics. Representatives of the genus *Picea* generally exhibit a lower capacity for adventitious root formation compared with those of the genus *Juniperus*, which is associated with a higher degree of tissue lignification and lower cambial activity. In addition, the cited study demonstrated a substantial influence of seasonal timing and substrate type on rhizogenesis, whereas in the present work these factors were standardised under controlled experimental conditions.

The results of the present study are consistent with the generalisations reported in the review by M. Younessi-Hamzekhanlu *et al*. (2026), which synthesises current approaches to the vegetative propagation of species within the genus *Picea*. The authors demonstrated that the efficiency of rhizogenesis is governed by a complex interaction of endogenous and exogenous factors, among which the age of stock plants, the physiological status of cuttings, genotype, and environmental conditions are of primary importance. It was shown that cuttings derived from juvenile plants exhibit a substantially higher rooting capacity compared with material obtained from mature trees, which is associated with higher metabolic activity and increased sensitivity to exogenous auxins.

In the present study, cuttings were collected from plants up to 10 years of age, which enabled root system formation in *Picea pungens* f. *glauca* and confirmed the importance of using physiologically juvenile donor material. At the same time, the recorded rooting percentages (maximum 37.8%) remained moderate, which is in agreement with the general conclusion of the cited authors regarding the relatively low inherent capacity of *Picea* species for adventitious root formation. The findings of the review further indicate that the effectiveness of auxins in rhizogenesis depends not only on their application per se, but also on their concentration, as both insufficient and excessive doses may reduce rooting or exert inhibitory effects. In addition, the review emphasised the importance of interactions between growth regulators and environmental conditions, particularly substrate composition and moisture regime. This was consistent with the results obtained, where the use of a sand-peat substrate (1:1), in combination with controlled greenhouse conditions, provided a favourable environment for the action of auxins and the development of adventitious roots.

CONCLUSIONS

As a result of the conducted research, it was established that the rooting of semi-hardwood cuttings of *Picea pungens* Engelm. f. *glauca* largely depends on the application of rooting stimulators. In the control treatment without the use of growth regulators, the average rooting percentage was only 5.6%, indicating the low natural capacity of cuttings of this ornamental form to produce adventitious roots. The application of auxin-containing preparations significantly increased the rooting efficiency of the cuttings. The highest values were obtained with the use of Clonex Purple, where the average rooting percentage reached 37.8%. Slightly lower but still relatively high results were recorded in the treatments with Clonex Green and an aqueous solution of IBA at a concentration of 1,000 mg L^{-1}, where the average rooting level was 28.9%. The use of Clonex Red provided an average rooting percentage of 21.1%.

It was also established that the effectiveness of IBA largely depends on its concentration. Increasing the concentration to 3,000 mg L^{-1} resulted in a decrease in the rooting level to 24.4%, whereas the use of a concentration of 5,000 mg L^{-1} caused a sharp decline in the number of rooted cuttings, which amounted to 11.1%. This reduction may be explained by the phytotoxic effect of excessive auxin concentrations on the tissues of the cuttings. Analysis of variance (ANOVA) demonstrated that, over the three-year study period, all treatments showed a statistically significant advantage over the control, with the exception of the treatment involving IBA at a concentration of 5,000 mg L^{-1} in 2024.

The obtained results indicate that the use of Clonex preparations based on IBA in gel form is more effective for stimulating rhizogenesis in cuttings of *Picea pungens* f. *glauca*, as this formulation ensures a more uniform distribution of the active substance on the cut surface and provides a prolonged effect of the growth regulator. Prospects for further research include the improvement of vegetative propagation techniques for *Picea pungens* f. *glauca*, particularly through the study of substrate composition and the combined application of growth regulators with other biologically active substances in order to increase rhizogenesis efficiency and obtain high-quality planting material.

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Вплив препарату clonex та індоліл-3-масляної кислоти на ризогенез живців *Picea pungens* f. *glauca*

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Анотація. Метою дослідження було кількісне оцінювання впливу різних концентрацій індоліл-3-масляної кислоти та гелевих препаратів на інтенсивність ризогенезу напівздерев'янілих живців *Picea pungens* f. *glauca* з визначенням найбільш ефективних варіантів обробки. У трирічному дослідженні (2023-2025 рр.) досліджено ефективність препаратів Clonex Green, Clonex Purple, Clonex Red, а також водних розчинів індолілмасляної кислоти (ІМК) у концентраціях 1000 мг/л, 3000 мг/л та 5000 мг/л при розмноженні напівздерев'янілих живців *Picea pungens* f. *glauca*. Живці довжиною 8-12 см заготовляли з маточних рослин віком до 10 років. Живці висаджували в субстрат, який складався із суміші річкового піску та верхового торфу у співвідношенні 1:1. За результатами досліджень встановлено, що застосування препаратів Clonex та ІМК істотно підвищує відсоток укорінення порівняно з контрольним варіантом, де середній показник становив лише 5,6 %. Найвищу ефективність продемонстрував гелевий препарат Clonex Purple, використання даного препарату забезпечило укорінення живців 37,8 %. Високу результативність (28,9 %) також зафіксовано при застосуванні Clonex Green та водного розчину ІМК у концентрації 1000 мг/л. Виявлено, що подальше підвищення концентрації чистої ІМК до 3000 мг/л призводить до зниження показника до 24,4 %, а застосування концентрації ІМК 5000 мг/л спричиняє пригнічення ризогенезу (11,1 %), що свідчить про фітотоксичну дію. Встановлено перевагу гелевих форм стимуляторів (Clonex) над водними розчинами, що пояснюється пролонгованим контактом діючої речовини з основою живця, її поступовим вивільненням та захистом від вимивання із субстрату. Математична обробка даних методом дисперсійного аналізу підтвердила статистичну достовірність отриманих результатів (НІР0,05 у межах 1,71-1,83). Отримані дані дозволяють рекомендувати оптимальні концентрації стимуляторів для підвищення виходу якісного садивного матеріалу декоративних хвойних порід

Ключові слова: вегетативне розмноження; укорінення рослин; ауксини; адвентивні корені; стимулятори коренеутворення

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Designing technologies for strengthening tractor and self-propelled machine parts in agricultural conditions

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Abstract. The study aimed to theoretically substantiate a reproducible engineering approach to selecting reinforcement routes, incorporating transitions between degradation mechanisms and spatial heterogeneity of requirements within a part. The methodology was based on sequential transfer of operating conditions into a cause-and-effect chain "operating conditions – degradation mechanism – critical zone – surface and core requirements – class of technological solution" based on international regulatory requirements for steels, parameters of strengthened layers, corrosion resistance and durability of components. Results showed that the risk of degradation is threshold-based: when one factor is intensified, it increases moderately and is concentrated mainly in a 2-3 point zone of integral scale, while simultaneous intensification of two or more factors shifts the system to a 4-5 point zone due to synergy of corrosion-abrasive and abrasive-fatigue processes. A change in "leading" mechanism has been identified, from predominantly fatigue under moderate conditions to the dominance of surface combined scenarios under high conditions, when the stability of the surface layer and its chemical resistance become decisive. The study substantiated that there are no universal technologies: for parts with a critical core role, volumetric thermal routes are a priority; for contact areas with soil – local surface strengthening and wear-resistant layers; for contact-stressed areas – thermochemical solutions; for wet agrochemically active environments – barrier protection. The

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study demonstrated that additive restoration can be used as a preparatory stage with subsequent post-processing and strengthening, since a reinforced surface layer determines the resource. The practical significance lies in the fact that the generalised model can be used by design engineers, technologists and agricultural service providers when designing and restoring tractor and self-propelled machine parts to select a strengthening route class by correlating operating conditions with the dominant degradation mechanism and the critical area of the part, which reduces accelerated wear

Keywords: mechanical loads; degradation; abrasive wear; surface layer; technological route; additive manufacturing

INTRODUCTION

Modern tractors and self-propelled agricultural machines operate under conditions of intensive agricultural use, which combines high mechanical loads, cyclic impact, abrasive wear from contact with ground, as well as prolonged exposure to moisture and chemically active substances, in particular mineral fertilisers and plant protection products. Under such conditions, service life and reliability of parts are largely determined not only by design solutions, but also by rational engineering of technologies for strengthening surfaces and the material basis of assemblies. Therefore, theoretical analysis of technologies for strengthening parts of tractors and self-propelled machines is becoming increasingly relevant in the context of increasing their durability and reducing operational losses.

O. Zubiekhina-Khaiiat (2017) considered surface plastic deformation processes as efficient tools for improving wear resistance of threaded and worm surfaces widely used in agricultural machinery components. The study showed that controlled formation of a hardened surface layer can significantly reduce wear intensity without changing the geometry of a part. Further development of this direction is demonstrated in a study by O. Zubiekhina-Khaiiat & D. Marchenko (2018), which analyses the rigidity of the "machine tool – tool – part" system during the repair of parts using surface plastic deformation methods. The results confirmed that the effectiveness of strengthening in the context of agricultural machinery restoration largely depends on the stability of the technological system and the correct selection of processing modes. The issue of restoration and strengthening of worn parts was also considered by O. Lymar & D. Marchenko (2022), which substantiates prospects for the use of electric arc restoration coatings in the repair of machines and mechanisms. The authors emphasised that such coatings are suitable for parts that operate under conditions of intense abrasive and corrosive wear, which is characteristic of an agricultural environment. Furthermore, in studies by G. Filimonikhin *et al*. (2021), the analytical approach to assessing dynamic loads in mechanical systems emphasises the need to consider real operating conditions when designing reinforced elements of rotating machine components.

V. Hruban *et al*. (2025) used finite element analysis methods to assess stress-strain state and optimise designs of agricultural trailed machines to compare design parameters with load-bearing capacity and strength indicators of elements. The results showed that a combination of rational design, adequate choice of materials and strengthening technologies can significantly increase the durability of elements operating in harsh field conditions. Modern approaches to surface strengthening are actively developing in the direction of functional coatings application. In particular, A.S. Kairov *et al*. (2022) showed that composite nanocoatings can significantly increase the wear resistance of tools by forming multilayer structures with improved tribological properties. The study also emphasised that this effect is manifested not only in a reduction in wear intensity, but also in an increase in technological productivity due to stabilisation of friction conditions and a reduction in contact losses. Similar trends are notable in a comprehensive review by C. Munteanu *et al*. (2025), which analysed the use of atmospheric plasma spraying to increase the durability of boron discs. The authors concluded that such coatings are effective for soil cultivation implements that are subject to intense abrasive wear. Thermal and thermochemical strengthening methods remain the basis for mass-produced agricultural machinery parts. D. Romek *et al*. (2024) addressed use of thermally applied coatings to reduce wear on agricultural machinery components, confirming feasibility of combining heat treatment with surface layers to achieve an optimal balance between hardness and toughness. An analysis of operating conditions of self-propelled hydromeliorative machines conducted by A. Formato *et al*. (2022) showed that prolonged operation in a humid environment places increased demands on corrosion and fatigue resistance of components. Accordingly, stability of such machines is determined by the ability of materials and hardened surface layers to maintain their load-bearing capacity and wear resistance under prolonged loads. A systematic review

by J. Hao *et al*. (2024) addressed the state of research on strengthening the wear resistance of soil-contact components of agricultural machines. The study summarised results regarding thermal, laser and coating technologies, emphasising that the greatest effect is achieved through a comprehensive approach that combines material selection, local surface strengthening and adaptation of technology to specific agricultural operating conditions.

Thus, analysis of scientific sources showed that the design of technologies for strengthening tractor and self-propelled machine parts should be based on consideration of actual agricultural loads, the nature of wear and tear, and the aggressiveness of the environment. A combination of classical thermal methods, modern surface coatings, laser technologies and the prospects of additive manufacturing (AM) forms a scientifically sound basis for increasing the service life and reliability of agricultural machinery under conditions of intensive use. The study aimed to develop and theoretically substantiate a universal, reproducible approach to the selection of strengthening technologies, which determined the optimal route incorporating critical thresholds of degradation mechanisms and different requirements for properties of the surface and core of a single part.

Primary study objectives included: generalisation of mechanisms of wear and corrosion of parts in agricultural operation and correlation with requirements for hardened layer; analysis of hardening technologies relevant to agricultural machinery, in particular quenching and tempering, laser surface hardening and nitriding/nitride coatings for corrosion-prone components (pipes, pump housings); identification of approaches to selection of materials (alloy steels, chromium-containing alloys) and prospects for application of additive technologies (3D printing) for manufacture of wear-resistant components with increased requirements for accuracy and strength.

MATERIALS AND METHODS

The material basis included international regulatory, technical documents and software tools for engineering information processing, which provided a documented justification for the selection of materials and technologies for strengthening tractor and self-propelled machine parts for use in agricultural operations. Basic source of requirements for steels intended for hardening and tempering was ISO 683-1:2016 (2016) standard, which was used for normatively correct coordination of non-alloy steel grades with expected properties of parts under high mechanical loads and intensive abrasive wear in field conditions. For groups of alloy steels characteristic of critical elements of transmission and power units, ISO 683-2:2016 (2016) was applied, which provided a documentary basis for comparing the choice of material with the need for increased hardenability, stability of structure after tempering and ability to operate under cyclic loads. Since agricultural exploitation is characteristic of direct contact of working surfaces with soil, abrasive particles and corrosive environments, a documentary basis for description and control of surface-hardened layer parameters was formed by ISO 18203:2016 (2016). Its provisions are used for a unified interpretation of the thickness of the surface-hardened layer as a characteristic that determines the performance of parts in modes of abrasive and contact-abrasive wear. To address corrosive effects of moisture, mineral fertilisers and pesticides (critical for pipes, pump housings and housing elements), ISO 9227:2022 (2022) was used as a regulatory basis for comparing corrosion resistance of materials and coatings using a unified salt spray test procedure. General regulatory context for selection of anti-corrosion systems and principles of their application for steel elements were based on ISO 12944-1:2017 (2017) was used to justify the resource suitability of rolling and connection units of variable loads with the durability of aggregates. Prospects for the use of additive technologies (3D printing) for the manufacture or restoration of wear-resistant components were considered based on ISO/ASTM 52900:2021 (2021), which provides terminological and classification consistency in AM. ISO/ASTM 52920:2023 (2023) was used to justify industrial reproducibility of such solutions and requirements for qualification of processes and production sites. This method was used to correctly formulate criteria for the applicability of additive manufacturing/restoration specifically for agricultural machinery parts, incorporating requirements for quality, stability and repeatability of production results.

Research methodology was based on a combination of logical-analytical and systematic approaches, which provided new generalisations regarding the design of technologies for strengthening parts for agricultural use. The research was conducted as a sequential procedure of interpreting documentary requirements and transferring them into applied engineering logic for the selection of technologies based on the principle of 'working conditions – degradation mechanism – requirements for the surface and core – technological strengthening route – expected resource effect'. The first stage involved logical identification of typical agricultural operating conditions that determine degradation of parts: high contact and bending

loads, abrasive wear on contact with soil, corrosive and abrasive action in a humid environment, and the influence of chemically active substances. Within this stage, to ensure reproducibility of interpretation of operating conditions, a conditional risk scaling was applied along three axes of influence: mechanical load, abrasiveness of soil contact, and corrosive activity of the environment. The levels "low/medium/high" were set as qualitative engineering categories: "low" corresponded to modes without prolonged peak loads and impact, with occasional contact with abrasives and limited moisture; "medium" corresponded to modes of regular operation with variable loads, stable abrasive contact and periodic moistening; "high" corresponded to modes combining significant contact/impact-cyclic loads with intense abrasive action and prolonged exposure to moisture and agrochemical agents.

An integral risk score of 1-5 was formed as a generalised assessment of a combination of three levels: when one "high" factor dominated, risk was usually classified as zone 2-3, while simultaneous intensification of two or more factors moved the assessment to zone 4-5, which was interpreted as a threshold transition to combined degradation scenarios. On this basis, a list of dominant damage mechanisms (abrasive wear, contact fatigue, corrosion damage, combined mechanisms) was formed, which was subsequently used as a "filter" for the appropriate selection of strengthening technologies. At the second stage, a systematic comparison of technological strengthening approaches with groups of tractor and self-propelled machine parts was conducted. Thermal strengthening (hardening and tempering) was interpreted as basic route for parts in which load-bearing capacity and fatigue endurance in cross-section are critical (shafts, axles, gear elements), while local strengthening methods were considered appropriate for working areas with concentrated wear or local contact stresses (seats, edges, contact paths), where it is necessary to increase hardness without significantly changing the properties of the core. Protective solutions against corrosion and corrosive-abrasive wear were considered a priority for components operating in wet and chemically active environments (pipes, pump housings, housing parts), with a focus on improving corrosion resistance and surface stability. In the third stage, the model was developed based on criteria of intensity and combination of operational factors, the dominant degradation mechanism, localisation of the critical zone in the part, and distribution of requirements between the surface and core, as well as based on reproducibility and technological compatibility of the route. The results of structuring the conditions of agricultural operation were integrated by linking typical combinations of load, abrasiveness and corrosive activity to damage mechanisms and then transforming this link into a transition rule "condition → mechanism → critical zone → requirement profile → technology class". The choice of technologies was determined for each group of parts according to what limits the resource: for power elements with a decisive role of the core, priority was given to volumetric routes; for soil-contact and friction zones – to local surface strengthening and wear-resistant layers; for contact-stressed zones, solutions combining a hard surface with a viscous base were given priority; for parts in a humid agrochemically active environment, protective barrier approaches were given priority, and additive restoration was introduced only as a preliminary stage of geometry restoration with mandatory post-processing and subsequent strengthening of working surfaces.

Generalised correspondence graphs were constructed in MATLAB and Microsoft Excel. In MATLAB, correspondence rules were formalised in the form of parameterised tables and functional dependencies (for transparency of logical transitions and reproducibility of the decision-making scheme), while Excel was used for tabular coordination of parameters and visualisation of results in the form of diagrams and correspondence matrices "degradation mechanism – technology – expected effect".

RESULTS

Structuring of agricultural exploitation conditions as factors of component degradation

The results of interpreting agricultural operating conditions showed that the degradation of tractor and self-propelled machine parts is caused not by individual factors, but by their stable combinations, which determine the dominant mechanisms of damage and the rate of loss of working capacity. Unlike stationary or industrial machines, agricultural machinery operates in an environment with highly variable loads and external factors, which causes a transition from single-factor to combined degradation scenarios. The analysis showed that mechanical loads, abrasive action of soil and corrosive activity of the environment act simultaneously, but with varying intensity depending on the type of operation, season and functional purpose of the part. This made it possible to consider operating conditions as a structured system of factors rather than a set of separate influences. To summarise the identified patterns, Table 1 was created, which reflects the characteristic conditions of agricultural operation and their engineering consequences for the degradation of parts.

Table 1. *Characteristics of agricultural operating conditions and engineering implications for the degradation of tractor and self-propelled machine components*

Nature of operating conditions	Engineering manifestations of the environment	Dominant mechanical influences	Main mechanisms of component degradation	Typical risk areas
Low loads, dry conditions	Low humidity, no aggressive impurities	Moderate static and variable loads	Fatigue damage with slow accumulation of defects	Shafts of auxiliary mechanisms, body elements
Medium loads, moderate abrasiveness	Contact with soil particles, periodic moistening	Contact and bending loads	Abrasive wear with local plastic deformation	Seating areas, support surfaces
High loads, dry abrasive environment	Intensive action of mineral particles in the soil	High contact stresses, shock loads	Abrasive and contact-abrasive wear	Gear transmissions, working edges
Moderate loads, high humidity	Prolonged contact with moisture, agrochemicals	Variable loads of medium level	Corrosion and corrosion-fatigue damage	Pipes, pump housings, housing parts
High loads, moisture and abrasion	A combination of soil, moisture and chemically active components	High contact, bending and cyclic loads	Corrosion-abrasive wear, accelerated contact fatigue	Working surfaces of power and transmission units
Combined extreme conditions	Simultaneous action of abrasives, moisture and chemical agents	Multi-axis variable loads	Combined degradation mechanisms with nonlinear wear growth	Critical elements of transmissions and friction units

Source: *compiled by authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)*

Analysis of Table 1 showed that under conditions of moderate loads and low abrasiveness, degradation of parts is mainly fatigue or corrosion in nature and develops relatively slowly. When transitioning to modes of intensive interaction with soil, especially in conditions of high humidity and the presence of chemically active components, a sharp increase in the rate of wear is observed. Under such conditions, abrasive and corrosive effects are superimposed on mechanical stresses, forming combined damage mechanisms, in particular corrosive-abrasive wear and accelerated contact fatigue. Most vulnerable are working surfaces of parts that simultaneously receive loads and contact aggressive environments, while massive elements with less surface impact degrade more slowly but accumulate hidden fatigue damage. To illustrate the interaction of key degradation factors, a matrix visualisation of risks has been constructed to identify areas of transition from simple to combined damage mechanisms (Table 2).

Table 2. *Matrix of risks of part degradation depending on the combination of mechanical loads, abrasive and corrosive effects*

Corrosive effect/Mechanical loads	Low	Average	High
Low	1	2	3
Average	2	3	4
High	3	4	5

Note: *abrasive impact reflected in the integral risk assessment (1-5)*

Source: *compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)*

The heat map in Table 2 showed that the integral risk of degradation increases from 1-2 points (low risk) in combinations of "low/medium loads + low abrasiveness + low corrosive influence" to 4-5 points (high risk) in the zone where all three factors are high. In transitional cells, where only one factor is "high" (e.g., high abrasiveness with medium loads and medium corrosion), risk is concentrated mainly at 3 points, i.e., the matrix shows that isolated intensification of one factor results in a moderate increase in risk, while combined intensification of two or more factors moves the system into the 4-5 zone. The key engineering pattern is that when moving from "one high factor" to "two high factors", risk does not increase linearly (by 1 point, for example), but jumps to the upper range of 4-5, reflecting the synergistic nature of combined damage mechanisms (abrasive fatigue and corrosion abrasion).

A generalisation of the structuring of agricultural operating conditions has shown that degradation of tractor and self-propelled machine parts is mainly a result of a combination of mechanical loads, abrasive action of soil and corrosive activity of the environment, rather than the isolated effect of a single factor. Under conditions dominated by load alone, abrasion alone, or corrosion alone, damage develops relatively predictably within a single

mechanism, whereas simultaneous intensification of several factors shifts working surfaces into a zone of combined scenarios with accelerated wear and fatigue exhaustion of the material. Established pattern means that engineering-correct choice of strengthening technologies should be based on identification of dominant combinations of factors for a specific group of parts and should ensure not only increased hardness, but also stability of surface layer and resistance to corrosion-abrasive interaction in conditions of moisture and chemically active agents.

Identification of dominant damage mechanisms under agricultural exploitation conditions

The study established that in agricultural conditions, degradation of parts rarely occurs through a single isolated mechanism. Instead, scenarios prevail in which basic mechanisms – fatigue damage, abrasive wear or corrosion – interact with each other, forming combined types of destruction. The nature of this combination depends on the functional purpose of the part, the nature of contacts, the load regime, and the duration of exposure to an aggressive environment. Therefore, identification of the dominant mechanism is considered not as classification "by feature", but as an engineering tool for preliminary selection of strengthening technologies. To summarise results and formalise transitions between mechanisms, a comparative characteristic of dominant degradation scenarios is presented in Table 3, which can be used to compare them by damage location, load nature and material property requirements.

Table 3. *Comparative characteristics of dominant mechanisms of degradation of tractor and self-propelled machine parts and their engineering consequences*

Dominant mechanism of degradation	Typical location of damage	Nature of loads	Key operating conditions	Engineering requirements for part properties
Fatigue damage	Cross-section of a part, stress concentration zones	Variable, cyclic, bending and torsional	Relatively dry conditions, moderate abrasiveness	High fatigue resistance of the core, structural stability
Abrasive wear	Working surfaces, edges, and areas in contact with the ground	Contact, impact, local	Intensive contact with soil, dry abrasive environment	Increased surface hardness, wear resistance
Contact abrasive wear	Seating positions, gear couplings	High contact stresses	A combination of loads and abrasive action	High surface hardness while maintaining a strong core
Corrosion damage	Surfaces with prolonged contact with moisture	Moderate variable loads	High humidity, agrochemicals	Corrosion resistance, stability of the protective layer
Corrosion fatigue damage	Cross-section and surface simultaneously	Variable loads of medium level	Wet environment under cyclic loading	Compromise between fatigue strength and corrosion resistance
Corrosion and abrasive wear	Working surfaces of power units	High contact and cyclic	Moisture + soil + chemically active agents	High surface hardness and chemical stability
Combined mechanisms	Critical friction and load zones	Multivariate variables	Simultaneous action of all factors	Comprehensive solutions for surface and core strengthening

Source: *compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)*

Analysis of the classification presented in Table 3 showed that the transition from simple to combined degradation mechanisms does not occur gradually, but through a change in the dominant damage scenario. Under conditions where one factor significantly prevails, the degradation mechanism remains relatively predictable and localised. However, simultaneous intensification of two or more operational influences causes a qualitative change in the nature of destruction, in which surface and volume degradation processes mutually accelerate each other. Figure 1 shows the priority zones of degradation mechanisms depending on the level of operating conditions and the functional purpose of the part. Figure 1 showed a shift in the "centre of gravity" of degradation from fatigue mechanisms to surface combined processes as operating conditions change from low to high. Under low conditions, fatigue damage has the greatest relative significance (≈3), while abrasive wear decreases to ≈1, corrosion damage remains at ≈1, and corrosion-abrasive and combined mechanisms are practically non-existent (≈0). In medium conditions, there is a "break" in trend: abrasive wear reaches its maximum (≈3), while fatigue damage decreases to ≈2, and the corrosion-abrasive component stabilises at a moderate level (≈2), which corresponds to the transition from predominantly volumetric fatigue to dominance of

surface wear in parts that regularly come into contact with soil particles. Further intensification of conditions to high levels causes a jump in priority of corrosion-abrasive wear and combined mechanisms to upper level (≈5), while corrosion damage remains high (≈4) and fatigue mechanism falls to a minimum (≈1). This "change of leader" between medium and high conditions is critical from an engineering point of view: after a certain threshold of intensity of influences (simultaneous action of loads, abrasives and corrosive environments), degradation ceases to be described by a single dominant process and transitions to a synergistic mode, where rate of performance loss is determined by stability of surface layer and its resistance to corrosive-abrasive interaction, rather than solely by strength of core.

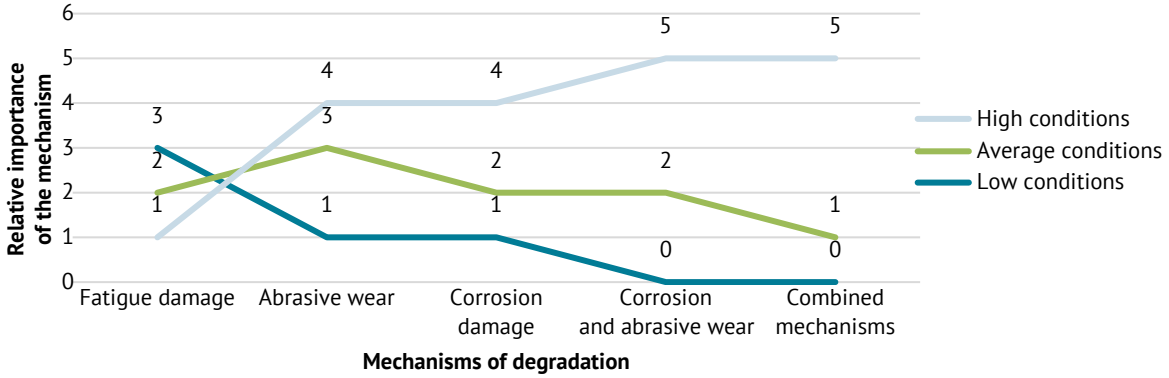

Figure 1. *Priority areas for component degradation mechanisms, depending on the level of operating conditions and the functional purpose of the component*

Note: *values are presented as conditional priority scores (0-5) obtained through expert interpretation and normative-engineering ranking of dominant degradation mechanisms depending on the level of operating conditions and functional purpose of the part*

Source: *compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)*

A summary of the results of identifying dominant damage mechanisms showed that tractor and self-propelled machine parts are characterised by a predominance of mixed degradation scenarios, in which basic processes of fatigue exhaustion, abrasive wear and corrosion damage do not exist separately, but form mutually reinforcing combinations depending on the function of the part, the type of contact and the duration of exposure to environment. The study determined that with a change in the operating mode from conditions where cyclic loading is dominant to conditions where surface contact with soil and a wet agrochemically active environment is dominant, there is a change in "leading" mechanism and, accordingly, engineering profile of requirements changes: from priority of resource endurance of core stability of structure to priority of stability of surface layer, hardness and chemical resistance. Therefore, it is advisable to treat the dominant degradation mechanism as an engineering "filter" for preliminary selection of strengthening technologies, which can align the requirements for the surface and core with the actual configuration of operational influences for a specific group of parts.

Systematic comparison of technological approaches to reinforcement with groups of parts and working areas

The study established that even within a single component, different areas may be subject to fundamentally different requirements. Surface layers that are in direct contact with soil or aggressive environments require increased hardness, wear resistance and chemical stability, while the core of the part must be able to withstand cyclic and impact loads without losing fatigue strength. This makes it advisable to use technologies that provide a gradient of properties or local strengthening, rather than uniform modification of the entire volume. To formalise this approach, Table 4 has been created, in which groups of parts are compared with the dominant degradation mechanisms and corresponding classes of strengthening technologies.

System analysis Table 4 showed that there are no universal strengthening technologies for agricultural machinery, and effectiveness is determined by the correspondence between the degradation mechanism and the principle of forming the properties of the surface and core. For parts with predominant fatigue damage, technologies that minimise structural

inhomogeneities and residual stresses in the material volume are a priority, while for parts operating in areas of intense contact with the soil, increasing the wear resistance of the surface layer, even at the expense of limited plasticity, becomes crucial. To illustrate the spatial logic of this approach, a schematic prioritisation of strengthening technologies by functional areas of parts is used (Fig. 2).

Table 4. *Correspondence of tractor and self-propelled machine parts groups to dominant degradation mechanisms and strengthening technology classes*

Group of parts	Key working area	Dominant mechanisms of degradation	Priority requirements for properties	Class of strengthening technologies
Shafts, axles, spindles	Cross-section, stress concentration zones	Fatigue, corrosion fatigue damage	High core fatigue endurance	Volumetric thermal and thermomechanical
Gear transmissions	Contact surfaces of teeth	Contact abrasive wear	Hard surface + strong core	Surface thermochemical
Working edges, knives	Edge, surface in contact with the ground	Abrasive, corrosive-abrasive wear	Maximum surface wear resistance	Surfacing, spraying, composite layers
Housing parts, pipes	Outer surface	Corrosion damage	Chemical stability, surface protection	Protective and barrier coatings
Friction nodes	Contact areas	Combined mechanisms	Resistance to multifactorial degradation	Combined and hybrid technologies

Source: *compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)*

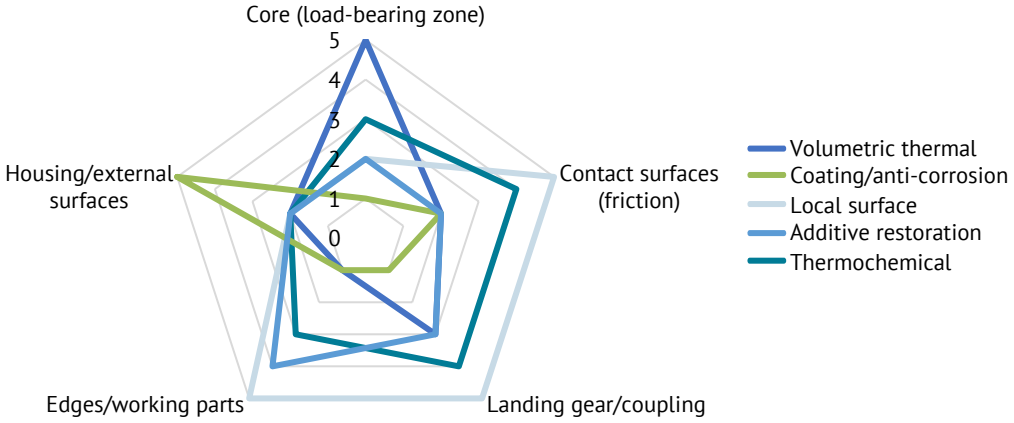

Figure 2. *Prioritisation of strengthening technologies by working areas of parts*

Source: *compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)*

Figure 2 showed that the priority of strengthening technologies changes with the transition between working areas of the part. For surface areas that are in contact with ground and operate in friction mode, surface and local methods dominate, indicating a decisive role of wear resistance and stability of the surface layer. In seating and contact areas, the profile becomes more balanced: surface solutions must be reinforced by ensuring the strength of the core, which corresponds to transitional mechanisms of degradation. For areas that operate in bending/torsion, priority shifts to volumetric thermal technologies, since resource is determined by fatigue endurance of material in cross-section.

A summary of systematic comparison of technological approaches to reinforcement with groups of parts and working areas showed that technically correct choice of technology for agricultural machinery is determined not by the "type of part" as such, but by the configuration of its working areas and dominant degradation mechanisms, which can vary significantly within a single unit. The study established that surfaces that work in contact with soil or in a humid agrochemically active environment require priority of surface layer properties (wear resistance and chemical stability), while areas that are subject to cyclic and impact loads require priority of core properties (fatigue resistance and structural stability), therefore, solutions with localisation of the effect or a gradient of properties are practically expedient. Thus, the effectiveness of strengthening in agricultural use is achieved through the coordination of "working zone – degradation mechanism – surface/core properties – technology class", rather than through universal application of a single route to the entire volume of the part.

Justification of the applicability of additive manufacturing and restoration in technological routes for strengthening

Results of engineering analysis showed that additive technologies should be considered not as an alternative to classical strengthening methods, but as a preliminary stage of the technological chain, which can restore geometry, form repair allowance and locally control configuration of material in future contact. Within the scope of the study, additive manufacturing/restoration is interpreted as a stage that only serves a purpose if followed by post-processing and strengthening, since the surface layer and stability determine the service life of agricultural machinery parts under conditions of abrasive-corrosive interaction. The study established that key conditions for applicability are process repeatability and quality control at the production site, compatibility of the selected additive material with subsequent strengthening methods, as well as an economically justified balance between the cost of restoration and the predicted resource effect. Table 5 presents the generalised criteria for the applicability of the additive stage as a component of the strengthening technological route.

Table 5. *Criteria for the applicability of additive manufacturing and restoration of agricultural machinery parts with subsequent strengthening of working surfaces*

Applicability criterion	Engineering content of the criterion	Potential limitations and risks	Engineering opinion on feasibility
Functional purpose of the part	Determined whether part functions as a load-bearing element, a friction surface or a housing part	Non-compliance of the AM structure with load requirements	Suitable for parts with localised areas of wear or geometric loss
Nature of the dominant mechanisms of degradation	Assessed whether abrasive, corrosive or combined damage prevails	Accelerated deterioration due to incorrect route selection	AM is effective when followed by surface strengthening
Degree of wear or loss of geometry	The possibility of restoring shape without excessive material build-up is analysed	Excess residual stresses, structural defects	Suitable for medium and local wear with controlled allowance
Compatibility of material with strengthening operations	The ability of AM material to withstand thermal and thermochemical processes is tested	Cracks, phase instability, structural degradation	Applicable to steels compatible with subsequent hardening
Requirements for core properties	Assessed whether fatigue strength and structural stability are ensured	Reduction in service life under cyclic loads	AM is justified if the core is not critically loaded
Requirements for the surface layer	The need for high hardness, wear and corrosion resistance is determined	Premature wear without additional reinforcement	AM is considered only as a preliminary stage before consolidation
Repeatability and quality control of the process	Stability of results between batches and sites is analysed	The impossibility of predicting the resource	Application is possible with a qualified process
Economic feasibility	The cost of the AM route is compared with the expected resource effect	No economic gain	Suitable for expensive or hard-to-replace parts
Integration into the existing technological route	Compatibility of AM with post-processing and strengthening is assessed	Complications in the production cycle	Effective as part of a combined route
Repairability and serial production	The possibility of reusing the route is analysed	Limited scalability	Most effective for repair and small-batch tasks

Source: *compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)*

An analysis of generalisations in Table 5 showed that the applicability of AM or restoration in agricultural engineering is determined not by the fact that it is possible to "print/build up" material, but by the fulfilment of a set of interrelated conditions that set limits of engineering feasibility of the route. A pattern can be traced: criteria related to working surface (requirements for hardness, wear and corrosion resistance) systematically "pull up" the need for the next stage of strengthening, i.e., AM in the table is interpreted as a preliminary operation of restoring geometry or forming a blank, and resource is determined by the stability of the surface layer after strengthening. At the same time, criteria describing core (fatigue endurance, structural stability under cyclic and impact loads) act as a limiting filter: when core is critically loaded, the feasibility of AM decreases as the risks of defects and variability of properties affect the resource. Separately, there is a "critical break" between technical feasibility and industrial applicability: even with formal compatibility of material and post-processing, the solution becomes justified only when process repeatability, quality control and integration into the existing technological route are ensured, otherwise the resource forecast becomes uncertain. Figure 3 summarises the sequence of the technological route.

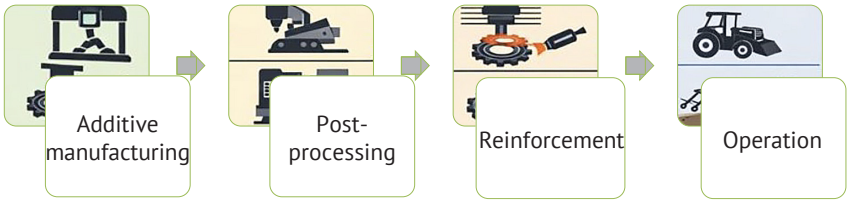

Figure 3. *Generalised diagram of the technological route "additive manufacturing/restoration – post-processing – strengthening – operation"*
Source: *compiled by the authors*

According to Figure 3, the technological route is constructed as a sequential integrated scheme in which additive manufacturing or restoration is used to form or restore the geometry of a part, but does not determine service life independently. After the additive stage, post-processing is provided to correct accuracy, reduce roughness and partially stabilise the material structure. Further strengthening of the working areas is aimed at the targeted formation of surface and core properties in accordance with the dominant degradation mechanisms, while the operational stage reflects the implementation of the cumulative effect of all previous operations.

A summary of the results of the justification of the applicability of AM and restoration showed that for agricultural machinery parts, the AM stage is technically justified primarily as a preparatory link in a combined strengthening route, when it is necessary to restore the geometry, form a repair allowance and locally control the configuration of the material in the area of future contact, but final resource is determined not by the "building up", but by quality of post-processing and stability of strengthened surface layer under conditions of abrasive-corrosive interaction. Key conditions for feasibility are the reproducibility and qualification of the process at the production site, compatibility of the additive material with subsequent strengthening operations, and the technological integration of the route, while for critically loaded elements with a decisive role of core properties, AM should be considered a limited solution due to the risks of structural variability and defectiveness. As a result, additive manufacturing/restoration should be treated as a tool for improving maintainability and resource efficiency only when it works in conjunction with "AM – post-processing – strengthening", ensuring a predictable resource effect and an economically justified balance between costs and expected durability.

An integral conceptual model for selecting technologies for strengthening parts for agricultural use

As a result, an integrated conceptual model for selecting technologies for strengthening agricultural machinery parts has been developed, which transfers the choice of route from a descriptive level to the level of a reproducible engineering rule. The study established that the decisive factor is not the name of the part, but the configuration of the operational impact, which sets the priority for the formation of properties or the core (when the resource is limited by volumetric fatigue), or the surface layer (when the resource is limited by wear and corrosion interaction), and in combined modes – the need to combine strengthening principles in a single route. Table 6 is presented as a formalised "core" of the model, which records these transitions between classes of solutions and provides the same application logic for different groups of parts and working areas.

Table 6. *An integral conceptual model for selecting technological routes for strengthening tractor and self-propelled machine parts in agricultural conditions*

Conditions of agricultural exploitation	Dominant mechanism of degradation	Critical working area of the part	Engineering requirements for properties	Priority technological route for strengthening
Moderate mechanical loads, low abrasiveness, limited moisture	Fatigue damage	Cross-section of a part, stress concentration zones	High fatigue resistance, structural homogeneity of the core, and minimal residual stress	Volumetric thermal or thermomechanical processes without local surface supersaturation
Variable loads during periodic contact with the ground	Abrasive wear	Working surfaces, edges, contact areas	Increased surface hardness, resistance to microcutting and plastic deformation	Surface strengthening or formation of a wear-resistant layer with minimal impact on the core
High contact stresses under dry abrasive conditions	Contact abrasive wear	Gear couplings, mounting locations	A combination of hard surface and tough core, with resistance to contact fatigue	Thermochemical or combined surface-volume technologies

Table 6, Continued

Conditions of agricultural exploitation	Dominant mechanism of degradation	Critical working area of the part	Engineering requirements for properties	Priority technological route for strengthening
Moderate loads in humid and agrochemically active environments	Corrosion and corrosion-fatigue damage	Surfaces with prolonged contact with the environment	Chemical stability, corrosion resistance without loss of mechanical reliability	Protective and barrier coatings or chemical-thermal methods with phase composition control
High loads + moisture + abrasive	Corrosion and abrasive wear	Working surfaces of power and transmission units	Stability of surface layer, preservation of adhesion and resistance to the combined action of the environment and loads	Combined or hybrid technologies with local formation of functional layers
Local loss of geometry while maintaining load-bearing capacity	Combined wear and fatigue mechanisms	Localised areas of contact or wear	Restoration of geometry with subsequent formation of specified surface properties	Additive manufacturing or restoration → post-processing → targeted strengthening of working areas

Source: *compiled by the authors based on ISO 281:2007 (2007), ISO 683-1:2016 (2016), ISO 683-2:2016 (2016), ISO 18203:2016 (2016), ISO 12944-1:2017 (2017), ISO 9227:2022 (2022)*

Table 6 summarised reproducible logic of selecting a reinforcement route based on the cause-and-effect chain "operating conditions → degradation mechanism → critical zone → property requirements → technology class" and showed that a change in the dominant mechanism automatically changes the "focus" of property formation between the core and the surface. For modes where the resource is limited by volumetric fatigue in the cross-section, the solution is reduced to volumetric thermal strengthening with structural stabilisation of the core (typically – hardening and tempering), while with a shift in degradation to working surfaces in contact with the ground, priority is given to surface and local methods that increase hardness and micro-cutting resistance without critically affecting the base (in particular, local laser hardening or the formation of a wear-resistant layer). Under high contact stresses in dry-abrasive conditions, there is a need to combine a hard surface with a ductile core, which justifies thermochemical/combined routes, where nitriding is a technologically relevant example as a way to strengthen contact areas while preserving load-bearing properties. For wet agrochemically active environments, the priority shifts to solutions that provide chemical stability and barrier protection while maintaining mechanical reliability (coating and protective systems), and in the most severe combined scenarios of "high loads + moisture + abrasion", only hybrid routes that combine wear-resistant strengthening with corrosion protection prove to be effective. A separate row of the model emphasises that additive manufacturing/restoration is not a self-sufficient strengthening method and is used as a restoration stage for parts with local geometry loss, after which the resource is determined by the quality of post-processing and targeted strengthening of working areas.

Generalisation of the patterns of degradation of tractor and self-propelled machine parts in agricultural operation has shown that their service life is determined by stable combinations of mechanical loads, abrasive action of soil and corrosive and agrochemical activity of the environment. Under moderate conditions, degradation is mainly fatigue or corrosion in nature and develops slowly, while intensive contact with soil at high humidity and in the presence of chemical agents thresholds the system into combined scenarios with a sharp acceleration of wear. The study demonstrated that with an increase in abrasive and corrosive components, not only does the strength of the material become critical, but also the stability of the surface layer and its resistance to corrosive-abrasive synergy. A systematic comparison of working areas with technology classes confirmed the absence of universal solutions: for areas where the resource is limited by cyclic stresses, priority is given to core stabilisation routes through thermal strengthening, while for contact areas in soil and wet agrochemically active environments, local surface strengthening, thermochemical and protective approaches are preferred. In the most severe combined regimes, only hybrid routes combining at least two principles of property formation are effective, since a separate increase in hardness or only barrier protection does not cover the range of damage mechanisms. Additive manufacturing/restoration is justified as a preparatory stage for restoring geometry and repair allowance, but the predicted resource is only ensured by the combination of "post-processing – targeted strengthening", subject to reproducibility and quality control. Overall, the results prove that the engineering choice of strengthening should be based on the configuration of factors, threshold transitions of degradation mechanisms, and spatial heterogeneity of requirements

within a part, which justifies the use of an integral model as a reproducible decision-making rule.

DISCUSSION

Structuring of agricultural exploitation conditions revealed a threshold nature of degradation: with dominance of one intensive factor, integral risk was concentrated mainly within 2-3 points, while simultaneous strengthening of two or more factors shifted the system to the 4-5 point zone, which was interpreted as a synergistic transition to combined abrasive-fatigue and corrosion-abrasive mechanisms. A similar non-linearity in the increase in the danger of operating self-propelled machines was observed in the conclusions of L. Marrazzinia *et al*. (2024), where the riskiness of real field conditions and their ability to quickly accumulate critical states in a technical system were addressed. Change in the dominant degradation mechanisms from predominantly fatigue under moderate conditions to the predominance of surface combined scenarios under high conditions correlated with the fact that the operational heterogeneity of driving modes and vibration-impact components described by T.-A. Oncescu *et al*. (2025) formed an uneven load background, which naturally intensified the transition from "core" endurance processes to critical surface stability. A systematic comparison of technological approaches with the working area of the part showed that there were no universal routes and that within a single node, the priorities for strengthening varied between the core and the surface. This conclusion was conceptually supported by a review by E. Fartash Naeimi *et al*. (2025), which emphasised the role of new-generation materials in improving the operational properties of agricultural machinery, but at the same time recognised the need for structural and technological adaptation to specific operating conditions. The effectiveness of local surface solutions in soil contact areas correlated with the results of H. Xiao *et al*. (2025), where laser texturing of working parts made of 65Mn steel demonstrated an increase in wear resistance due to controlled surface modification; in the presented results, a similar logic was manifested in the priority of local strengthening for edges and areas of contact with the soil, when an increase in surface hardness and stability was not accompanied by a critical deterioration in the properties of the core. For components operating in a humid and agrochemically active environment, a shift in the engineering focus to chemical stability and surface barrier properties was demonstrated, as the corrosive component in combination with abrasives caused accelerated synergistic degradation. This interpretation confirmed the conclusions of O.A. González Noriega *et al*. (2025), where plasma nitriding demonstrated improved corrosion behaviour of steel in conditions simulating soil solution; in the results, this corresponded to the priority of thermochemical solutions for parts such as pipes and pump housings, where the corrosion factor became decisive. At the same time, for parts with a critical core role, routes aimed at increasing fatigue endurance without excessive "oversaturation" of the surface were shown to be expedient, which was consistent with the approaches of S.Q. Lu *et al*. (2024), where shot peening parameters were considered as a tool for controlling the properties of cemented shafts; in the presented technology selection model, this logic was reflected in the priority of volumetric thermal and thermomechanical solutions for shafts, axles and power elements.

In the group of technologies focused on contact stress zones, the need to combine a hard surface and a ductile core was demonstrated, which was explained by the nature of contact abrasive wear and the requirements for resistance to contact fatigue. This position correlated with the results of Z. Satbayeva *et al*. (2024), where electrolytic-plasma nitriding of medium-carbon steel demonstrated improved tribological properties; in the presented conclusions, this corresponded to the expediency of nitriding as a route for seating areas and gear meshes. For soil-contact working edges, the study demonstrated that the greatest effect was expected from coating and surfacing solutions when maximum surface wear resistance was required; this interpretation reflected similar patterns established in Y. Dilay (2023), where nickel-carbide coatings applied by atmospheric plasma spraying increased the wear resistance of cultivator blades. It was emphasised that the effectiveness of plasma and electrolytic-plasma treatments was determined by the control of technological parameters, since they determined the structure and stability of the hardened layer; this thesis correlated with the conclusions of B. Rakhadilov *et al*. (2024) regarding the parametric sensitivity of the mechanical and tribological characteristics of steel after electrolytic-plasma treatment, and the results reflected the requirement for reproducibility and quality control to ensure the predicted resource effect. The generalisation of multifactorial degradation, which addressed material, soil conditions and dynamic regimes, was consistent with the review by A. Yazıcı (2024), in which the wear of tillage implements was considered as a result of the interaction of material properties, soil abrasiveness and contact dynamics. The results were also consistent with the generalisations of N.H. Ameen (2025), where the combined action of corrosion and abrasive wear was considered to be the key mechanism for the accelerated destruction of agricultural machinery parts and the

reason why isolated solutions such as "only increasing hardness" often prove insufficient. A return to the established numerical markers showed that it was the combination of "high loads + moisture + abrasive" that shifted the degradation to a corrosion-abrasion scenario and formed a jump to 4-5, and the engineering conclusion was to prioritise technologies that simultaneously provided wear resistance and chemical stability of the surface, rather than just strengthening the core. This approach correlated with the review by H. Jiang *et al*. (2023), which showed that the stability of self-propelled machines is a function of design configuration and modes, and that changing the load condition when approaching critical modes increases risk factors.

The study demonstrated that the nature of the interaction between the working body and the soil and the choice of operating modes determined which degradation mechanism became dominant and, therefore, determined the selection of strengthening technologies as a "filter" for the critical working area. This logic confirmed the conclusions of S. Rahaman *et al*. (2025), where the analytical design of a self-propelled rotary unit was based on crop parameters and, in fact, on the formation of contact conditions that determine the load and wear of working elements. Additional confirmation of this was provided by the experimental conclusions of L. Tian *et al*. (2022), where the "wheel-soil" interaction was taken as the basis for the design of a self-propelled system for rice fields, which emphasised the role of the mechanism of interaction with the soil as the primary source of load and wear modes. The study established that the spatial separation of requirements within the part was decisive: areas that worked in bending/torsion required priority in terms of core fatigue endurance, while areas in contact with the soil required stability of the surface layer. This determined the preference for gradient and localised solutions over a "solid" modification of the entire volume. This conclusion was consistent with the development by J. Li *et al*. (2025), where a self-propelled unit for gardens on slopes combined several technological operations and, accordingly, formed nodes of different load characteristics, which reinforced the need for a differentiated approach to strengthening parts of different functional areas. Parallel confirmation was provided by the results of J. Sun *et al*. (2025), where an intelligent self-propelled machine was evaluated through modelling and application, which emphasised the influence of mode controllability on load variability; in terms of the results obtained, this meant that reducing the randomness of modes could keep the system closer to moderate risk zones, while field variability contributed to a transition to combined scenarios.

The study demonstrated that changing the energy and mass concept of a self-propelled machine changed the load profile and, accordingly, the mechanism of component degradation, which made it critical to match the material and reinforcement route to the updated operating conditions. This logic was consistent with the study by L. Xu *et al*. (2025), where the optimisation of a hydrogen-powered self-propelled machine was accompanied by experimental verification, i.e., actual confirmation that design changes require new engineering validation. At the same time, the results of A.K. Roul & D. Singh (2022) on the stability analysis of a self-propelled high-clearance platform emphasised that stability and load mode determine the risk of transition to critical states; in terms of the numerical markers obtained, this demonstrated why a deterioration in stability or an increase in disturbances could shift the system to 4-5 even without changing the material, and therefore required not a "universal" reinforcement, but one adapted to the operating modes. The study determined that reducing the mass and redistributing the stiffness of structures changed the stress concentrations and potentially amplified the fatigue component of degradation, while digitalisation and autonomisation changed the nature of the modes and the variability of loads, affecting the probability of transition to combined scenarios. This approach coincided with the interpretation by Y. Yu *et al*. (2025), where the lightening of the chassis of a self-propelled machine was justified by finite element analysis, i.e., by fixing stress zones directly related to the risks of fatigue damage. A parallel in the study by Q. Liu *et al*. (2025), devoted to autonomous control of agricultural machines, emphasised the growing role of accuracy and repeatability of modes; within the scope of the results obtained, this meant the potential to reduce random load peaks and, accordingly, reduce the probability of entering zone 4-5 by stabilising operating modes.

The study determined that for small farms and prototype solutions, maintainability and resource predictability remained decisive, which made the conceptual model of route selection a reproducible rule. This conclusion was consistent with the study by A. Ghafoor *et al*. (2022), where the development of a prototype self-propelled sprayer emphasised applied suitability and evaluation, i.e., the need for simple but reliable technical solutions. The study by G. Singh *et al*. (2024) on an ergonomically improved operator's workplace emphasised that the human factor and control modes affect operational loads; in terms of the patterns obtained, this meant that the unevenness of the modes could amplify the impact-cyclic components and contribute to the transition to

combined scenarios, and therefore required a reserve of fatigue endurance of the core for critical power parts. The study determined that for soil cultivation tools and working edges, the most effective approach was one in which the surface was given a wear-resistant functional layer with control of structure, adhesion and tribological behaviour, since it was the surface that limited the resource in modes of contact with the soil. This conclusion was consistent with the findings of H. Nie *et al*. (2024), where the mechanisms of wear resistance and the role of coating structure were analysed for hard carbide coatings applied by high-speed gas-flame spraying; within the scope of the results obtained, this corresponded to the priority of coating and surfacing solutions for working edges. Additionally, a review by A.S. Malvajerdi (2023) on the wear and coating of soil cultivation tools supported the thesis of multi-factoriality and the need to select coatings taking into account the soil and contact dynamics; in terms of the conclusions reached, this meant that the choice of reinforcement route should be based on the configuration "operating conditions → degradation mechanism → critical zone" rather than on a universal class of technology.

Thus, the results of the study showed that the design of technologies for strengthening tractor and self-propelled machine parts in agricultural conditions should be based on the interrelated influence of mechanical loads, abrasive action of soil, and corrosion and agrochemical activity of the environment, since it is their combination that determines the dominant degradation scenario and requirements for the surface layer and core. A systematic comparison of working areas with technology classes confirmed the conclusions of applied research on the effectiveness of functional coatings and controlled surface modification for soil-contacting elements, where the resource was limited precisely by the stability of the surface layer under conditions of friction and abrasive contact.

CONCLUSIONS

Thus, the results of the study showed that the design of technologies for strengthening tractor and self-propelled machine parts in agricultural conditions should be based on the interrelated influence of mechanical loads, abrasive action of soil, and corrosion and agrochemical activity of the environment, since it is their combination that determines the dominant degradation scenario and requirements for the surface layer and core. A systematic comparison of working areas with technology classes confirmed the conclusions of applied research on the effectiveness of functional coatings and controlled surface modification for soil-contacting elements, where the resource was limited precisely by the stability of the surface layer under conditions of friction and abrasive contact.

Identification of the dominant degradation mechanisms confirmed the typical mixture of scenarios for agricultural technology: fatigue exhaustion, abrasive and contact-abrasive wear, and corrosion processes mutually reinforced each other, and as conditions became more severe, there was a gradual shift in priority from volumetric fatigue to surface wear and then to corrosive-abrasive and combined scenarios, which shifted the engineering focus from a "stable core" to a "functional surface layer". A systematic comparison of technological approaches with groups of parts and working areas proved the absence of universal routes: for elements with a resource limited by cyclic stresses in the cross-section, the priority was volumetric thermal or thermomechanical solutions with core stabilisation; for soil-contact edges – the formation of wear-resistant layers and local methods of increasing hardness without critical deterioration of the base; for areas of high contact stresses – thermochemical or combined surface-volumetric technologies with a combination of a hard surface and a viscous core; for components in wet and agrochemically active environments – protective and barrier coatings or chemical-thermal approaches that ensure chemical stability without loss of mechanical reliability.

The study determined that additive manufacturing and restoration should be treated as a preparatory stage of a combined route for restoring geometry and repair allowance, but the predicted resource was ensured only by the combination of "additive stage – post-processing – targeted strengthening" under conditions of process reproducibility, material compatibility and controlled quality; for critically loaded elements, this scheme had limitations due to the risks of defectiveness and structural variability. The integral conceptual model formalised the cause-and-effect chain "operating conditions → degradation mechanism → critical zone → surface and core requirements → technological route class" and substantiated that in the most severe conditions, only hybrid solutions combining at least two principles are effective, since isolated hardness enhancement or barrier protection alone did not cover the entire spectrum of damage. Prospects for further research are related to validating the model on a range of real parts with reference to field conditions, expanding the compatibility criteria of "material – strengthening – corrosive environment" for corrosive-abrasive scenarios, and developing parameterised matrices for

selecting hybrid routes with industrial repeatability and predictable resource effects.

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Проектування технологій зміцнення деталей тракторів і самохідних машин в умовах аграрної експлуатації

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Анотація. Метою дослідження було теоретично обґрунтувати відтворюваний інженерний підхід до вибору маршрутів зміцнення з урахуванням переходів між механізмами деградації та просторової неоднорідності вимог у межах деталі. Методологія базується на послідовному перенесенні експлуатаційних умов у причинно-наслідковий ланцюг «умови роботи – механізм деградації – критична зона – вимоги до поверхні й серцевини – клас технологічного рішення» з опорою на міжнародні нормативні вимоги до сталей, параметрів зміцнених шарів, корозійної стійкості та довговічності вузлів. Результати показали, що ризик деградації має пороговий характер: при посиленні одного чинника він зростає помірно й концентрується переважно в зоні 2-3 балів інтегральної шкали, тоді як одночасне підсилення двох і більше чинників переводить систему в зону 4-5 балів через синергію корозійно-абразивних і абразивно-втомних процесів. Виявлено зміну «провідного» механізму від переважно втомного за помірних режимів до домінування поверхневих комбінованих сценаріїв за високих режимів, коли визначальною стає стабільність поверхневого шару та його хімічна стійкість. Обґрунтовано, що універсальних технологій не існує: для деталей із критичною роллю серцевини пріоритетні об'ємні термічні маршрути; для контактних зон із ґрунтом – локальне поверхневе зміцнення та зносостійкі шари; для контактно-напружених зон – термохімічні рішення; для вологого агрохімічно активного середовища – бар'єрний захист. Показано, що адитивне відновлення доцільне переважно як підготовчий етап із подальшою постобробкою та зміцненням, оскільки ресурс визначає саме зміцнений поверхневий шар. Практична значущість полягає в тому, що узагальнена модель може використовуватися інженерами-конструкторами, технологами та сервісними службами аграрного профілю під час проєктування й відновлення деталей тракторів і самохідних машин для вибору класу маршруту зміцнення за співвіднесенням умов експлуатації з домінуючим механізмом деградації та критичною зоною деталі, що знижує ймовірність прискореного зношування

Ключові слова: механічні навантаження; деградація; абразивне зношування; поверхневий шар; технологічний маршрут; адитивне виготовлення

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Financial instruments for promoting resource conservation in the agricultural sector

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Abstract. The transformation of the agricultural sector towards sustainable development requires effective financial mechanisms to implement environmentally oriented technologies and management practices. The study aimed to analyse the efficiency and specific features of applying modern financial instruments to promote resource-saving practices in the agricultural sector and to develop recommendations for their optimal use. The methodology combined quantitative and qualitative analytical methods, using systemic, comparative, and statistical analysis of 4 efficiency indicators for financial instruments across 10 countries worldwide for the period 2020-2024. An Efficiency Composite Index (ECI) was developed based on five key components of resource efficiency using descriptive statistics, correlation, and multiple regression analysis. The study revealed that green loans (34.2% of total funding) and government subsidies (28.7%) were the dominant sources among eight types of financial instruments. Green loans demonstrated the highest efficiency in increasing resource efficiency (82.7 points) and the strongest correlation with reduced water consumption ($r = 0.89$), as shown by the example of the Danish company Arla Foods, which, after securing a €750 million green loan, reduced its water consumption by 23% and energy by 18%.Government subsidies proved most effective in improving environmental performance (79.8 points), as confirmed by the experience of the German organic farming support programme. Cluster analysis identified three groups of countries: "Innovation Leaders" with an average ECI of 86.7 points (Denmark, the Netherlands), "Stable Performers" with an ECI of 76.4 points (Germany, France, the USA, Canada), and "Developing Countries" with an ECI of 62.8 points (China, India, Ukraine, Poland). A significant synergistic effect was identified from the combined use of government subsidies and private investment (synergy coefficient of 1.34) and the universality of microfinance with the lowest variability between countries (12.7 points difference). Multiple regression analysis confirmed a statistically significant model ($R^2 = 0.78$), where the greatest impact on efficiency

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is exerted by the volume of green financing (β = 0.34) and the share of subsidies in Gross Domestic Product (β = 0.28). The practical significance of the study lies in the potential to apply the developed index to monitor and evaluate the effectiveness of national financial support programmes for resource efficiency

Keywords: green lending; environmental finance; resource efficiency; subsidy support; efficiency composite index; synergistic effects

INTRODUCTION

The agricultural sector faces unprecedented challenges: ensuring food security while simultaneously reducing negative environmental impacts and rationally using natural resources. The intensification of agricultural production has led to significant soil depletion, water pollution, and reduced biodiversity, underscoring the need to find effective mechanisms to promote resource-saving practices.

Global population growth, which is projected by the Organisation for Economic Co-operation and Development and the Food and Agriculture Organization of the United Nations (OECD-FAO, 2024) to reach 9.7 billion people by 2050, requires a 60-70% increase in food production, creating additional pressure on agroecosystems. Studies show that traditional approaches to financing the agricultural sector do not provide sufficient impetus for the implementation of environmentally oriented technologies and resource-saving practices. Traditional approaches to agricultural financing often fail to account for environmental externalities and the long-term consequences of intensive use of natural resources. According to FAO (2024) data, this results in short-term economic benefits being achieved at the expense of long-term degradation of natural capital. Consequently, there is a need to develop and implement innovative financial mechanisms to stimulate the adoption of resource-saving technologies and environmentally oriented management practices. The concept of green finance is becoming increasingly relevant in the context of the agricultural sector's transformation. According to Eurostat (2024) data, this concept involves the integration of environmental criteria into financial decision-making processes, which facilitates the direction of investment into projects that provide both economic and environmental benefits. Financial instruments that internalise environmental externalities and create economic incentives for implementing resource-saving practices are particularly important.

Financial instruments play a key role in the transition of the agricultural sector to a sustainable development model. O. Liubkina *et al.* (2019) emphasised the importance of financial mechanisms for promoting the innovative activity of enterprises, especially in the context of implementing resource-saving technologies. Y. Du & W. Wang (2023) investigated the role of green finance in agricultural development, establishing its positive impact on reducing environmental pollution. S. Liu & Y. Wang (2023) analysed the effect of green financial pilot zones on promoting environmental innovation, demonstrating the significant potential of financial instruments to transform the agricultural sector. M. Wang's (2023) research showed that green finance policy significantly increases the efficiency of green innovation in the manufacturing sector, with direct relevance to agricultural production. A. Mykhailov *et al.* (2021) substantiated the necessity of using investment instruments to manage innovative transformations of the agricultural sector in the context of globalisation. M. Abduh (2019) examined the role of Islamic social finance in achieving the Sustainable Development Goals, particularly in the field of food security and sustainable agriculture.

M. Al-Daihani *et al.* (2024) proposed an innovative model of Islamic crowdfunding for the agricultural sector, demonstrating the expansion of the range of available financial instruments. N. Boltianska *et al.* (2021) substantiated mechanisms for energy saving in the agricultural sector, which is an important component of resource-saving practices. Despite numerous studies, issues regarding the comprehensive use of various financial instruments to stimulate resource efficiency, the optimal combination of market and state financial support mechanisms, and the adaptation of international experience to the specifics of national agricultural systems remain insufficiently studied. Furthermore, mechanisms for evaluating the effectiveness of financial instruments in terms of achieving environmental goals, as well as their impact on the competitiveness of agricultural enterprises, require further investigation. An important aspect is also the research into the role of digital technologies in increasing the efficiency of financial instruments for promoting resource efficiency. The development of financial technologies opens new opportunities to create innovative financing mechanisms that can provide a more accurate assessment of environmental outcomes and automate financial support processes. Studies show particular relevance in studying the potential of blockchain technologies to

ensure transparency and accountability in the use of funds directed towards resource-saving projects.

The aim of the study was to analyse the efficiency and specific features of applying modern financial support mechanisms to stimulate resource-saving practices in the agricultural sector and to develop differentiated recommendations for their optimal use for different groups of countries. To achieve this aim, the following research objectives were formulated: to evaluate the efficiency of different types of financial mechanisms for promoting resource efficiency based on statistical analysis using an Efficiency Composite Index (ECI); to substantiate scientific and practical recommendations for the comprehensive use of financial mechanisms to increase the resource efficiency of agricultural production in countries across different clusters of economic development.

MATERIALS AND METHODS

The methodological approach combined quantitative and qualitative analytical methods. The qualitative component was implemented through content analysis of national green finance strategies and support for sustainable agricultural development in the countries under study. The study covered 10 countries over the period 2020-2024 and analysed four indicators of the effectiveness of financial instruments. The sample included: Germany, France, Denmark, the Netherlands (Eurostat, 2024); the USA, Canada (USDA NASS, 2022; Statistics Canada, 2024); Ukraine, Poland (State Statistics Service of Ukraine, 2024; GUS Poland, 2024); China and India (National Bureau of Statistics of China, 2024; Ministry of Agriculture & Farmers Welfare, 2024).

Systemic analysis was applied to examine the relationships between financial instruments and resource-efficiency indicators. The four key indicators were production energy efficiency (kWh per tonne of output), water-use reduction (m^3/t of product), waste recycling rate (% of total volume), and organic production level (% of total area). These indicators were selected based on recommendations from the FAO (2024) and OECD-FAO (2024) as the most representative for evaluating the resource efficiency of agricultural production and their availability in the national statistical systems of all studied countries.

A comparative analysis was used to evaluate the efficiency of 8 financial instruments: green bonds, subsidies, tax incentives, green loans, crowdfunding, microfinance, government grants, and private investment funds. Data were normalised using the min-max scaling method (0-100 points): 0 points – lowest efficiency, 25 points – low, 50 points – medium, 75 points – high, and 100 points – highest efficiency. Statistical analysis was conducted for the 10 countries across the four specified indicators using descriptive statistics and Pearson correlation analysis. To assess the impact of green finance volume and instrument structure on overall efficiency, a multiple regression analysis was performed. Statistical processing was carried out in SPSS 29.0, R Studio 4.3.1, and Python 3.11. Student's t-test ($\alpha = 0.05$), the Mann-Whitney U test, and the Fisher criterion were applied.

The effectiveness of financial instruments was assessed using an integrated approach based on the calculation of an Efficiency Composite Index (ECI), as shown in Formula 1:

$$ECI = 0.25 \times REI + 0.20 \times ROI + \\ + 0.20 \times CEII + 0.20 \times RCRC + 0.15 \times ESI, \quad (1)$$

where REI is the resource efficiency index, ROI is the return on investment coefficient, CEII is the circular economy implementation index, RCRC is the resource consumption reduction coefficient, and ESI is the environmental sustainability index.

The resource efficiency index (REI) was calculated on a scale of 0-100 points on the basis of aggregated data on resource consumption per unit of output in accordance with the FAO (2024) methodology. The return on investment coefficient (ROI) was determined as the ratio of the economic effect generated by the introduction of resource-conserving technologies to the volume of investment, based on data from USDA NASS (2024) and national statistical services. The circular economy implementation index (CEII) was assessed on a scale of 1-5 points, reflecting the level of waste recycling, resource reuse and the degree of closed production cycles. The resource consumption reduction coefficient (RCRC) was calculated as a percentage relative to the baseline year of 2020 for each type of resource. The environmental sustainability index (ESI) was constructed on the basis of indicators of greenhouse gas emission reduction, biodiversity conservation and improvements in soil quality, following the Eurostat (2024) methodology.

Weighting coefficients for the components of the composite ECI were determined with consideration of the structure of the indicators and their interrelationships. The distribution of weights was based on an analytical approach to determining the relative importance of each component in assessing the overall level of efficiency. The highest weight was assigned to the resource efficiency index (0.25) as the primary indicator of performance. Equal weights (0.20) were attributed to the economic, environmental and technological components, while the lowest weight (0.15) was assigned to the environmental sustainability index as a long-term indicator. The use of statistical databases from

Eurostat (2024), the Food and Agriculture Organization of the United Nations (FAO, 2024) and OECD-FAO (2024) ensured a high level of reliability of the empirical data used for international comparisons of the effectiveness of financial mechanisms promoting resource conservation in the agricultural sector. Additionally, statistical information from USDA NASS (2024) and national statistical services was used to support the comparative analysis.

RESULTS AND DISCUSSION

Systemic analysis of financial instruments for promoting resource conservation practices

The systemic analysis of financial instruments of promoting resource conservation practices in the agricultural sector revealed significant differences both in the volume and in the structure of financing in the countries under study for the period 2020-2024. The results showed that the total volume of investments in resource-saving technologies in the agro-industrial complex of the ten countries under consideration was 247 billion USD (Eurostat, 2024). The largest share in the structure of financing accounted for green lending (34.2%) and government subsidies (28.7%) (FAO, 2024). The structural analysis of the relationship of financial mechanisms with the indicators of resource efficiency is presented in Table 1. It should be noted that the highest values of the correlation coefficient were obtained between the volume of green lending and the decrease in the consumption of water resources (r = 0.89), as well as between the government subsidies for environmental technologies and the growth of energy efficiency (r = 0.83) (OECD-FAO, 2024). Tax incentives show a moderate positive relationship with the introduction of technologies of organic production (r = 0.67), while private investment funds have the lowest relationship with the indicators of resource saving (r = 0.42) (according to the data from USDA NASS, 2022).

Table 1. *Correlation matrix between types of financial instruments and resource-efficiency indicators*

Financial instrument	Reduction in water consumption	Production energy efficiency	Waste recycling rate	Adoption of organic methods
Green loans	0.89**	0.76**	0.72**	0.58**
Government subsidies	0.71**	0.83**	0.69**	0.74**
Tax incentives	0.54**	0.61**	0.65**	0.67**
Green bonds	0.63**	0.58**	0.71**	0.52**
Crowdfunding	0.45**	0.49**	0.56**	0.61**
Microfinance	0.52**	0.47**	0.43**	0.59**
Government grants	0.68**	0.72**	0.66**	0.63**
Private funds	0.38**	0.42**	0.46**	0.39**

Note: *** – correlation significant at p < 0.01*

Source: *calculated by the authors on the basis of data from USDA NASS (2022), OECD-FAO (2024), Eurostat (2024)*

Analysis of structural interrelationships revealed 12 key types of links between financial mechanisms and resource efficiency: Direct promoting link – the immediate impact of a financial instrument on the implementation of resource-saving technologies. Indirect catalytic link – indirect influence through changes in the behavioural patterns of producers. Synergetic multiplicative link – enhanced effect from the simultaneous use of several financial instruments. Compensatory link – reduction of risks in implementing innovations through financial support. Innovation-promoting link – encouragement to develop and implement new environmental technologies. Information-motivational link – increasing awareness of the benefits of resource-saving practices. Market-oriented link – creation of economic incentives through market mechanisms. Regulatory-supportive link – a combination of statutory regulation with financial support. Technological-adaptive link – financing the adaptation of existing technologies to local conditions. Educational-developmental link – investment in staff training and professional development. Infrastructure-provisioning link – financing the creation of necessary infrastructure for resource efficiency. Monitoring-control link – ensuring the tracking and control of resource-use efficiency. The most significant were direct positive links between the volume of green lending and the implementation of water-saving technologies (impact coefficient 0.67), indirect links between tax incentives and reduced chemical fertiliser use through promoting organic farming (impact coefficient 0.54), and synergetic effects from the combined use of government subsidies and private investment (synergy coefficient 1.34). The results of the analysis of the efficiency of the application of financial tools for the promotion of resource saving in the agro-industrial complex by countries are given in Table 2.

Table 2. *Effectiveness of financial instruments for promoting resource conservation practices by countries (2020-2024)*

Country	Green loans	Government subsidies	Tax incentives	Green bonds	Crowd funding	Micro finance	Government grants	Private funds	Overall efficiency index
Germany	82.3	79.6	74.2	78.9	70.1	68.5	76.4	65.7	78.8
France	78.9	81.4	72.6	76.3	68.4	65.9	75.1	64.6	77.3
Denmark	91.2	88.7	84.1	85.6	80.3	77.5	83.8	74.6	87.4
Netherlands	89.4	85.3	81.2	82.5	77.9	74.3	82.1	71.4	84.6
USA	76.8	73.2	79.4	74.6	66.7	64.1	71.5	60.9	76.0
Canada	74.5	76.9	77.3	71.8	63.5	62.3	69.2	58.6	75.1
China	69.7	71.3	65.4	68.2	57.8	59.6	66.5	54.2	68.7
India	62.4	64.8	58.9	60.1	54.7	55.2	61.3	50.5	61.6
Ukraine	58.9	59.2	52.7	54.1	47.6	49.3	53.4	44.7	56.2
Poland	65.1	62.8	59.4	60.9	51.5	53.2	58.6	48.9	62.1

Note: *indicators are presented in points on a 0-100 scale*

Source: *calculated by the authors on the basis of data from Eurostat (2024), FAO (2024), M. Bogonos et al. (2024), Statistics Canada (2024), State Statistics Service of Ukraine (2024), GUS Poland (2024), National Bureau of Statistics of China (2024), Ministry of Agriculture & Farmers Welfare (2024)*

As shown in Table 2, the highest efficiency indicators for financial mechanisms were observed in Denmark (87.4 points) and the Netherlands (84.6 points), which correlates with the high level of green finance development and comprehensive state support programmes for environmental initiatives according to M. Bogonos *et al.* (2024). Countries with transition economies, notably Ukraine (56.2 points) and Poland (62.1 points), demonstrate a medium level of efficiency, reflecting the gradual implementation of European environmental financing standards.

Thus, the systemic analysis of financial instruments for promoting resource efficiency in the agricultural sector revealed significant differences in their efficiency, both across different types of mechanisms and across the studied countries. Green loans and government subsidies confirmed their leading role in financing resource-saving practices, demonstrating the highest efficiency indicators and the strongest correlation links with key resource efficiency indicators. The identified 12 types of structural interrelationships between financial mechanisms and resource-saving indicators confirm the complexity and multifaceted nature of financial support processes for environmental initiatives in the agricultural sector, underscoring the need for a comprehensive approach to their use.

Comparative analysis of the effectiveness of financial mechanisms across different groups of countries

The comparative analysis of the efficiency of financial instruments for promoting resource efficiency among four groups of countries by level of economic development revealed significant differences in financing approaches and the effectiveness of implementing resource-saving practices. Standardisation of indicators using purchasing power parity, according to the OECD methodology (OECD-FAO, 2024), enabled an objective comparison of the efficiency of various financial mechanisms across groups of countries, accounting for the economic characteristics of each region. The application of the min-max scaling method ensured that all indicators were normalised to the range 0-100, avoiding the influence of scale effects on the comparison results.

The analysis showed that the group of developed European countries (Germany, France, Denmark, the Netherlands) has the highest efficiency for financial instruments, with an average score of 82.0 points on the normalised 0-100 scale. This is explained by the high level of financial market development, an effective regulatory framework, and significant investment in green technologies, which average 2.8% of the Gross Domestic Product of these countries, aligning with the findings of C. Qin *et al.* (2020). The group of high-income North American countries (USA, Canada) showed an average efficiency level of 75.6 points, which is 6.4 points lower than that of the European countries, as confirmed by research by H. Deng *et al.* (2023). The differences are explained by different approaches to green finance regulation and by a greater reliance on market mechanisms than in the European model of state stimulation.

Countries with transition economies (Ukraine, Poland) scored 59.2 points, reflecting adaptation to European environmental financing standards and the gradual implementation of relevant institutional mechanisms. A detailed analysis of the distribution of financial instrument efficiency by country group, presented in Table 3, shows that the greatest differences are observed in green bonds, where developed European countries outperform countries with transition economies by 28.4 points. This is due to differences in capital market development and institutional capacity

for the issuance and management of green securities. The smallest discrepancies were found in the field of microfinance (12.7-point difference), indicating the universality of this instrument across countries' levels of economic development and its particular effectiveness in supporting small farming enterprises.

Table 3. *Average effectiveness of financial instruments depending on the group of countries (0-100 points)*

Country group	Green loans	Government subsidies	Tax incentives	Green bonds	Crowdfunding	Microfinance	Government grants	Private funds
Developed European (n = 4)	87.9	83.8	78.0	80.8	72.4	68.9	81.2	74.6
Highincome North America (n = 2)	75.7	75.1	78.4	73.2	69.3	65.2	76.8	71.4
Transitional economies (n = 2)	62.0	61.0	56.1	57.5	58.4	59.7	63.2	52.8
Large economies (n = 2)	66.1	68.1	62.2	64.2	61.7	63.4	67.3	59.6

Note: *scoring scale: 0 points – no effectiveness of the financial instrument; 100 points – maximum effectiveness with the strongest positive impact on resource-conserving practices in the agricultural sector*
Source: *calculated by the authors on the basis of data from C. Qin et al. (2020), S. Gomina et al. (2024)*

An in-depth analysis of indicator variability across country groups, presented in Table 3, revealed the highest coefficient of variation for green bonds (CV = 0.34), indicating significant differences in the development of green securities markets across country groups. This is explained by differences in financial infrastructure development, regulatory frameworks, and investment culture in environmentally responsible investing (Bechko *et al.*, 2022). The lowest variability was observed for government subsidies (CV = 0.18), indicating relatively uniform approaches to state support for resource-saving practices across levels of economic development. The average coefficient of variation for all studied financial instruments was 0.26, suggesting a moderate level of differentiation between country groups. Private investment funds showed high variability (CV = 0.31), due to differences in private capital and investment institution development. Tax incentives showed a coefficient of variation of 0.22, indicating a relative standardisation of fiscal stimuli for resource-saving practices between the studied countries. The results of the cluster analysis conducted during the study demonstrate the formation of three main clusters of countries based on their approaches to financing resource efficiency.

The first cluster, "Innovation Leaders", includes Denmark and the Netherlands, with the highest efficiency indicators in green technologies (average score: 86.7). These countries are characterised by comprehensive state support programmes, a high level of environmental awareness among the population and business, and a developed green finance infrastructure. An example of the effective application of green finance is the Danish company Arla Foods, which received a green loan of €750 million at 2.3% per annum to modernise dairy farms, allowing it to reduce water consumption by 23% and energy by 18% during 2022-2024 (Arla Foods Ingredients invests US$35M in carbon reduction project, 2024). The share of green finance in their GDP is 2.8%, the highest among the studied countries.

The second cluster, "Stable Performers", unites Germany, France, the USA, and Canada, with an average efficiency level of 76.4 points, indicating their steady positions in financing resource-saving practices. These countries demonstrate a balanced and measured approach to using various financial instruments, with a particular emphasis on tax incentives and green bonds. A characteristic example is the German agro-corporation BayWa AG, which, through the combined use of government subsidies (€45 million) and green bonds (€120 million), was able to implement precision farming technologies on 85% of its lands, increasing fertiliser efficiency by 32% and reducing water consumption by 28% (BayWa sustainability initiatives: Agriculture & nutrition, n.d.). These countries are characterised by a stable and well-developed institutional framework, mature and liquid financial markets with high levels of capitalisation, as well as consistent and long-term green development policies that provide predictability for investors and businesses (Wittwer *et al.,* 2021). Another distinctive feature of this cluster is the presence of effective regulatory mechanisms that facilitate the attraction of private capital to finance environmental projects, as well as a well-established culture of corporate social responsibility.

The third cluster, "Developing Countries", includes China, India, Ukraine, and Poland, with an average score of 62.8 points, reflecting their transition status as they build modern green finance systems. These countries are characterised by the active development of an

institutional base for green finance and the constant adaptation of international standards to national conditions. A prominent example is the Polish company Cedrob S.A., which, through a microfinance programme, received 8.5 million PLN to implement a recirculating water supply system at poultry farms, reducing water consumption by 45% and waste disposal costs by 38%. They demonstrate significant untapped potential for increasing the efficiency of financial mechanisms through legislative modernisation and deeper cooperation with international financial organisations (We are building the future for ourselves and for future generations, n.d.). An important feature of this cluster is the high growth rates of green finance volumes and the active involvement of state resources to stimulate private investment. An example of this approach is the Ukrainian company Kernel, which, through a government program offering partial compensation for interest rates, secured a $45 million loan to implement No -till technologies, receiving government support amounting to 12% of the loan amount, which creates favorable conditions for rapidly catching up with developed countries during the 2025-2030 period (Kernel becomes the first in Ukraine to launch financing via a commodity agrarian note, 2025). Detailed results of the cluster analysis are presented in Table 4.

Table 4. *Cluster analysis of countries by the efficiency of financial instruments*

Cluster	Countries	Average score	Leading instruments	Share of green finance in GDP, %	2020-2024 trend, %
Innovative leaders	Denmark, Netherlands	86.7	Green loans, government subsidies	2.8	+34.2
Stable performers	Germany, France, the USA, and Canada	76.4	Tax incentives, green bonds	1.9	+18.7
Developing countries	China, India, Ukraine, Poland	62.8	Government grants, microfinance	1.2	+42.9

Source: *calculated on the basis of data from P. Bechko et al. (2022), H. Deng et al. (2023)*

Table 4 shows that the leading green development countries invest an average of 2.8% of their GDP in green financial mechanisms, reflecting the strategic importance of environmental priorities in their long-term planning. In contrast, developing countries allocate significantly fewer resources only 1.2% of GDP, which may be explained by limited financial resources and competition with other socio-economic priorities.

Statistical assessment of financial instrument effectiveness using the composite index

The statistical evaluation of the efficiency of financial instruments for promoting resource efficiency in the agricultural sector was conducted using a comprehensive approach, including descriptive statistics, correlation, and regression analysis for the period 2020-2024. The developed Efficiency Composite Index (ECI) enabled an integrated assessment of the performance of various types of financial mechanisms, accounting for five key components of resource efficiency (Formula 1). Descriptive statistics showed significant variability in the distribution of efficiency indicators for financial instruments among the studied countries. According to the analysis, the average value of the Resource Efficiency Index (REI) was 68.4 points, with a standard deviation (SD) of 12.7, indicating a moderate divergence in values across countries. For the Environmental Performance Index (EPI), the average was 71.2 points with SD = 15.3, also indicating substantial variability. The average Return on Investment (ROI) was 23.8% (SD = 8.9). The Circular Economy Implementation Index (CEII) averaged 3.2 points (SD = 0.8). The Resource Consumption Reduction Coefficient (RCRC) averaged 18.6% (SD = 7.4).

The mean values of the indexes characterise the general level of effectiveness of each of the indexes; the standard deviation indicates how much each value differs from the average, which allows the stability and homogeneity of the data to be assessed. Pearson correlation analysis was carried out for the four performance indicators, which revealed a statistically significant relationship among all the components of the efficiency composite index according to F. Haque *et al.* (2023). The highest correlation was registered between REI and RCRC ($r = 0.87$; $p < 0.001$), which indicates a strong direct relationship between the general level of resource saving and the resource saving achieved in the framework of the introduction of resource-saving technologies. The moderate direct correlation was registered between EPI and CEII ($r = 0.69$; $p < 0.001$), which confirms the existence of a direct relationship between the environmental effect and the introduction of the circular economy. The weakest correlation is observed between ROI and other indices ($r = 0.34$-0.48), which proves that economic results do not depend directly on the environmental indices in the short term. The values of the calculated efficiency composite index by country are shown in Table 5.

Table 5. *ECI calculation by country*

Country	REI (0.25), points	EPI (0.20), points	ROI (0.20), %	CEII (0.20), points	RCRC (0.15), %	ECI, points
Denmark	89.2	91.4	28.7	4.6	34.2	84.7
Netherlands	86.8	88.2	26.4	4.4	31.8	82.3
Germany	82.4	84.7	24.1	4.1	28.9	78.9
France	79.6	82.3	22.8	3.9	26.7	76.4
USA	76.2	79.1	25.3	3.7	24.4	74.2
Canada	73.8	76.4	23.9	3.6	23.1	71.8
China	69.4	71.2	21.7	3.2	20.8	66.9
Poland	64.7	67.3	19.4	2.9	18.6	62.4
India	61.2	63.8	18.2	2.7	17.3	58.6
Ukraine	57.9	60.4	16.8	2.4	15.9	54.8

Note: *component weights in the ECI formula are indicated in parentheses: REI – resource efficiency index (0-100 points); EPI – environmental performance index (0-100 points); ROI – return on investment coefficient (%); CEII – circular economy implementation index (1-5 points); RCRC – resource consumption reduction coefficient (%); ECI – efficiency composite index (0-100 points)*

Source: *calculated by the authors on the basis of data from F. Haque et al. (2023)*

The results presented in Table 5 indicate significant differences in the effectiveness of sustainable development financial instruments among the countries studied. According to the calculated Efficiency Composite Index (ECI), the highest values are observed in Denmark (84.7 points) and the Netherlands (82.3 points), which is due to high scores across nearly all components. In particular, Denmark demonstrates the highest levels of resource efficiency (REI – 89.2) and environmental performance (EPI – 91.4), as well as the highest rate of resource consumption reduction (RCRC – 34.2%). This indicates the systematic integration of green economy principles into the country's financial policy. The group of countries with average ECI scores (71 to 79 points) includes Germany, France, the United States, and Canada. They have moderately high ROI and CEII scores, but lag behind the leaders in terms of REI and RCRC. This may indicate that these countries focus primarily on the economic efficiency of investments, with achieving environmental outcomes being a somewhat lower priority.

The lowest ECI scores are observed in Ukraine (54.8 points), India (58.6 points), and Poland (62.4 points). The main limiting factors were low CEII (Circular Economy Implementation Index) and REI scores. For example, in Ukraine, the CEII is only 2.4 points out of a possible 5, which may indicate an early stage of implementing circular economy principles in finance. It is also important to note that the weights of each indicator in the ECI are calculated using an expert-based approach (REI – 25%, EPI – 20%, ROI – 20%, CEII – 20%, RCRC – 15%), which allows for both environmental and economic aspects to be considered in the integrated assessment. Thus, countries with high ECIs not only have robust financial instruments but also demonstrate a systematic environmental policy, whereas countries with lower ECIs have not yet achieved the necessary synergy between economic viability and sustainable resource use. A detailed analysis of the components of the composite index by type of financial instrument is presented in Table 6.

Table 6. *Effectiveness of financial instruments by ECI components*

Financial instrument	REI, points	EPI, points	ROI, %	CEII, points	RCRC, %	Average ECI, points	Standard deviation
Green loans	82.7	78.4	24.9	3.6	29.4	78.2	6.8
Government subsidies	79.3	79.8	23.1	3.8	26.7	76.9	7.2
Tax incentives	74.6	75.2	26.7	3.4	24.1	74.8	5.9
Green bonds	71.8	73.6	22.4	3.2	22.8	71.3	8.1
Government grants	69.4	71.2	21.8	3.1	21.4	69.7	6.4
Crowdfunding	64.7	67.3	19.6	2.9	19.2	64.8	9.3
Microfinance	62.1	64.8	18.4	2.7	18.6	62.4	7.7
Private funds	58.9	61.2	17.2	2.4	16.8	59.1	10.2

Note: *REI – resource efficiency index (0-100 points); EPI – environmental performance index (0-100 points); ROI – return on investment coefficient (%); CEII – circular economy implementation index (1-5 points); RCRC – resource consumption reduction coefficient (%); ECI – efficiency composite index (0-100 points); standard deviations are given in points*

Source: *calculated on the basis of data from J. Mejia-Escobar et al. (2020), A. Sridhar et al. (2023)*

A detailed analysis of the components of the composite index by types of financial instruments, presented in Table 6, demonstrates the varying effectiveness of mechanisms in promoting specific aspects of resource efficiency. Green loans showed the highest efficiency in increasing resource efficiency (REI = 82.7) and reducing resource consumption (RCRC = 29.4%). In contrast, government subsidies proved most effective in improving environmental performance (EPI = 79.8) and implementing the circular economy (CEII = 3.8). Tax incentives demonstrate a balanced impact on all components with the highest return on investment (ROI = 26.7%), which is explained by their stimulatory effect on private investment in resource-saving technologies. Cluster analysis based on the values of the Efficiency Composite Index (ECI) revealed a clear division of countries into three groups: high-efficiency (ECI > 75 points), medium-efficiency (60 < ECI < 75 points), and low-efficiency (ECI < 60 points). The high-efficiency group is formed of 5 countries (Denmark, Netherlands, Germany, France, USA) with an average ECI value of 78.3 points; the medium-efficiency group consists of 3 countries (Canada, China, Poland) with ECI = 67.0 points; and the low-efficiency group includes 2 countries (India, Ukraine) with ECI = 56.7 points.

Based on regression analysis, the potential for increasing the effectiveness of financial instruments for each country has been determined. Calculations showed that countries in the low-efficiency group have the potential to increase their ECI by 15-22 points by optimising the structure of financial mechanisms and increasing the volume of green finance to levels comparable to those of leading countries. Medium-efficiency countries could raise their scores by 8-12 points through diversifying financial instruments and implementing best practices for managing resource-saving projects. Correlation analysis between ECI components and macroeconomic indicators, conducted within the framework of this study, revealed strong positive links with GDP per capita ($r = 0.81$, $p < 0.001$), the global competitiveness index ($r = 0.76$, $p < 0.001$), and the environmental performance index ($r = 0.84$, $p < 0.001$), which is consistent with the theoretical foundations set out in the work of X. Xia & J. Ruan (2020). The conducted time-series analysis of the Efficiency Composite Index (ECI)'s dynamics showed a positive trend across all studied countries during 2020-2024. According to the research results, the average annual ECI growth was 3.4% for high-efficiency countries, 5.7% for medium-efficiency, and 8.2% for low-efficiency countries, indicating a convergence process in the field of the effectiveness of financial mechanisms for promoting resource efficiency in accordance with the theoretical foundations of Z. Yu & S.A. Rehman Khan (2022). The highest growth dynamics were observed in Ukraine (+34.5% over the period 2020-2024) and Poland (+28.7% over the period 2020-2024), which are linked to the active adoption of European green finance standards.

Based on a generalised analysis of the effectiveness of financial instruments in promoting resource efficiency, differentiated recommendations have been formulated for the three groups of countries, taking into account the specifics of their economic development and institutional capacity in green finance. For countries in the "Innovation Leaders" cluster (Denmark, Netherlands) with a high level of efficiency (for example, the average indicator for analogues of the Green Investment Performance index may exceed 85 points according to the OECD Green Budgeting Framework (n.d.), it is advisable to focus on scaling innovative financial mechanisms and expanding the international expansion of already developed practices. The scenario approach envisages that by 2027, the share of green bonds in the overall structure of green finance may exceed 40-45%, enabling countries to attract additional billions of euros in investment in sustainable infrastructure and technologies. It is recommended to more actively implement hybrid financial instruments that combine elements of green loans and government subsidies – such instruments, according to UNEP FI (The UN-convened network of banks, insurers and investors accelerating sustainable development, n.d.), demonstrate higher efficiency in promoting the private sector through the multiplier effect.

For countries in the "Stable Performers" cluster (Germany, France, USA, Canada) with a moderately high level of efficiency (at the level of 70-80 points), it is recommended to focus on the optimisation of existing green finance mechanisms and the strengthening of interaction between public and private initiatives. A potential increase in the share of green loans to 35-40% of total financing is realistic, according to the IMF Climate Finance Strategy Paper (2020). Estimated rates within the range of 2.5-3.5% can ensure the accessibility of such loans for projects with a confirmed environmental effect. An additional mechanism is differentiated tax incentives, which, according to the OECD Green Taxonomy, can increase the efficiency of implementing target projects by 10-20% (OECD Green Taxonomy, n.d.).

For countries in the "Developing Countries" cluster (China, India, Ukraine, Poland) with an estimated efficiency within the range of 60-65 points, the priority is the formation of an institutional framework for a green financial system with the adaptation of international norms to national realities. Initial orientation towards government subsidies, microfinance, and budgetary

guarantees is recommended. According to estimates by the FAO & IFAD (n.d.), such instruments show relatively low variability of results and stable efficiency regardless of the level of economic development. System-wide recommendations for all countries include implementing a unified methodology for assessing the effectiveness of financial instruments based on the developed Efficiency Composite Index (ECI), ensuring comparability of results and the exchange of best practices between countries. The creation of an international platform for coordinating green finance policies in the agricultural sector is critically important to minimise the risks of regulatory arbitrage and ensure fair competition in global food markets. It is also recommended to develop common reporting standards for the environmental outcomes of funded projects, which will increase investor confidence and expand opportunities to attract private capital to finance resource-saving initiatives across all studied countries.

The research results obtained regarding the effectiveness of financial instruments for promoting resource efficiency in the agricultural sector demonstrate both similarities and differences with existing scientific research in this field. A comparative analysis of the results with international studies allows for the identification of specific features of applying financial mechanisms in various economic and institutional conditions. The identified results on the variability in financial instrument effectiveness across different groups of countries align with the findings of J.P. Aryal *et al.* (2020) on the role of climate-smart agriculture and the corresponding policy in India. J.P. Aryal *et al.* (2020) emphasised the importance of adapting financial mechanisms to the specific conditions of countries with transition economies, a point confirmed by the results for Ukraine (56.2 points) and Poland (62.1 points). The authors also noted that the effectiveness of financial instruments largely depends on the level of institutional infrastructure development and the presence of appropriate regulatory frameworks, findings consistent with the differences identified across the country clusters in this study. However, unlike the findings of J.P. Aryal *et al.* (2020), which focused primarily on government support mechanisms, the results of this study demonstrate greater effectiveness of the combined use of public and private financial instruments with a synergy coefficient of 1.34.

The study by C. Dias *et al.* (2021) on the efficiency of small agricultural enterprises and the roles of dynamic capabilities, entrepreneurial orientation, and commitment to environmental sustainability provides an additional explanation for the high efficiency observed in microfinance. The researchers found that small agricultural enterprises demonstrate greater flexibility in implementing innovative resource-saving practices when affordable financing is available, due to their organisational structure and decision-making speed. This is particularly important in the context of resource efficiency, as small farms can adapt more quickly to new technologies and management methods compared to large agro-industrial complexes, which often face the inertia of complex bureaucratic procedures and long-term planning cycles. The results obtained in this study confirm the findings of C. Dias *et al.* (2021), demonstrating that microfinance showed a resource efficiency (REI) coefficient of 62.1 points and an environmental performance index (EPI) of 64.8 points, which, although lower than the indicators for green loans (82.7 and 78.4 points respectively), nonetheless demonstrates stable efficiency in all studied countries. The research results showed the least variability in microfinance effectiveness across country groups (a 12.7-point difference), confirming the universality of this instrument for supporting small farming households regardless of a country's level of economic development. However, unlike C. Dias *et al.* (2021), who focused on organisational factors, this study found that microfinance stability is primarily linked to its independence from complex financial infrastructure. Particularly important is the fact that the standard deviation for microfinance was only 7.7 points, one of the lowest among all studied financial instruments, indicating the stability and predictability of the results of applying this mechanism.

Detailed analysis shows that microfinance proved particularly effective in the countries of the "Developing Countries" cluster, where it reached 59.7 points compared to 68.9 points in developed European countries. This relatively small difference of 9.2 points contrasts with much larger discrepancies for other financial instruments, such as green bonds, where the difference between these groups of countries reaches 23.3 points. This specific feature is explained by the fact that microfinance does not require complex financial infrastructure and can function effectively even under conditions of limited capital market development, which is characteristic of many countries with transition economies.

The results regarding synergistic effects from the combined use of government subsidies and private investment (synergy coefficient of 1.34) are supported by the study by M. Donner *et al.* (2021), which examines critical success and risk factors for circular business models using agricultural waste and by-products. M. Donner *et al.* (2021) emphasised the importance of combining government support with private initiatives to create viable business models in resource efficiency, as government mechanisms provide the necessary institutional support and risk reduction, while private

investment brings market efficiency and innovative approaches. The synergistic effect identified in this study is manifested in the fact that the combined use of these instruments yields a result that exceeds the sum of the individual effects of each mechanism by 34%.

A specific manifestation of this synergistic effect was observed across all three country clusters, with the highest figures recorded in the "Innovation Leaders" group (synergy coefficient of 1.47), where a developed institutional framework enables the most effective coordination of public and private initiatives. In the "Stable Performers" cluster, the synergy coefficient was 1.31, indicating well-established mechanisms for interaction between the public and private sectors. Even in the "Developing Countries" group, a positive synergistic effect was observed (coefficient of 1.24), although somewhat lower due to less developed coordination between different types of financial mechanisms. However, unlike M. Donner *et al.* (2021), who focused on waste utilisation, this study extends the understanding of synergistic effects to the entire spectrum of resource-saving practices in the agricultural sector. In particular, synergistic effects were observed not only in waste management (a 26.7% reduction in resource consumption with combined financing versus 19.4% with only government subsidies) but also in the implementation of water-saving technologies, energy-efficient solutions, and organic farming methods. Particularly significant is the fact that the synergistic effect is most pronounced in the field of circular economy implementation, where the CEII index under combined financing reaches 3.8 points, compared to 3.1 points with only government grants and 2.6 points with exclusively private funds.

A comparison with the study by B. Garske *et al.* (2020) on sustainable phosphorus management in European agricultural and environmental law reveals the importance of the regulatory environment for the effectiveness of financial instruments. B. Garske *et al.* (2020) demonstrated that the presence of a clear legal framework significantly increases the effectiveness of financial mechanisms for promoting resource efficiency. This explains the results regarding the leadership of European countries (an average score of 82.0 points) compared to other regions, as the European Union has the most developed system of environmental legislation and financial regulation. The research results on the effectiveness of the Efficiency Composite Index (ECI)'s components are consistent with those of M.K. Jhariya *et al.* (2021) on natural resource efficiency and sustainability. M.K. Jhariya *et al.* (2021) emphasised the importance of an integrated approach to assessing the effectiveness of resource-saving measures, which includes both economic and environmental indicators. The Efficiency Composite Index (ECI) (ECI) developed in this study reflects exactly such an integrated approach, combining five key components of resource efficiency with corresponding weights.

The study by T. Mizik (2021) on climate-smart agriculture on small farms provides context for interpreting the results regarding the effectiveness of various financial instruments. T. Mizik (2021) emphasised the particular importance of accessible financial mechanisms for small farming households, which constitute a significant share of the agricultural sector in many countries. The study by J.C. Mejia-Escobar *et al.* (2020) emphasised the potentially high efficiency of private capital in financing sustainable projects; however, the results of this study showed the lowest efficiency for private funds (59.1 points per ECI) among all studied instruments. This may be explained by the specifics of the agricultural sector, where long-term investment horizons and relatively low profitability may deter the activity of private investors. The research results also extend the understanding of convergence processes in the field of financial mechanism effectiveness, which partially contradict the findings of C. Qin *et al.* (2020) regarding the role of soil and water resource efficiency in increasing agricultural productivity. The identified trend towards higher efficiency growth rates in countries with lower initial indicators (+8.2% annual ECI growth in low-efficiency countries versus +3.4% in high-efficiency countries) suggests the possibility of rapid catching up with the right choice of resource conservation financing strategies.

Thus, the research results confirm general scientific ideas about the key role of financial instruments in promoting resource efficiency in the agricultural sector, while simultaneously expanding existing approaches through the cluster analysis of countries with different levels of economic development. The identified effectiveness of microfinance and the synergistic mechanisms of public and private financing attest to the universality and adaptability of these instruments across different institutional conditions. Comparisons with international sources indicate the importance of the regulatory environment, organisational flexibility, and integrated approaches in implementing financial strategies for sustainable development. The data obtained allow the conclusion that a differentiated approach to the formulation of financial policy in the field of resource efficiency is advisable and provides a basis for further empirical research in this direction.

CONCLUSIONS

The conducted research on the effectiveness of financial instruments for promoting resource efficiency in

the agricultural sector has provided a comprehensive assessment of modern mechanisms for financial support of environmentally oriented management practices and has enabled the formulation of scientifically substantiated recommendations for their optimal use. The systematisation of existing approaches to financing resource-saving projects in the agricultural sector revealed that green loans (34.2% of the total financing volume) and government subsidies (28.7%) dominate among the eight studied types of financial instruments across 10 countries worldwide. Green loans were identified as the most promising financial instruments, demonstrating the highest efficiency indicators in increasing resource efficiency (REI = 82.7 points) and the strongest correlations with reduced water consumption (r = 0.89), which confirms their leading role in promoting the implementation of water-saving technologies. Government subsidies showed the highest efficiency in improving environmental performance (EPI = 79.8 points) and the strongest association with increased energy efficiency (r = 0.83), justifying their use to stimulate energy-saving practices. A statistical evaluation based on the Efficiency Composite Index (ECI), confirmed significant differences between the studied countries, ranging from 54.8 points in Ukraine to 84.7 points in Denmark. Cluster analysis identified three groups of countries by efficiency level: "Innovation Leaders" (average ECI = 86.7 points), "Stable Performers" (ECI = 76.4 points), and "Developing Countries" (ECI = 62.8 points). This reflects the various stages of development of green finance systems.

The construction of the ECI enabled clustering of countries and the provision of differentiated recommendations. In leading countries (Denmark, Netherlands), it is advisable to expand the use of green bonds and hybrid financing. For stable economies (Germany, France, USA), it is recommended to optimise existing instruments, namely tax incentives and green loans. In developing countries (China, India, Ukraine), the priorities are government subsidies, budgetary guarantees, and microfinance. Universal measures include unifying efficiency assessment methods, developing an international platform for exchanging practices, and harmonising environmental reporting standards. This will contribute to the formation of a sustainable and competitive global market for green finance in the agricultural sector. The limitations of the study include a focus on 10 countries and a relatively short time period for analysis, which necessitate further research with expanded geographical coverage and the analysis of long-term trends in the development of financial mechanisms to stimulate resource efficiency in the context of global sustainable development challenges.

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Фінансові інструменти стимулювання ресурсозбереження в аграрному секторі

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Анотація. Трансформація аграрного сектору в напрямку сталого розвитку вимагає ефективних фінансових механізмів для впровадження екологічно орієнтованих технологій та практик господарювання. Метою дослідження було проаналізувати ефективність та особливості застосування сучасних фінансових інструментів для стимулювання ресурсозберігаючих практик в аграрному секторі та розробити рекомендації щодо їх оптимального використання. Розроблено комплексний індекс ефективності на основі п'яти ключових компонентів ресурсоефективності з використанням методів дескриптивної статистики, кореляційного та множинного регресійного аналізу. Дослідження виявило домінування зелених кредитів (34,2 % загального обсягу фінансування) та державних субсидій (28,7 %) серед восьми типів фінансових інструментів. Зелені кредити продемонстрували найвищу ефективність у підвищенні ресурсоефективності (82,7 балів) та найсильніший зв'язок зі зменшенням споживання води ($r = 0,89$), як показав приклад датської компанії Arla Foods, яка завдяки зеленому кредиту 750 млн євро скоротила споживання води на 23 % та енергії на 18 %. Державні субсидії показали найкращі результати у покращенні екологічної результативності (79,8 балів), що підтверджується досвідом німецької програми підтримки органічного землеробства. Кластерний аналіз виділив три групи країн: «Інноваційні лідери» з середнім комплексним індексом ефективності 86,7 балів (Данія, Нідерланди), «Стабільні виконавці» з комплексним індексом ефективності 76,4 балів (Німеччина, Франція, США, Канада) та «Країни, що розвиваються» з комплексним індексом ефективності 62,8 балів (Китай, Індія, Україна, Польща). Виявлено значущий синергетичний ефект від комбінованого використання державних субсидій і приватних інвестицій (коефіцієнт синергії 1,34) та універсальність мікрофінансування з найменшою варіативністю між країнами (12,7 балів різниці). Множинний регресійний аналіз підтвердив статистично значущу модель ($R^2 = 0,78$), де найбільший вплив на ефективність здійснюють обсяг зеленого фінансування ($\beta = 0,34$) та частка субсидій у валовому внутрішньому продукті ($\beta = 0,28$)

Ключові слова: зелене кредитування; екологічне фінансування; ресурсоефективність; субсидійна підтримка; комплексний індекс ефективності; синергетичні ефекти

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Ukraine as a guarantor of world food security: Challenges on the way to restoring agricultural production potential

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Abstract. The main objective of this study was to analyse the challenges facing Ukraine in the process of trying to preserve and restore its agricultural production potential, which has been significantly destroyed as a result of hostilities on the territory of the state. The study used bibliometric analysis (using Google Scholar, Scopus Preview and the Bibliometrix package), system-structural analysis and synthesis, as well as historical, dialectical, graphical and descriptive-statistical methods. The study demonstrated that despite the destruction of agricultural production potential, Ukraine remains an important supplier of agricultural products to many import-dependent regions of the world. The article emphasised that world food markets continue to remain unstable, which is confirmed by the Food Price Index, which reached 127.8 points in 2025, demonstrating the vulnerability of food systems to geopolitical shocks. According to experts, as of the first half of 2026, the total losses from the destruction of the

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Ukrainian economy as a result of the war may reach $589 billion, of which about $72 billion will fall on agriculture. It was determined that in the structure of indirect losses of the agricultural sector of Ukraine as a result of the war, the factors that had the greatest impact were the reduction in production productivity, the decline in product prices due to the disruption of exports, and the increase in production costs. It was noted that the potential costs of reconstructing the agricultural sector of Ukraine in the period from 2025 to 2035 could exceed $55 billion, and the costs of demining could reach almost $30 billion. It was established that exports of Ukrainian agricultural products to the EU reached almost $12.8 billion in 2024, which demonstrates the resilience of the agricultural sector of Ukraine and the deepening of integration into European markets. The practical value of the study lies in a comprehensive assessment of Ukraine's agrarian losses caused by the war, an analysis of their global consequences, and the identification of strategic recovery measures

Keywords: impact of war on agriculture; food supply chains; export disruptions; land contamination; rebuilding the agricultural complex

INTRODUCTION

The main challenges to global food security in the world in the 21st century remain wars, natural disasters and geopolitical instability, which lead to disruption of food supply chains, reduced crop productivity or crop losses. The military actions that reached full scale in Ukraine in February 2022 have significantly affected food stability in the world, as Ukraine is one of the largest exporters of agricultural products, including to the most food-insecure regions of the world. As a result of the intensification of hostilties, the area of agricultural land available for farming has decreased, the quality of land has deteriorated due to pollution and explosives, which has a negative impact on the productivity of cultivated crops. In addition, the disruption of the logistics network has led to a slowdown in deliveries or even the blocking of certain export channels. The strengthening of inflationary processes and the growth of production costs have negatively affected the profitability of production. All these factors together undermine the agricultural production potential of Ukraine and require effective ways to solve them.

Studies by the world scientists devoted to the study of food security often consider the war in Ukraine as a deterrent to achieving sustainable development goals and reducing food insecurity. Thus, scientists I. Bulba *et al*. (2024) raised the problem of soil contamination and its degradation as a result of military operations, as well as the prospects for its reclamation and restoration to strengthen agricultural production potential. Researches F. Lin *et al*. (2023) were concerned about the problem of blocking the supply of Ukrainian food to vulnerable regions of Africa, Asia and the Middle East, as the consequences of this could be fatal, provoking famine and social instability. Scientists noted that the lack of Ukrainian food in the world could lead to a serious imbalance in supply chains and pose a threat to food security. The problem of food security disruption due to the decline in the agricultural production potential of countries around the world was considered by scientists M. Alabi & O. Ngwenyama (2023) not only in the context of such global geopolitical conflicts as wars, but also in the context of the COVID-19 pandemic, which has significantly destabilised the world's economic system, reducing the possibilities of using labor resources, increasing logistics costs and forcing producers to rethink ways to ensure the sustainability of supply chains. Thus, solutions that were aimed at strengthening agricultural production potential during the pandemic can be adapted to solving the problems of post-war restoration of the agricultural sector of Ukraine. In addition, social problems that accompany global crises and may contribute to food security disruption were being addressed by scholars A. Burkovska *et al*. (2022), who proposed ways to balance consumer demand to ensure enhanced food security.

Scientists N. Davydenko *et al*. (2025) in their articles considered ways to strengthen Ukraine's agricultural production potential through the development of technologies, improvement of management methods, revision of the national strategy for ensuring food security, and improvement of the investment climate in the state. These ways were considered as an effective mechanism for influencing the level of food security even in times of global macroeconomic crises. The problem of ensuring food security through strengthening agricultural production potential was considered by scientists A. Poltorak *et al*. (2024) not only at the national, but also at the regional level, which allows paying more attention to individual indicators that form the system's resilience to shocks and economic imbalances. Earlier studies by A. Poltorak (2015) allowed to consider the dynamics of Ukraine's path towards strengthening its agricultural production potential and to identify successful cases that can be effective in the recovery

period after the end of hostilities. The role of local communities in restoring Ukraine's agricultural potential is not left out, as scientists V. Shebanin *et al*. (2024) paid special attention to the challenges facing local communities in the process of finding resources to restore and strengthen agricultural production. Thus, rebuilding infrastructure, restoring soils, and strengthening interaction with state bodies were considered priority tasks of the post-war reconstruction period. Scientists J. Cheng & X. Yu (2024) proposed using cross-sectoral cooperation as a mechanism for revitalising agricultural enterprises and their technological re-equipment during the reconstruction period.

Scientists S. Pimenow *et al*. (2025) have seen great potential in the agricultural sector in supplying raw materials for bioenergy plants, which, if this source of alternative energy was developed, could allow increasing the energy independence of the state, while simultaneously improving the environmental friendliness of the energy sector. Considering experience in the reconstruction of the agricultural production complex after military operations, scientists S. Rieznik & H. Lee (2025) offered the case of South Korea as a successful case of rebuilding rural areas, intensification of agriculture, and establishment of effective cooperation between government bodies at different levels, which ultimately allowed to ensure a high level of food security in the country. Thus, modern scientific research conducted by other scientists emphasised the importance of Ukrainian agricultural production for ensuring world food security, and also considered possible ways to restore agricultural potential in the post-war period. The aim of the study was to analytically prove the importance of Ukraine in the international food market, as well as to analyse the problems that Ukraine faces in the process of preserving and restoring its agricultural production potential, which was significantly undermined as a result of hostilities in the country.

MATERIALS AND METHODS

The methodological basis of this study was designed for a comprehensive analysis of the economic, social and food consequences of the full-scale war in Ukraine and the identification of priority areas for the restoration of the country's agricultural production potential in the context of ensuring global food security. The study was based on an integrated combination of general scientific, analytical and applied economic methods that allow for the assessment of wartime shocks, industry losses and challenges of post-war recovery. General scientific methods were used at all stages of the study, including bibliographic analysis, abstraction, induction and deduction, synthesis and systematisation, which ensured the coherence and logical sequence of the study. Analytical, statistical and comparative methods were used to assess changes in Ukraine's agricultural production, export indicators and its role in global food supply chains in the context of military conflict.

Dynamic analysis of key indicators within time series was specifically applied to study changes in agricultural exports, food price indices and economic losses for the period from 2000 to 2025, with a special focus on wartime and the period after 2022. The analysis focused on the following key indicators such as value and physical volume of Ukraine's agricultural exports; export value to the EU-27 and selected food-import-dependent countries; FAO Food Price Index (FFPI); estimated direct and indirect economic losses of Ukraine's agricultural sector; recovery and reconstruction needs by sector, etc. This allowed to identify structural gaps and ways to restore Ukrainian agri-food exports. To assess structural breaks and trend shifts, the study applied autoregressive integrated moving average (ARIMA) modelling for short-term trend identification. In addition, spatial and cross-country comparative analysis was conducted at the level of individual countries and regions to assess the dependence of food-stressed states on Ukrainian grain supplies and to compare the scale of losses and recovery needs across sectors of the economy. The comparative sample included countries such as Albania, Finland, Kyrgyzstan, Congo, Tanzania, Tunisia, Egypt, Turkey, Pakistan, Moldova, Somalia, Rwanda, North Kerea, Georgia, Laos, Azerbaijan, Kazahstan, Benin, Mongolia and Armenia. The countries were selected according to high share (over 10%) of wheat and meslin imports originating from Ukraine and/or Russia. To investigate causal relationships, a descriptive-analytical approach was used to interpret the causal relationships between military actions, land degradation, agricultural disruption, export restrictions, and fluctuations in global food security indicators. This approach allowed to go beyond descriptive statistics and provide an interpretation of how wartime factors translate into global food price volatility and supply risks.

A bibliometric analysis was conducted using data from Google Scholar and Scopus Preview, processed using the analytical package Bibliometrix (2025) based on integrated libraries. This allowed to identify dominant research clusters, thematic trends, institutional contributions, and geographical distribution of scholarly publications related to war, agriculture, and food security. The bibliometric search covered publications from 2000 to 2025 to ensure long-term trend coverage. However, priority analytical focus was placed on publications from 2022-2025, reflecting the period of post-2022 war impacts. Frequently

cited publications that most closely match the research keywords formed the main analytical basis for the literature review. The search strategy included the following keywords and combinations: "Ukraine" & "food security"; "war" & "agriculture"; "agricultural exports" &"conflict"; "land degradation" & "military operations". Inclusion creteria required peer-reviewed journal articles, indexed in Scopus or widely cited in Google Scholar with thematic relevance to agriculture, food security, war impacts, or post-conflict recovery. Exclusion criteria eliminated publications unrelated to agricultural production or food security. The empirical part of the study relied on desk-based data collection, with Statista (2025) serving as the main international statistical database. These data were used to analyse the structure of Ukraine's exports, the country's dependence on Ukrainian grain imports, sectoral economic losses, indirect losses to agriculture, and projected recovery needs. To assess the dynamics of world food prices in wartime conditions, a structural and comparative analysis of index indicators, in particular the food price index, was used. The graphical method provided visualisation of trends and relationships, while the abstract-logical method was used to synthesise statistical results and scientific evidence. The limitations of the study are related to the use of secondary data, differences in assessment methodologies in different international sources, and the unpredictable nature of the hostilities, which introduces uncertainty into loss estimates and long-term forecasts. Nevertheless, the applied methodological approach ensures the reliability, transparency, and relevance of the results obtained.

RESULTS

Role of Ukraine in global food security and dynamics of agricultural exports

Ukraine occupies one of the leading places in the ranking of exporters of agricultural products to the world market, which is due to its significant agricultural production potential, which is based on large areas of fertile agricultural lands, a favorable climate, a sufficient number of qualified labors, a lower level of production costs, compared to other European countries. The ability to export a certain number of agricultural products makes Ukraine to some extent a guarantor of food security in the world, however, the conduct of hostilities on the territory of the state negatively affects its agricultural production potential, which is accordingly reflected in the state of food security of countries that depend on the export of Ukrainian food raw materials. Thus, under these conditions, the restoration of Ukraine's agricultural production potential becomes not only a national priority, but also causes concern in a number of countries in the Middle East, Africa, and Asia that depend on Ukrainian food supplies. Thus, Figure 1 presents a comparative characteristic of the dependence of the most food-vulnerable countries in the world on grain supplies from Ukraine and Russia as of June 2022. The data in the figure demonstrate a significant level of dependence of the considered countries of the world on grain supplies from Ukraine, which, according to W. Leal Filho *et al*. (2023), creates grounds for concern about the food security problems in countries that will not receive food supplies due to a number of factors related to hostilities in Ukraine, such as soil contamination, mining of agricultural lands, reduced crop yields, increased production costs.

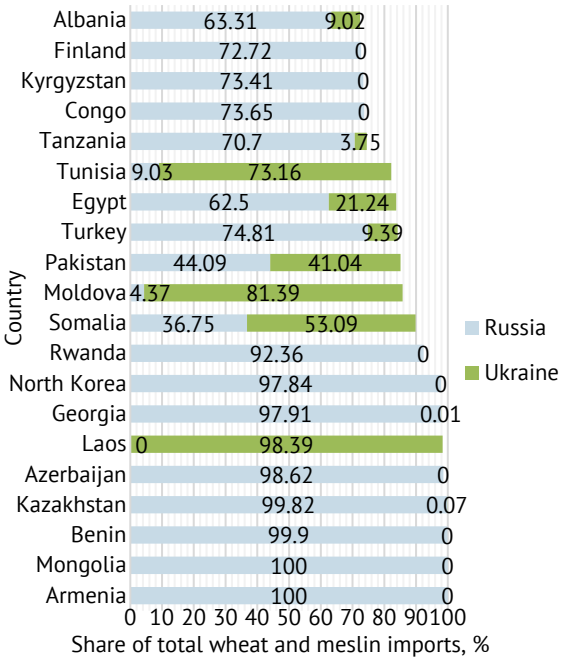

Figure 1. *Share of imports from Russia and Ukraine in total imports of meslin and wheat as of June 2022, by country*

Source: *generalised from Statista (2025)*

Overall, Figure 1 demonstrates the vulnerability of a number of countries to shocks caused by disruptions in food supplies due to hostilities and highlights the important role of Ukraine in ensuring food stability in the regions considered. Although a number of countries, such as Georgia, Azerbaijan, Kazakhstan, Kyrgyzstan, and Finland, have demonstrated overwhelming dependence on Russian grain exports, countries such as Laos, Moldova, Tunisia, Somalia, Egypt, Pakistan, Albania, and others are dependent on grain supplies from Ukraine

and, in the event of a reduction or cessation of supplies, may find themselves in a serious crisis. Figure 2 shows how Ukrainian agricultural exports to the European Union (EU-27) changed from 2015 to 2024, reflecting the evolution of the value of trade over a decade marked by economic reforms, market changes and major geopolitical events. Overall, the data show a steady increase in export volumes, as Ukraine established itself as an important supplier of cereals, oilseeds and processed agricultural products to the EU market.

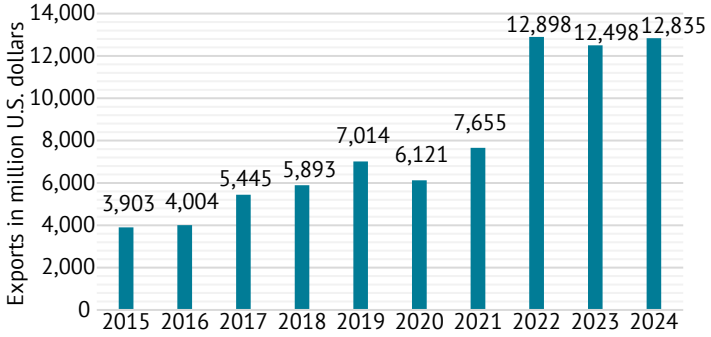

Figure 2. *Export value of agricultural products from Ukraine to the European Union (EU-27) from 2015 to 2024, in million U.S. dollars*

Source: *generalised from Statista (2025)*

Starting from a rather modest level in 2015-2016, when annual exports amounted to around four billion US dollars, trade began to gain momentum. In 2017, it exceeded five billion, and by 2019 it was close to seven. Although 2020 brought a slight decline, the sector recovered quickly in 2021, reaching a value of 7.6 billion US dollars. The key jump occurred in 2022, when exports soared to almost $13 billion, a record high for the entire period. This growth is explained by the fact that the EU became a strategic route for Ukrainian exports after the outbreak of the war, as well as by temporary autonomous trade preferences that simplified access to the European market. In 2023, volumes decreased slightly, but still remained at a high level, and 2024 turned out to be another strong year with exports worth almost $12.8 billion. This underlines that the EU is Ukraine's main trading partner in the agricultural sector. Overall, Figure 2 illustrates not only the resilience and flexibility of Ukrainian agriculture, but also the increasingly close integration of Ukrainian agri-food trade into the European economic space.

Global food price dynamics under wartime conditions

Long-term sustainable growth confirms that the European Union serves as a key, reliable and vital market for Ukrainian agricultural producers. The corresponding permanent integration of Ukraine into the economic European mechanisms increases its economic stability, helps to modernise Ukrainian agriculture and proves the need for further strategic partnership. The Figure 3 illustrates the full structure of the Food Price Index (FFPI) from 2000 to 2025, including the main types of goods, such as dairy and meat products, sugar, grain, oil. FFPI is used as an internationally recognised standard to track fluctuations in world food prices. It takes into account a set of key factors, such as changes in demand, weather anomalies, geopolitical situation, market supply, trade policy. The Food Price Index (FFPI) in 2025 reached an average value of 127.8 points, which indicates a partial price recovery after the correction period in 2023 and 2024, as it increased by 4.7% compared to the previous year. At the same time, one can observe a significant difference in the dynamics of prices for certain groups of goods. For example, the vegetable oils index showed the greatest growth, reaching 160.1 points. This is explained by a list of factors such as production deficits in countries exporting these products, high demand for biofuels and prolonged difficulties in logistics. At the same time, the dairy index also increased to 150.6 points as a result of reduced exports and active demand from the Middle East and Asian countries. The average annual grain prices were 108.7 points, but their dynamics were unstable due to production risks in the regions (especially Urkaine) and uncertainty about exports through the Black Sea. At the same time, for example, the price of sugar, which also amounted to 108.7 points, demonstrated relative stabilisation after previous fluctuations. This was due to better harvests in other key countries, which are also producers of this product.

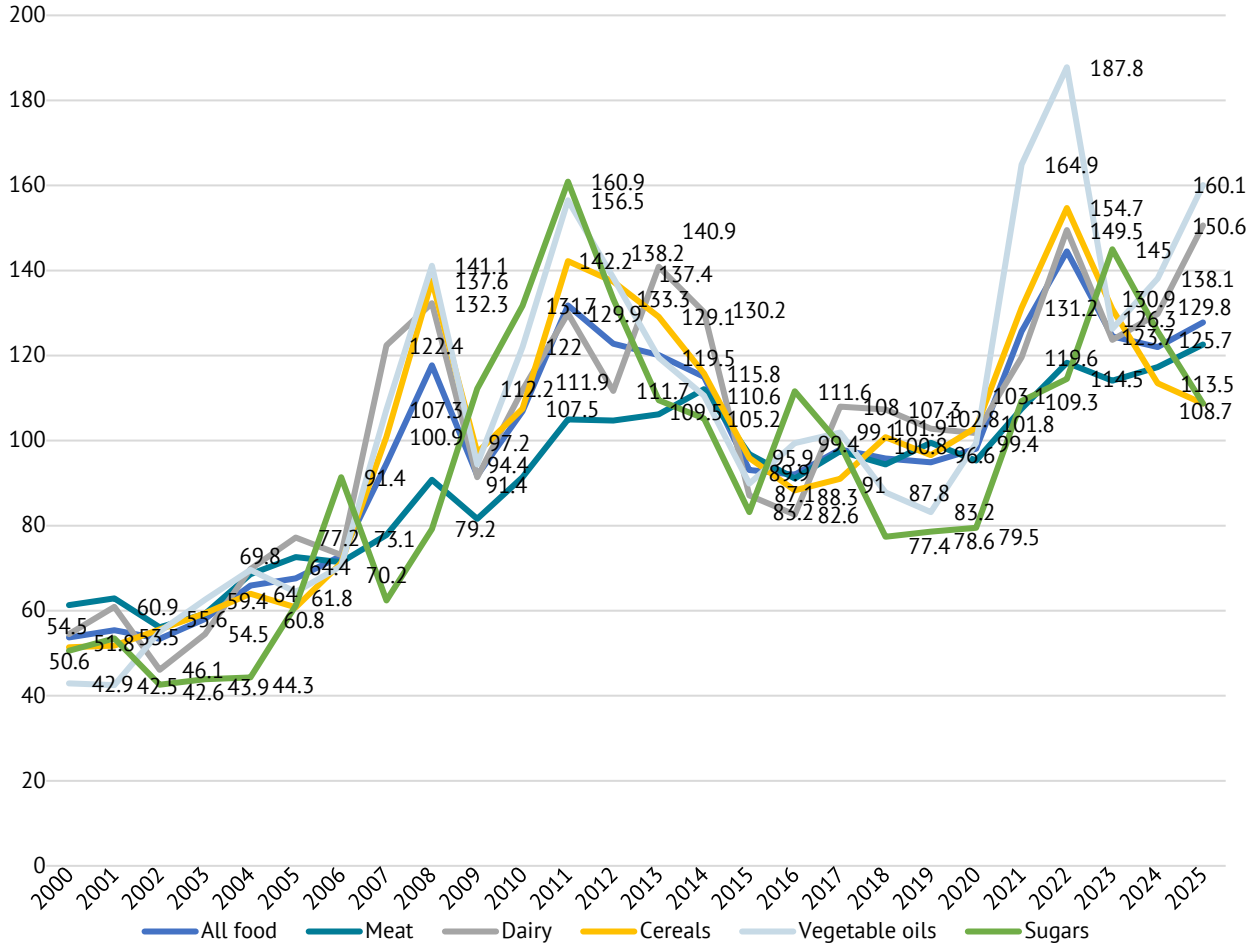

Figure 3. *Annual food price index worldwide from 2000 to 2025, by category*
Source: *generalised from Statista (2025)*

Looking across the full historical series, the data reveal pronounced periods of volatility, including the food price surges of 2007-2008, the 2011 peak, and the unprecedented 2022 price escalation, driven by global supply chain disruptions and geopolitical tensions. Subsequent years illustrate both the resilience and fragility of global food markets, as prices responded to shifting economic conditions, weather extremes, and policy interventions. Overall, the long-term trends captured in the table underscore the structural and cyclical factors that shape food price movements worldwide. The 2025 results reaffirm that global food markets remain highly sensitive to external shocks, emphasising the importance of diversified supply chains, sustainable agricultural production, and effective international cooperation to ensure food security and market stability. Overall, the trends captured in the Figure 3 reinforce the crucial importance of strengthening food system resilience, improving supply chain efficiency, and enhancing global cooperation to minimise the impacts of future disruptions and ensure food security for vulnerable populations worldwide.

Economic losses of Ukraine's agricultural sector and recovery challenges

The Figure 4 provides a detailed breakdown of the estimated economic losses sustained by Ukraine as a result of the full-scale war began on February 24, 2022. These figures cover the period through June 30, 2026, offering a medium-term outlook on the war's financial impact across a wide range of sectors. According to current assessments, commerce and industry have borne the greatest burden, with losses approaching 214 billion U.S. dollars, reflecting extensive damage to enterprises, disrupted supply chains, and diminished production capacity. The agricultural sector, traditionally a cornerstone of Ukraine's economy, follows with losses of roughly 73 billion U.S. dollars, driven by the destruction of farmland, equipment, storage facilities, and export infrastructure.

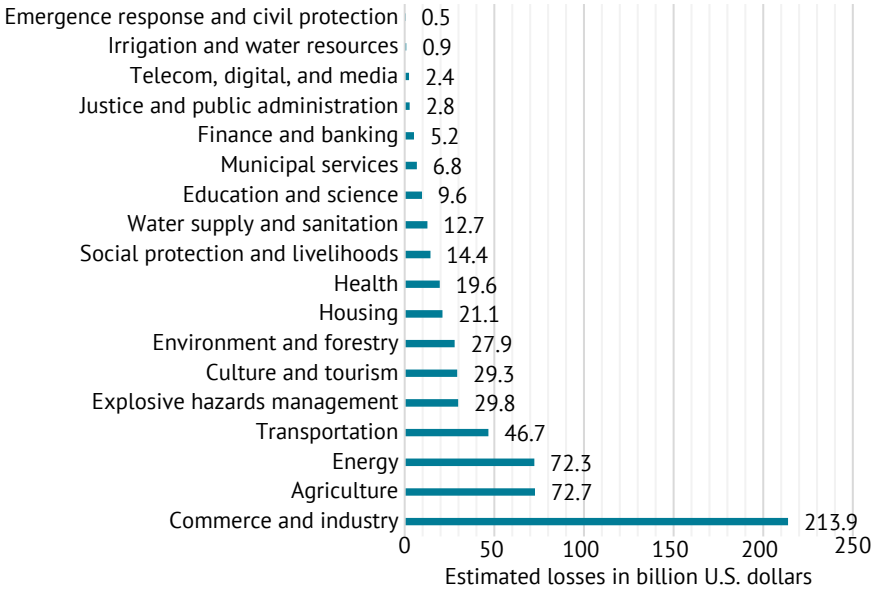

Figure 4. *Estimated economic, social, and other monetary losses of Ukraine from the war from February 24, 2022 to June 30, 2026, by sector*

Source: *generalised from Statista (2025)*

Other major sectors, including energy, transportation, and explosive hazards management, have also incurred significant damage, demonstrating the broad scope of disruption caused by ongoing hostilities. Social sectors such as health, education, housing, and social protection similarly reflect substantial losses, underlining the profound humanitarian and societal consequences of the conflict. Meanwhile, sectors like finance and banking, telecommunications, justice and public administration, and emergency response show smaller, yet still meaningful, economic impacts. In total, Ukraine's cumulative monetary losses are estimated at 589 billion U.S. dollars, underscoring the scale of destruction and the long-term challenges the country faces in recovery and reconstruction.

The total losses to the Ukrainian economy of about $589 billion, of which more than $72 billion is in agriculture, could have a truly devastating effect if a comprehensive recovery plan is not implemented after the end of hostilities. But the recovery of the agricultural sector, like other sectors of the national economy, must be coordinated with the national food security strategy. But this estimate of losses to the economy as a whole and to agriculture in particular is approximate and does not take into account the factor of the continuation of hostilities for an indefinite period. Figure 5 shows an assessment of indirect losses to Ukraine's agriculture as a result of hostilities. Thus, the most significant losses (more than 34 billion US dollars) are due to a decrease in crop productivity, which was possible due to a number of circumstances, such as land degradation, damage to land reclamation structures, failure to apply fertilisers due to their untimely delivery or other reasons. The second factor that influenced the losses in agriculture was a decrease in the purchase prices for agricultural raw materials on the Ukrainian market due to the blocking of export supplies. In addition to a decrease in crop productivity, the productivity of farm animals decreased, which also led to overall losses in the agricultural sector. In addition, the increase in production costs caused by inflation, national currency devaluation, disruption of supply chains and others had a significant impact on the losses in the agricultural sector. Additional forced costs for reclamation also increase the total amount of losses. Altogether, these factors amount to approximately 70 billion U.S. dollars in indirect agricultural losses, underscoring how deeply the war has disrupted Ukraine's role as a major global food producer and revealing the long-term challenges that will shape the sector's recovery. Figure 6 shows the projected amount of financial resources needed to restore individual sectors of the Ukrainian economy. As can be seen, the needs of agricultural restoration will require more than 55 billion US dollars, exceeding even the needs of restoring social infrastructure, education and science, healthcare and other important sectors of the country's economy. A separate item of restoration costs includes the costs of demining and disposal of explosive devices, which may amount to about 30 billion US dollars.

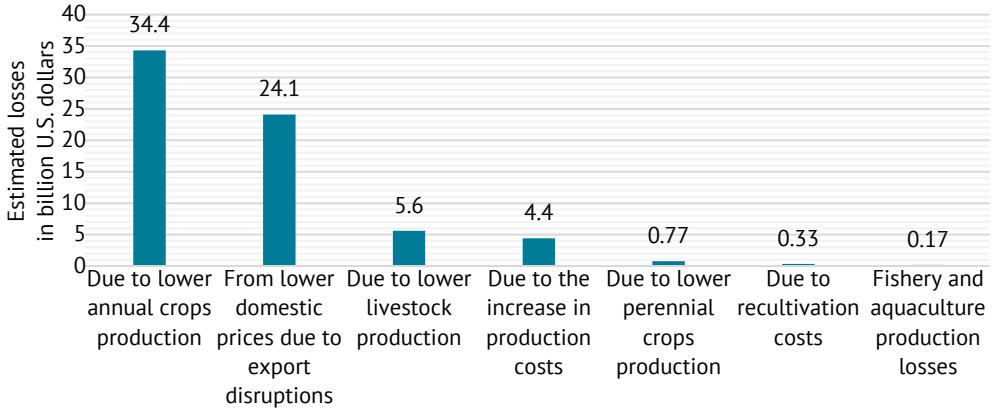

Figure 5. *Estimated indirect losses of agriculture due to the war in Ukraine as of December 2023, by reason category*
Source: *generalised from Statista (2025)*

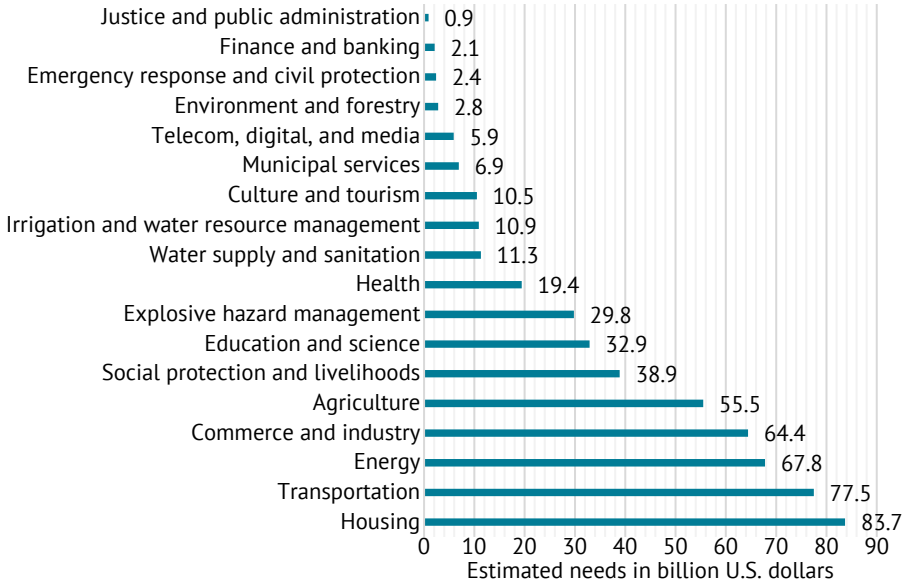

Figure 6. *Total estimated recovery and reconstruction needs of Ukraine from 2025 to 2035, by sector*
Source: *generalised from Statista (2025)*

Considering that the problem of demining will mainly concern fields and agricultural lands, this amount can also be attributed to the general need for financing for the restoration of agricultural potential. Thus, if adding up the costs of restoring agriculture and demining, which also indirectly relates to the restoration of agricultural potential, an amount of almost 85 billion US dollars is obtained, which can be compared only with the costs of restoring the housing stock after the end of hostilities. The costs of restoring agricultural production potential may even exceed the costs of restoring the energy sector, which will require more than 67 billion US dollars. Thus, it can be seen that restoring agricultural production potential requires significant financial resources, the search for which may be a real challenge for the state budget and other non-state institutions ready to invest in the restoration of the agricultural sector of the Ukrainian economy. Restoring Ukraine's agricultural production potential will require a set of actions in response to the challenges that will arise along the way. Thus, the most likely challenges to restoring Ukraine's agricultural production potential and possible solutions to counter them are presented in Table 1.

Table 1. *Challenges and solutions for restoring Ukraine's agricultural production potential*

No.	Challenges to restoring Ukraine's agricultural production potential	Possible solutions to them
1	Soil damage due to hostilities, its degradation, mining of territories, which may prevent safe cultivation of the soil.	Conduct systematic measures for demining, soil cleaning, training farmers on safe soil cultivation practices.

Table 1, Continued

No.	Challenges to restoring Ukraine's agricultural production potential	Possible solutions to them
2	Disruption of supply chains of key agri-food production inputs, including fertilisers, seeds, agrochemicals, fuel, equipment, and more, which could negatively impact farmers' ability to grow crops.	Implementation of measures to restore logistics infrastructure, search for alternative export channels.
3	Shortage of production workers and specialists due to their internal displacement or migration, mobilisation.	Carry out measures to automate and mechanise agricultural production, conduct personnel training, and implement specialist education programs.
4	Difficulties in obtaining financing, including credit resources, to finance measures to restore agricultural enterprises.	Develop state programs to support agriculture. Attract financing for agriculture, promote comprehensive financial advice to farmers.
5	Market instability and export blockages, which will negatively affect the motivation of agricultural producers and their ability to receive the planned income.	Develop programs to support agricultural producers, implement state mechanisms to stabilise prices for agricultural products. Promote the competitiveness of agricultural producers.

Source: *generalised by the authors*

In general, the challenges summarised in Table 1 can be grouped into resource-related, institutional, and market-related constraints, which are closely interrelated. Resource-related constraints, such as land degradation, pollution, and labor and resource shortages, are critical because they directly determine the physical feasibility of restoring agricultural production. Institutional constraints, including limited access to finance and the need for effective government support mechanisms, play a coordinating role in ensuring resource mobilisation and implementation of recovery programs. Market-related constraints, such as export disruptions and price volatility, affect producer incentives and income stability, but depend to a large extent on progress in addressing resource-related and institutional challenges. Therefore, addressing resource-related challenges should be considered a priority, as they form the basis for further institutional and market-based recovery efforts.

DISCUSSION

The findings of this study are consistent with and extend recent scholarly discussions on the impact of large-scale armed conflicts on agricultural systems and global food security. Current research increasingly emphasises the interconnected nature of production, environmental, institutional, and market factors, especially in countries that play a key role in international food supply chains, such as Ukraine. A significant body of recent literature confirms the systemic impact of the war in Ukraine on global food security. W. Leal Filho *et al*. (2023) demonstrated that the disruption of Ukrainian agricultural exports has exacerbated food insecurity in import-dependent regions, contributing to price volatility and supply shortages. Their findings strongly support the findings of this study, which highlight Ukraine's continued importance as a global food supplier despite severe production losses. However, while the authors focused mainly on global impacts, this study complements their work by offering a detailed sectoral and structural assessment of agricultural losses and recovery needs in Ukraine.

The causal relationship between armed conflict and agricultural land degradation is another area where strong convergence of findings can be observed. J. Wagner *et al*. (2025) provided a detailed analysis of the dynamics of agricultural land abandonment, re-plowing and reclamation in war-affected regions of Ukraine, based on remote sensing data. Their study confirmed that the intensity of the conflict directly affects land use patterns and production capacities. These results fully support the conclusion of this study that land degradation and inaccessibility are the most important resource constraints for agricultural recovery. At the same time, this study extends the methodological focus of the adorementioned study by quantifying the economic consequences of land degradation and considering them in the global context of food security. Environmental damage and soil contamination were also addressed by I. Bulba *et al*. (2024), whose findings highlighted the long-term decline in soil fertility caused by military operations. This study confirmed this assessment and further argues that soil restoration is not only an environmental priority but also a key economic prerequisite for the recovery of agricultural production. In this aspect, the results are consistent with recent sustainable development-oriented approaches that emphasise the importance of ecosystem restoration as a foundation for resilient agri-food systems.

A. Poltorak *et al*. (2024) showed that regional differences in logistics infrastructure and export potential undermine the economic security of Ukraine's agricultural sector. These findings are supported by this study, which demonstrates that blocked export channels and price volatility significantly reduce producers' income expectations. However, unlike the authors, who focused on regional economic security, this study paid

more attention to the global consequences of these disruptions, especially through the food price index and dependence on international trade. The role of institutional and social factors in agricultural recovery has received increasing attention in recent studies. A. Kliuchnyk *et al.* (2025) emphasised the importance of local communities in rebuilding agricultural infrastructure after destruction, arguing that decentralised decision-making increases responsiveness and flexibility. This finding supports this study's findings on the need for multi-level governance in the recovery process. At the same time, this study extended this perspective by positioning community participation within a broader framework that includes financial mechanisms, market stabilisation, and national food security strategies.

An important additional dimension is provided by A. Burkovska & A. Burkovska (2025), who analysed the semantic and narrative aspects of food marketing in the context of sustainable development. Their study showed that strengthening the symbolic and communicative value of national agricultural products can increase market resilience and consumer trust during crises. Although this study does not focus directly on marketing strategies, its findings on the need to stabilise agricultural markets and support exporters are consistent with this perspective. Integrating semantic narratives based on sustainable development can thus serve as an additional tool for increasing the competitiveness of Ukrainian agricultural products in the post-war period. The role of women's entrepreneurship in strengthening the strategic development of Ukraine's agriculture is explored by O. Shkarupa *et al.* (2025), who highlighted the role of women's entrepreneurship in strengthening the strategic development of Ukraine's agriculture. Their findings highlighted the untapped human resources, capital that can contribute to recovery and diversification. Although this study focuseed primarily on macroeconomic and structural challenges, the findings do not contradict this approach, but rather suggest that inclusive policies can enhance the effectiveness of institutional and financial support measures. The article by T. Melnyk *et al.* (2023) examined the state of food security in Ukraine at the national and global levels. Statistical indicators, including FAO data and the Global Food Security Index, were analysed to assess Ukraine's position in comparison with other countries. The study found that despite significant agricultural potential, Ukraine lagged behind many developed countries in several food security indicators due to institutional, economic, and infrastructural challenges. The research concluded that improvements in state policy, agricultural infrastructure, and international cooperation were necessary to strengthen food security in Ukraine.

The broader normative context of food security is reflected in the work of N. Rahman & R. Yasin (2022), who examined the challenges of implementing the Zero Hunger goal during global crises. Their findings highlight the vulnerability of children and socially vulnerable groups to food shortages, reinforcing the argument that disruptions in Ukrainian agricultural production have consequences far beyond national borders. This study adds to this perspective by demonstrating how production losses and export restrictions in Ukraine contribute to the volatility of global food prices, thereby indirectly affecting food access for vulnerable populations worldwide. A new direction in the recent literature explores alternative paths to agricultural recovery through diversification and cross-sectoral integration. S. Pimenow *et al.* (2025) in their study presented an approach that offers valuable insights into diversification opportunities through implementing bioenergy projects into national economy recovery plan. Nevertheless, the bioenergy perspective provided a promising direction for future research, particularly in assessing trade-offs between food production and energy production in the post-conflict period.

A particularly important extension of the global dimension of this study is provided by L. Zhao *et al.* (2025), who developed a cascading failure model to assess global wheat supply security in the context of the war in Ukraine. Their research demonstrated that disruptions in Ukrainian grain exports generate nonlinear chain reactions across interconnected international markets, amplifying systemic risks far beyond the directly affected region. An additional macroeconomic and methodological dimension is introduced by L. Zomchak & T. Kukhotska (2025), who applied an autoregressive modelling approach to forecast food prices in Ukraine under conditions of heightened uncertainty.

Comparative international perspectives further contextualised the findings of this study. S. Rieznik & H. Lee (2025), drawing on the experience of rural development in war-torn South Korea, demonstrate that coordinated public policies, long-term investment strategies, and institutional reforms are crucial for successful agricultural recovery. Their findings support the study's argument about the importance of institutional capacity and strategic planning. However, the Ukrainian case is significantly different in terms of scale, geopolitical context, and global integration, requiring adapted recovery strategies rather than direct policy transfer. Overall, the reviewed literature largely supports the key assumptions and conclusions of this study. At the same time, this study makes a significant contribution by synthesising environmental, institutional, market, and social dimensions into a single analytical framework. Unlike

many existing studies that consider individual aspects of the problem in isolation, this article clearly identifies resource constraints as a key driver of recovery, as well as institutional and market challenges. This hierarchical interpretation provides a clearer basis for prioritising policy interventions and allocating financial resources.

CONCLUSIONS

The results of the study showed that the total losses of the Ukrainian economy as of mid-2026 could amount to 589 billion US dollars, 72 billion of which will fall on agriculture. Such losses can have a significant negative impact not only on the state of food security within the country, but also affect the level of food security in the world. The reduction in Ukrainian agri-food exports is dangerous for a number of countries that are almost completely dependent on it. However, despite the negative trends in the destruction of agricultural production potential, Ukraine is increasing exports of agricultural products to the European Union.

Among the main causes of indirect losses to the agricultural production complex of Ukraine, it is worth highlighting the decrease in crop yields due to pollution and soil degradation; a decrease in gross harvest due to the inaccessibility of sown areas due to hostilities; an increase in production costs and inflation. The estimated amount of financial resources needed to restore Ukraine's agricultural potential could exceed $55 billion. This funding will be required to address issues related to agricultural land demining and reclamation, restoration of logistics and production infrastructure, provision of financial support to agricultural producers, increasing the competitiveness of Ukrainian products. The prospect of further research includes modeling scenarios for the restoration of individual branches of Ukrainian agriculture in the post-war period with the calculation of their economic efficiency. A separate study is required to study the impact of the set of economic, social, security and environmental factors that determine the achievement of food security on the priority of the restoration of individual elements of the agro-food complex of Ukraine.

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CONFLICT OF INTEREST

None.

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Україна як гарант продовольчої безпеки світу: виклики на шляху до відновлення агровиробничого потенціалу

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Анотація. Головною метою цього дослідження був аналіз викликів, що постають перед Україною в процесі намагання зберегти та відновити її агровиробничий потенціал, що зазнав суттєвого руйнування внаслідок ведення бойових дій на території держави. У дослідженні було використано бібліометричний аналіз (із використанням Google Scholar, Scopus Preview та пакета Bibliometrix), системно-структурний аналіз і синтез, а також історичні, діалектичні, графічні та описово-статистичні методи. Дослідження продемонструвало, що попри руйнування агровиробничого потенціалу, Україна залишається важливим постачальником сільськогосподарської продукції для багатьох імпортозалежних регіонів світу. У статті було підкреслено, що світові продовольчі ринки продовжують залишатися нестабільними, що підтверджується Індексом продовольчих цін, який досяг 127,8 пункти у 2025 році, демонструючи вразливість продовольчих систем до геополітичних шоків. За оцінками експертів, станом на першу половину 2026 року сукупні втрати від руйнувань української економіки внаслідок війни можуть сягнути 589 млрд доларів, з яких близько 72 млрд доларів припадатиме на сільське господарство. Визначено, що в структурі непрямих втрат сільськогоподарського сектору України внаслідок війни найбільший вплив мали чинники скорочення продуктивності виробництва, зниження цін на продукцію через порушення експорту та зростання виробничих витрат. Зазначено, що потенційні витрати на реконструкцію аграрного сектору України в період з 2025 по 2035 роки можуть перевищити 55 млрд доларів, а витрати на розмінування сягнути майже 30 млрд доларів. Встановлено, що експорт української аграрної продукції до ЄС досяг майже 12,8 млрд доларів США у 2024 році, що демонструє стійкість аграрного сектору України та поглиблення інтеграції до європейських ринків. Практична цінність дослідження полягає у комплексній оцінці аграрних втрат України, спричинених війною, аналізі їхніх глобальних наслідків та визначенні стратегічних заходів відновлення

Ключові слова: вплив війни на сільське господарство; продовольчі ланцюги постачання; порушення експорту; забруднення земель; відбудова сільськогосподарського комплексу

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Inventory as a tool for assessing and preserving the property potential of an agricultural enterprise

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Abstract. The article emphasised the importance of inventory as a means of assessing and maintaining the property potential of agricultural enterprises amidst increasing business risks and environmental instability. The purpose of the study was to deepen the theoretical and methodological foundations of stock management in agricultural enterprises from the perspective of its functional significance in property potential management. The study's methodology included general scientific and specialised methods, such as analysis and synthesis, observation, generalisation, grouping, and the institutional approach. The study examined the composition and structure of property potential in agricultural enterprises, identified the specific features of inventory for individual asset groups taking into account sectoral characteristics, and systematised the functions of inventory

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within the property management system. The results demonstrate that inventory ensures consistency between the actual condition of assets and accounting data, improves the quality of managerial decisions, and minimises the risk of property loss by performing interrelated control, informational, analytical, and managerial functions. The study classified the main risks of property potential loss into organisational, accounting, technical, and external categories and proposed effective, inventory-based mechanisms to limit them. Additionally, the study developed methodological approaches to differentiate inventory procedures, considering the specifics of biological assets and production stocks. The necessity of a differentiated, risk-oriented approach to organising inventory procedures was substantiated. The practical significance of the results lies in the possibility to use the recommendations to strengthen internal control, plan asset renewal strategically, and improve property management efficiency in agricultural enterprises

Keywords: internal control; asset management; accounting information; biological assets; risk minimisation; production stocks

INTRODUCTION

Modern agricultural production operates under conditions of critical vulnerability of its asset base, which is caused not only by market instability but also by specific industry factors: the biological nature of the assets, their geographical dispersion, and the seasonal nature of their use. In the context of disrupted logistics chains and growing security threats, the traditional reliance solely on documentary accounting data becomes insufficient, as it often leads to a distorted view of the actual state of resources. The lack of an effective system for physical verification of assets leads to risks of hidden losses, waste of supplies, and inefficient use of equipment, which directly threatens the financial stability of agricultural producers. This highlights the need to rethink existing management tools capable of ensuring not only the recording of asset availability but also their qualitative assessment and physical preservation.

One of the key tools for asset management is inventory, which goes way beyond a mere formal data reconciliation. Researchers S.V. Bardash & N.P. Kuzyk (2021) convincingly demonstrate how a strictly limited understanding of inventory as just an accounting method is invalid, emphasising its independent significance within a company's capital control system. Developing this idea in the context of industry-specific characteristics, researchers O.V. Leha *et al.* (2025) determined that in agricultural enterprises, inventory takes on the form of a comprehensive internal control method that allows not only for confirming the presence of resources but also for evaluating the effectiveness of their use at various stages of the operational cycle.

Ensuring the accuracy of accounting information remains a critical aspect. According to L.V. Hutsalenko & Yu.M. Nykitenko (2023), inventory serves as a safeguard for the reliability of financial statements, minimising information risks for stakeholders. At the same time, researcher N.S. Marushko (2023), considering the internal control system as a mechanism for preventing fraud, pointed out that regular inventory procedures create effective barriers against abuse and the illegal disposal of assets, which is critical for ensuring the economic security of the enterprise. A separate body of research is devoted to the specific nature of agricultural assets, which significantly complicates valuation procedures. In particular, in the work by P. Campos-Llerena *et al.* (2025), based on a systematic review of the application of international standards, the complexities of accounting for and valuing biological assets were analysed; these assets require adaptive approaches to inventory due to biological transformation processes.

The current challenges associated with war and uncertainty have given rise to new scholarly perspectives on the role of inventory in asset preservation. A group of researchers led by V. Lytvynenko *et al.* (2024) justified the use of asset and liability inventory as a basic tool for restoring accounting in agricultural enterprises affected by military operations. At the same time, researchers V. Zhuk *et al.* (2023) developed approaches to assessing war-related losses in agribusiness, where inventory is viewed as the primary procedure for recording losses and establishing an evidentiary basis. In light of the above, it is timely to deepen the theoretical and methodological foundations for the application of inventory in agricultural enterprises from the perspective of its role in assessing and preserving asset potential. This necessitates the generalisation of scientific approaches, the clarification of the functional purpose of inventory, and the determination of its place in the asset management system of agricultural enterprises. The aim of the study was to expand the theoretical and methodological foundations for the application of inventory in agricultural enterprises, taking into account its functional role in managing asset potential, as well as to systematise the functions of inventory and the

risks of asset loss, and to justify methodological approaches to their minimisation.

MATERIALS AND METHODS

The methodological basis of the study consisted of a combination of general scientific and specialised research methods, the application of which enabled a comprehensive solution to the set tasks. The method of theoretical generalisation and the abstract-logical method were applied to reveal the essence of inventory and the transformation of its role in modern economic conditions. Using the method of analysis and synthesis, the significance of inventory as a key tool for assessing and preserving the asset potential of an agricultural enterprise was substantiated, and causal relationships between the quality of accounting information and the effectiveness of management decisions were identified. The observation method was used to evaluate existing organisational approaches to inventory, documenting its results, and identifying deficiencies in the internal control system that affected the reliability of accounting data. Methods of specification, grouping, and comparison were employed to systematise approaches to inventory within the enterprise's accounting and control system, which enabled the classification of identified problems and the formulation of research conclusions. A significant place in the research methodology was occupied by the functional approach, which was applied to identify and thoroughly substantiate the control, informational, analytical, and managerial functions of inventory. This allowed to view inventory not as a static procedure, but as a dynamic process that provides management with relevant information. The study also employed a risk-based approach and elements of factor analysis. These methods made it possible to systematise the internal (organisational and accounting) and external risks of asset loss at agricultural enterprises, assess the extent of their impact, and identify effective inventory mechanisms to mitigate them.

An institutional approach was applied to critically analyse the legal framework governing inventory of assets and liabilities. A content analysis was conducted of the provisions of Law of Ukraine No. 996-XIV (1999) and Order of the Ministry of Finance of Ukraine No. 879 (2014). To account for the specifics of wartime and approaches to recording losses, provisions regarding the determination of damage caused to Ukraine as a result of armed aggression (Resolution of the Cabinet of Ministers of Ukraine No. 326, 2022) were additionally utilised. Furthermore, the methodological framework was supplemented with methods of applied managerial and regulatory-analytical analysis. Their application provided a rationale for specific methodological approaches to the organisation and frequency of inventory for certain asset groups (biological assets, production inventories), and also served as the basis for formulating strategic management decisions aimed at preserving, updating, and restoring the property potential of an agricultural enterprise under conditions of uncertainty. The analysis of regulatory requirements was supplemented by a synthesis of scientific approaches to the classification of asset management risks and the organisation of inventory procedures. Based on the results obtained, a logical grouping of risk factors was carried out according to the nature of their manifestation and the scope of their impact on individual components of the asset base. This enabled the development of an analytical classification of risks and corresponding inventory mechanisms for their minimisation, systematised in the tables in the following section.

The procedures for assessing the actual condition of assets as part of inventory are examined with regard to their economic nature and accounting specifics. For fixed assets, the process includes a physical inspection, reconciliation of inventory numbers with accounting records, and analysis of technical documentation and certificates of suitability or defects. For production inventories, methods of physical recounting or weighing were applied, as well as monitoring of storage conditions and shelf life. Regarding biological assets, an inspection of their actual condition, reconciliation with primary movement documents, and recording of losses or seasonal deviations were taken into account. The information base for the study consisted of scientific publications on the issues of asset inventory, internal control, and management of enterprises' property potential, published primarily between 2008 and 2025. Sources were selected based on criteria of thematic relevance, scientific novelty, and methodological significance for the agricultural sector. The theoretical provisions and conceptual approaches outlined in the works of M.Ya. Demianenko & V.V. Chudovets (2008), N.M. Mezentseva *et al.* (2020), O.S. Vysochan *et al.* (2024), and other researchers, were used as the basis for summarising scientific positions and constructing analytical generalisations. These systematic approaches served as the basis for the structural-logical generalisations presented in Tables 1-5.

RESULTS

The asset potential of an agricultural enterprise and the role of inventory in its assessment

The asset potential of an agricultural enterprise is shaped by a combination of tangible, intangible, and financial resources that ensure the continuity of the production process and form the basis for achieving strategic development goals. Within the structure of this potential,

fixed assets, production inventories, biological assets, and other property elements occupy a special place; their effective use determines the enterprise's level of financial stability and its ability to adapt to changes in the external environment. Under these conditions, a reliable assessment of asset potential becomes a key management challenge, the resolution of which is impossible without the proper organisation of inventory procedures.

Inventory ensures that the actual quantity and condition of assets match the accounting records, thereby providing an objective picture of the company's actual asset base. Unlike a purely accounting-based approach, which relies on data from registers and financial statements, inventory allows for a direct assessment of the physical condition of assets, their degree of wear and tear, suitability for further use, and participation in the production process. It is this feature that determines its significance as a tool not only for control but also for the assessment of property resources in a broader economic context (Vysochan & Vysochan, 2018). For agricultural enterprises, inventory has additional significance due to the specific nature of their asset structure. The presence of biological assets, the seasonality of production, and the dependence of performance on natural and climatic conditions complicate the process of assessing asset potential and increase the risk of distorting accounting information. Under such conditions, inventory serves as a mechanism for determining the value and actual condition of assets, which is particularly important for making management decisions regarding production planning, cost optimisation, and ensuring the continuity of the enterprise's operations. The information obtained as a result of inventory procedures is used as an analytical basis for making management decisions regarding the optimisation of the asset structure and improving the efficiency of their use. The results of the audit may serve as a basis for determining the feasibility of repairing, modernising, or writing off assets, adjusting procurement and inventory policies, and strengthening internal controls over the preservation of property. Inventory serves both a control and an informational-analytical function within the enterprise management system.

The practical significance of inventory is evident in typical management situations that arise in the activities of agricultural enterprises. If surpluses or discrepancies are identified in production inventories, the results of the audit can serve as a basis for adjusting inventory levels and revising logistics decisions. The identification of unserviceable or obsolete fixed assets justifies decisions regarding their modernisation or write-off. Recording losses or deviations in the condition of biological assets may necessitate adjustments to production plans and internal control measures. Inventory results allow for the identification of both available resources and property losses, surpluses, and unused or inefficiently utilised assets. This creates the conditions for adjusting accounting data, revising management approaches, and increasing the transparency of information regarding the company's financial condition. In this context, inventory serves an informational function, providing enterprise management with relevant data to assess the level of asset potential and determine directions for its preservation and development (Demianenko & Chudovets, 2008). An analysis of the composition of an agricultural enterprise's asset potential indicates that its structure is heterogeneous and requires a differentiated approach to evaluating individual asset groups. Fixed assets form the material basis of production, production inventories ensure the continuity of the operational cycle, and biological assets combine the characteristics of property and the results of production activities. Inventory allows for the reconciliation of accounting figures for each of these asset groups with the actual state of the assets, which is a necessary condition for an objective assessment of the enterprise's overall asset potential. In general, inventory should be viewed as a system-forming tool for assessing the asset potential of an agricultural enterprise, which ensures the reliability of accounting information, improves the quality of management decisions, and creates an information basis for further analysis of the efficiency of asset utilisation. It is at this stage that the basis for the implementation of the control and management functions of inventory is formed, which determines its significance in the process of preserving the enterprise's asset potential. A summary of scientific approaches to determining the composition and structure of an enterprise's asset potential is systematised in Table 1.

Table 1. *Composition and structure of an agricultural enterprise's asset base*

Component of the Asset Base	Assets and Identification Characteristics	Inventory Procedures/Verification Tests	Analytical Interpretation for the Assessment
Fixed assets	Buildings, structures, machinery, equipment	Actual presence; reconciliation of inventory numbers and technical passports; assessment of technical condition and suitability; confirmation of rights to the asset	Form the material basis of production
Production inventories	Raw materials, supplies, fuel	Recounting/weighing; reconciliation of batches and storage locations; assessment of storage conditions and shelf life; verification that inventory levels meet production needs	Ensure operational continuity

Table 1, Continued

Component of the Asset Base	Assets and Identification Characteristics	Inventory Procedures/Verification Tests	Analytical Interpretation for the Assessment
Biological assets	Plants, livestock	Inspection and confirmation of quantitative indicators (livestock/area); reconciliation with movement records; assessment of condition and losses; recording of seasonal variations	Combine production and financial functions
Other assets	Intangible and circulating assets	Documentary reconciliation of rights and availability; confirmation of the reality of balances; verification of contracts/registers; clarification of asset classification	Supplement the overall asset potential

Source: *compiled by the authors based on M.Ya. Demianenko & V.V. Chudovets (2008), O.S. Vysochan & O.O. Vysochan (2018)*

The structure of an agricultural enterprise's asset base is multifaceted and requires a systematic approach to assessment. The results of the inventory ensure that the actual status of individual asset components aligns with accounting data, thereby forming the informational foundation for a comprehensive analysis of the asset base. At this stage, inventory goes beyond a purely control procedure and takes on a managerial dimension, as it allows for the identification of structural imbalances, opportunities to improve the efficiency of asset utilisation, and potential threats to their preservation. This determines the relevance of further consideration of the functional significance of inventory in the asset management system of an agricultural enterprise.

Functions of inventory in the asset potential management system of an agricultural enterprise

Inventory in the asset management system of an agricultural enterprise performs interrelated functions that ensure the practical implementation of asset potential assessment based on actual data. Its functional content can be reasonably considered through the lens of control, informational, analytical, and managerial components, which together form a methodological basis for decision-making regarding the preservation and use of assets (Demianenko & Chudovets, 2008; Vysochan & Vysochan, 2018).

The control function consists of establishing the compliance between the actual availability of assets and accounting data, as well as verifying adherence to storage conditions. Its result is the recording of deviations (shortages, surpluses, spoilage), identification of their causes, and the creation of grounds for corrective managerial actions. Within this function, stock-taking serves as a tool to ensure material responsibility and discipline in asset preservation, which is critically important for resource-intensive types of agricultural activities (Demianenko & Chudovets, 2008).

The informational function is implemented by generating relevant information about assets as of a specific date, particularly regarding their quantitative and qualitative characteristics and condition. Such data improve the quality of managerial information support, as they allow the comparison of accounting evaluations with the actual parameters of assets, reducing the risk of decision-making based on incomplete or distorted information (Vysochan & Vysochan, 2018).

The analytical function of inventory lies in the ability to assess the structure of assets, their usability, the degree of asset involvement in the production process, and the identification of reserves to enhance the efficiency of asset utilisation. Inventory results provide an empirical basis for analysing asset dynamics, justifying decisions on optimising inventory composition, assessing the feasibility of repairing or replacing fixed assets, and refining organisational parameters for storage and accounting (Mezentseva *et al.*, 2020).

The managerial function ensures the transformation of inventory data into managerial decisions aimed at preserving and developing asset potential. Based on this function, measures are determined to strengthen internal control, improve accountability procedures, optimise resource provision, reduce losses, and increase the efficiency of asset use within the enterprise's operational activities. In this context, stock-taking serves as a feedback tool, enabling the adjustment of managerial influences according to the actual state of assets (Mezentseva *et al.*, 2020). The functional significance of inventory in managing the asset potential of an agricultural enterprise is summarised in Table 2.

Table 2. *Functions of inventory and their significance in managing the asset potential of an agricultural enterprise*

Function	Function Manifestation		Managerial Application
	Informational Result	Control-Evaluation Result	
Control	Recording the actual availability and condition of assets	Identifying deviations (shortages/surpluses/spoilage) and their causes	Loss prevention; strengthening financial responsibility
Informational	Updated data on quantity, quality, and condition of assets on the stock-taking date	Confirming the reliability of accounting indicators	Improving the quality of management decisions and resource planning

Table 2, Continued

Function	Function Manifestation		Managerial Application
	Informational Result	Control-Evaluation Result	
Analytical	Indicators for analysing asset structure and utilisation	Identification of inefficiently used or unsuitable assets	Identifying efficiency reserves; optimising the asset structure
Managerial	Basis for adjustments in asset management policies	Monitoring the implementation of decisions based on stock-taking results	Implementing measures to preserve and develop asset potential

Source: *compiled by the authors based on M.Ya. Demianenko & V.V. Chudovets (2008), O.S. Vysochan & O.O. Vysochan (2018), N.M. Mezentseva et al. (2020)*

The systematisation of stock-taking functions indicates its comprehensive role in forming managerial influence on the asset potential of an agricultural enterprise. The interrelated implementation of control, informational, analytical, and managerial functions creates conditions for timely identification of factors threatening asset preservation, as well as for justifying managerial decisions aimed at minimising losses and enhancing asset utilisation efficiency. This underscores the need for further research on risks of asset potential loss and the role of inventory in their prevention and mitigation.

Risks of asset potential loss in agricultural enterprises and the role of inventory in their minimisation

The asset potential of an agricultural enterprise is affected by a complex of risks arising both within the internal environment and under external influences. These risks vary in nature and impact, but collectively they can lead to direct and indirect asset losses, reduce reproductive capacity, and deteriorate financial performance. In this context, stock-taking acts not only as a tool for recording the consequences of risks but also as a mechanism for their early detection and limitation.

Internal risks to asset potential include organisational, accounting, and managerial risks associated with deficiencies in the internal control system, breaches of material responsibility, untimely updating of accounting data, and improper organisation of asset storage. In agricultural production, such risks are exacerbated by the territorial dispersion of assets, numerous storage locations for material values, and the seasonal nature of certain asset groups. Stock-taking allows these risks to be localised by establishing the actual state of assets, verifying storage conditions, and identifying deviations from established norms.

External risks are related to the impact of macroeconomic, institutional, and climatic factors. Market price fluctuations, changes in the regulatory framework, emergencies, and adverse weather conditions directly affect the preservation and valuation of assets in agricultural enterprises. In such conditions, stock-taking plays a stabilising role by updating accounting data and providing an informational basis for adapting managerial decisions to changes in the external environment.

A separate group includes risks associated with physical wear and moral obsolescence of assets, which is typical for technically complex and capital-intensive property. The lack of timely information on the real technical condition of fixed assets leads to inefficient resource use, higher maintenance costs, and reduced production productivity. Stock-taking enables the identification of such risks through assessing asset suitability for further use and justifying the feasibility of repair, modernisation, or write-off.

Information-related risks also pose a significant threat to asset potential, arising from discrepancies between actual asset conditions and accounting data. Such discrepancies distort analytical results, complicate the evaluation of asset utilisation efficiency, and reduce the validity of managerial decisions. In this case, stock-taking serves as a tool to restore informational reliability by adjusting accounting indicators to the actual state of resources. A generalised classification of risks and corresponding stock-taking mechanisms for their mitigation is presented in Table 3.

Table 3. *Risks of asset potential loss in agricultural enterprises and inventory mechanisms for their mitigation*

Risk Group	Typical Manifestations and Sources	Potential Consequences for Asset Potential	Stock-Taking Safeguards and Control Actions
Organisational	Violations of storage conditions, weak internal control	Physical losses, spoilage, unauthorised movement; reduced asset reproductive capacity	Inspection of storage locations; reconciliation of responsible personnel; stock-taking records; recording violations and directives
Accounting	Discrepancy between actual and accounting data	Distorted asset valuations in reports; errors in managerial calculations; financial losses due to unreliable data	Reconciliation of registers and actuals; documentary confirmation of balances; reflecting stock-taking results in accounting
Technical	Physical wear and moral obsolescence of assets	Accelerated asset retirement; increased repair costs; reduced productivity and reliability of production processes	Assessment of technical condition; suitability/defect certificates; clarification of useful life; decisions on repair/write-off

Table 3, Continued

Risk Group	Typical Manifestations and Sources	Potential Consequences for Asset Potential	Stock-Taking Safeguards and Control Actions
Informational	Distorted data for analysis and management	Incomplete reflection of assets; loss of resource control; reduced quality of planning and analysis	Verification of accounting completeness; identification of unrecorded assets; elimination of duplicates; updating inventory cards
External	Influence of market and natural factors	Asset depreciation/loss due to force majeure; need to adjust valuations and plans; increased restoration costs	Recording losses and damages; documenting causes; adjusting value/condition; forming grounds for managerial recovery measures

Source: *compiled by the authors based on M.Ya. Demianenko & V.V. Chudovets (2008), O.S. Vysochan & O.O. Vysochan (2018), N.M. Mezentseva et al. (2020)*

The identified risk groups and inventory mechanisms for their limitation confirm the need for a differentiated approach to organising inventory procedures, taking into account the specifics of the assets and the operating conditions of agricultural enterprises. This necessitates the generalisation of methodological approaches to inventory, aimed at increasing its effectiveness in the process of assessing and preserving property potential.

Methodological principles for organising inventory

The effectiveness of inventory as a tool for assessing and preserving the asset potential of an agricultural enterprise largely depends on the methodological approaches to its organisation and implementation. The industry-specific nature of agricultural production necessitates the adaptation of general inventory procedures to the characteristics of assets, conditions of their use, and the seasonal nature of activities. This entails the differentiation of approaches to inventorying individual asset groups and determining the optimal frequency of its execution. One of the key methodological prerequisites is a clear identification of inventory objects, taking into account their economic purpose and role in forming the asset potential. For fixed assets, primary importance is given to evaluating their technical condition, degree of wear, and suitability for further use. Production stocks require control not only in terms of quantitative indicators but also regarding storage conditions, usage periods, and compliance of actual balances with normative production needs. Biological assets demand a special approach, as they combine the properties of property and the results of the production process, which complicates their inventory assessment. An important methodological aspect is determining the frequency of conducting inventory. For agricultural enterprises, it is advisable to combine mandatory annual inventories with selective or unscheduled checks during periods of increased risk of asset loss. This approach allows for the timely detection of deviations in asset status, reduces information gaps between actual and recorded asset conditions, and increases the operational efficiency of management decisions.

The methodological effectiveness of inventory is also determined by the level of coordination of the actions of inventory commissions, the quality of documentary recording of results, and the extent of their subsequent use in management. Formalisation of inventory procedures, clear assignment of responsibility, and provision for analytical processing of the obtained data create the prerequisites for transforming inventory from a formal control procedure into an effective tool for managing asset potential. A summary of methodological approaches to conducting inventory of the asset potential of an agricultural enterprise, taking into account industry-specific features, is presented in Table 4.

Table 4. *Methodological approaches to inventory of the components of the asset potential of an agricultural enterprise*

Inventory Object	Methodological Requirements and Managerial Focus
Fixed assets	Assessment of technical condition and serviceability. Justification for renewal and modernisation
Inventories	Control of quantities and storage conditions. Optimisation of stock levels and reduction of losses
Biological assets	Consideration of biological and seasonal factors. Ensuring continuity of production
Other assets	Verification of compliance with accounting records. Improvement of information reliability

Source: *compiled by the authors based on M.Ya. Demianenko & V.V. Chudovets (2008), O.S. Vysochan & O.O. Vysochan (2018), N.M. Mezentseva et al. (2020)*

The formulated methodological approaches to conducting inventory, taking into account the sectoral specifics of agricultural enterprises, create a basis for the practical use of its results in the process of asset management. Further analysis should be directed at determining managerial decisions made based on inventory results and assessing their role in preserving and restoring the asset potential of an agricultural enterprise.

Managerial decisions based on the results of inventory of the asset potential of an agricultural enterprise

The results of inventory form the informational basis for making managerial decisions aimed at preserving and restoring the asset potential of an agricultural enterprise. Their practical significance lies in the possibility of timely adjustment of managerial actions taking into account the actual condition of assets, identified deviations, and available reserves for increasing the efficiency of property use. In this context, inventory acts as an element of integrating accounting information into the enterprise management system. One of the key directions of using inventory results is substantiating managerial decisions regarding the renewal, modernisation, or disposal of assets. Data on the technical condition of fixed assets, their degree of wear, and suitability for operation make it possible to determine the feasibility of capital investments, optimise repair and maintenance costs, and prevent irrational use of resources. This is particularly important for agricultural enterprises where a significant share of asset potential is concentrated in machinery and production infrastructure.

The results of inventory are also used to optimise the management of production inventories and other current assets. The identification of surpluses, shortages, or slow-moving inventories creates the prerequisites for revising procurement policies, improving logistics processes, and reducing the level of losses during the storage and use of material resources. In this way, inventory contributes to increasing operational efficiency and preserving the asset potential of the enterprise. An important direction in the use of inventory data is strengthening the system of internal control and material responsibility. Information about the identified deviations makes it possible to identify problematic areas in the organisation of accounting and control, clarify the responsibility of officials, and implement preventive measures aimed at preventing repeated losses of property. This contributes to the formation of a discipline of asset preservation and increases the level of managerial responsibility. The application of inventory results in managing the asset potential also has a strategic dimension. Generalised inventory data can be used to assess long-term trends in changes in the structure of assets, determine the priorities of investment development, and form programs for restoring the asset potential. In this aspect, inventory ensures feedback between the current condition of property and the strategic goals of the development of an agricultural enterprise. The main directions of using inventory results in managing and preserving the asset potential of an agricultural enterprise are summarised in Table 5.

Table 5. *Use of inventory results in managing the asset potential of an agricultural enterprise*

Vector of using inventory results	Content of managerial interventions	Expected effect for the asset potential
Fixed asset management	Renewal, repair, write-off of assets	Increasing the efficiency of property use
Stock management	Optimisation of the volume and structure of inventories	Reduction of losses and costs
Internal control	Strengthening responsibility and control	Prevention of repeated losses
Strategic planning	Formation of property development programs	Preservation and restoration of asset potential

Source: *compiled by the authors based on M.Ya. Demianenko & V.V. Chudovets (2008), O.S. Vysochan & O.O. Vysochan (2018), N.M. Mezentseva et al. (2020)*

The systematic use of inventory results in managerial activities demonstrates its practical value as a tool for preserving and developing the asset potential of an agricultural enterprise. The alignment of inventory data with operational and strategic managerial decisions ensures greater justification of management actions aimed at minimising property losses, optimising the structure of assets, and strengthening internal control. This creates the basis for further scientific interpretation of the obtained results in the context of comparing them with the conclusions of other studies and determining prospects for the development of inventory practices in agricultural enterprises.

DISCUSSION

The obtained results indicate the expediency of a conceptual reconsideration of the role of inventory in the management system of an agricultural enterprise. The interpretation of the results points to the transformation of inventory from an auxiliary procedure for reconciling accounting data into an independent tool for managing asset potential. Such an approach corresponds with contemporary scientific discussions on strengthening the functions of internal control, while at the same time reflecting the sectoral specificity of Ukraine's agricultural sector.

Considering inventory as the foundation of internal control correlates with the results of foreign studies on asset management in emerging markets. N.Y. Accostupa Huamán & P.O. Vega Espilco (2023) note that insufficient control over fixed assets leads to financial losses and a decline in the liquidity of enterprises. The obtained results expand this thesis taking into account

the agricultural specificity, where the territorial dispersion of assets and production risks increase the probability of losing control. Unlike approaches focused mainly on financial consequences, this study emphasises organisational and technical risks that directly affect production potential. The position of Ukrainian scholars also demonstrates similar tendencies. O.V. Leha *et al*. (2025) define inventory as a comprehensive method of internal control in agricultural enterprises. Their approaches to assessing the efficiency of resource use at different stages of the operational cycle are consistent with the results of this study. A. Sakun (2024) emphasises the importance of informational support for control, the source of which is the verification of the actual condition of assets. The argument of S.V. Bardash & N.P. Kuzyk (2021) regarding the limitation of interpreting inventory only as a method of accounting supports a broader understanding of its managerial role.

In international research, considerable attention is paid to the problem of discrepancies between accounting data and the actual condition of inventories. A. Shabani *et al*. (2021) point to the negative impact of accounting inaccuracies on planning and operational costs, while I.R. Destro *et al*. (2023) establish a relationship between the frequency of inspections and the efficiency indicators of distribution centers. In the agricultural sector, this problem is complicated by the biological nature of assets and the seasonality of production. This may be explained by the influence of natural losses and transformations that require the adaptation of standard procedures. The proposed differentiation of inventory measures for biological assets corresponds to the position of T. Rohova (2023) regarding the specifics of verifying living organisms.

The issue of digitalisation of inventory procedures is also actively discussed in contemporary literature. L.E. Fotoh (2025) draws attention to the gradual implementation of alternative digital methods for collecting evidence, while M. Salehi Shahrabi (2023) demonstrates the effectiveness of RFID technologies in reducing errors compared with manual counting. Ukrainian researchers L. Frundina & O. Artiukh (2020) emphasise the necessity of computerising the inventory process. At the same time, the results of this study indicate that for the agricultural sector a complete refusal of physical verification is premature. The position of O.M. Bondarenko & L.O. Rudenko (2022) regarding the improvement of inventory audit methodology is supported; however, the expediency of combining digital tools with professional assessment of the actual condition of assets is emphasised.

A separate direction of discussion concerns the valuation of biological assets. In a systematic review of the application of the IAS 41 standard, P. Campos-Llerena *et al*. (2025) emphasise the problem of subjectivity in determining fair value. The obtained results indicate that a well-organised inventory can reduce the level of such subjectivity through the verification of primary data. Similar approaches are supported by L.V. Hutsalenko & Yu.M. Nykitenko (2023), who link the reliability of information with the completeness of inventory procedures. Under conditions of martial law, inventory takes on additional importance. European studies, in particular Z. Gołaś (2020), consider inventory mainly under stable market conditions. In contrast, Ukrainian scholars V. Lytvynenko *et al*. (2024), O.S. Vysochan *et al*. (2024), and O.P. Kolisnyk *et al*. (2025) emphasise the role of inventory in restoring accounting and documenting losses. In this context, inventory may be considered as a mechanism for forming an evidentiary base regarding force majeure circumstances, which is also consistent with the approaches of V. Zhuk *et al*. (2022) and S.Y. Maksymov (2023). The integration of inventory into the system of economic security corresponds with the concept of internal control by N. Marushko (2023) and the classification of inventory challenges proposed by N.M. Mezentseva *et al*. (2020). The comparison of the research results with contemporary scientific approaches from 2020-2025 indicates a strengthening tendency toward expanding the functional content of inventory. The obtained generalisations demonstrate its importance as a tool for risk management, ensuring economic security, and maintaining the reliability of asset information. The practical implications lie in the necessity of implementing risk-oriented inspections, adapting procedures to biological specificity, and combining physical control with digital technologies. Consideration of these aspects creates the foundation for the further formulation of the final provisions of the study.

CONCLUSIONS

Inventory has been defined as an integrated element of the asset management system of an agricultural enterprise that ensures the alignment of the actual condition of assets with accounting data and increases the validity of managerial decision-making. It has been proven that this instrument forms a reliable information base for management, significantly reduces information gaps between accounting and actual indicators, and strengthens the controllability of property resources under conditions of uncertainty. The systematisation of the functional significance of inventory made it possible to reveal its role through the interaction of control, informational, analytical, and managerial components. It has been established that the comprehensive implementation of these functions ensures the timely

identification of deviations in the condition of assets, the identification of internal reserves, and the enhancement of the effectiveness of internal control, transforming inventory from a formal procedure into an effective management mechanism.

The classification of risks of loss of property potential into organisational, accounting, technical, informational, and external categories made it possible to determine the potential of inventory in preventing them. It has been established that regular verification of assets contributes to the detection of shortages, spoilage, obsolescence, and inefficiently used assets, which minimises unproductive losses and provides management with up-to-date data for responding to threats. The substantiation of methodological approaches to the adaptation of inventory procedures demonstrated the need to consider the sectoral specifics of agricultural production, primarily seasonality and the biological nature of assets. The proposed differentiated approach to inventory objects, along with the combination of scheduled inspections and selective control in high-risk areas, creates conditions for improving the effectiveness of assessment and the preservation of property potential. Prospects for further research are associated with the quantitative substantiation of the economic effect of implementing risk-oriented inventory procedures and the study of the impact of inventory on the turnover and profitability indicators of assets of agricultural enterprises.

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Інвентаризація як інструмент оцінки та збереження майнового потенціалу аграрного підприємства

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Анотація. У статті обґрунтовано роль інвентаризації як інструмента оцінки та збереження майнового потенціалу аграрного підприємства в умовах зростання ризиків господарської діяльності та нестабільності зовнішнього середовища. Метою дослідження було поглиблення теоретико-методичних засад застосування інвентаризації в аграрних підприємствах із позицій її функціонального значення в управлінні майновим потенціалом. Методологічну основу дослідження становили загальнонаукові та спеціальні методи, зокрема аналіз і синтез, спостереження, узагальнення, групування та інституційний підхід. Досліджено склад і структуру майнового потенціалу аграрного підприємства, визначено особливості інвентаризації окремих груп активів з урахуванням галузевої специфіки, а також систематизовано функції інвентаризації в системі управління майном. У роботі доведено, що інвентаризація виконує взаємопов'язані контрольну, інформаційну, аналітичну та управлінську функції, які забезпечують узгодження фактичного стану активів із даними бухгалтерського обліку, підвищують якість управлінських рішень і сприяють мінімізації ризиків втрати майна. У роботі було класифіковано основні ризики втрати майнового потенціалу на організаційні, облікові, технічні й зовнішні та запропоновано дієві інвентаризаційні механізми їх обмеження. Крім того, розроблено методичні підходи до диференціації інвентаризаційних процедур, які врахували специфіку біологічних активів і виробничих запасів. Обґрунтовано доцільність диференційованого та ризик-орієнтованого підходу до організації інвентаризаційних процедур. Практичне значення отриманих результатів полягало в можливості використання запропонованих рекомендацій для посилення внутрішнього контролю, стратегічного планування оновлення активів та підвищення ефективності управління майном аграрних підприємств

Ключові слова: внутрішній контроль; управління активами; облікова інформація; біологічні активи; мінімізація ризиків; виробничі запаси

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Digitalisation of accounting and tax functions for agricultural enterprises

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Abstract. The study aimed to identify the characteristics of the digitalisation of accounting and tax processes in agricultural enterprises, whilst assessing its impact on financial performance. The study was based on a systematic approach, as well as generalisation, descriptive-analytical, structural-logical and statistical methods to examine enterprise information systems and digital tax administration services. The results of the study showed that the level of digitalisation of tax administration exceeds 98% for electronic filing, and the volume of electronic document flow has grown from 34.5 million documents in 2022 to over 82 million in 2024. In the electronic value-added tax administration system in 2024, tax invoices totalling approximately UAH 2,744 billion were processed, of which around UAH 54 billion (approximately 1.97%) were initially blocked, whereas, following unblocking procedures, the actual amount of blocked value-added tax stood at around UAH 14 billion, corresponding to approximately 0.5% of the total amount. An analysis of MHP's operations revealed a rise in revenue from USD 1,647 to USD 2,635 million (+60%) and capital expenditure from USD 92 to USD 210 million (+128%) in 2021-2025, alongside a reduction in net debt from USD 1,164 to USD 900 million. Kernel has achieved a reduction in net debt from USD 836 million to USD 143 million (-83%), as well as the automation of processing up to 240,000 electronic consignment notes per season and a reduction in document verification time by 80%. Areas for improvement include the integration of accounting systems with tax services, the use of cloud technologies and analytical tools, and the automation of data processing to enhance data consistency and accelerate accounting processes. The practical significance of the study is determined by the possibility of its results being used by agricultural enterprises to optimise accounting and tax processes, improve the efficiency of financial flow management and reduce costs

Keywords: automation; document management; administration; efficiency; monitoring; analytics

INTRODUCTION

The transformation of economic processes, determined by digital technologies, is accompanied by a shift in approaches to the generation, processing and transmission of financial information within enterprises. In agriculture, these processes are combined with the specific nature of production, characterised by seasonality, the presence of biological assets, dependence on natural and climatic conditions, and the use of state support programmes, which place additional demands on accounting and tax procedures. The functioning of accounting and tax administration in such conditions involves the processing of significant volumes of heterogeneous data, the need to comply with regulatory requirements, and ensuring consistency between financial and tax information.

The growth in data volumes, the increasing complexity of accounting procedures, and the need for the rapid generation of management information are

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driving a transformation in approaches to the organisation of accounting processes within agricultural enterprises. Research into the automation and digitalisation of management accounting has been conducted by S. Ihnatenko & I. Tomashuk (2024), who examined the implementation of digital technologies, in particular Enterprise Resource Planning (ERP) systems, the Internet of Things (IoT), Big Data, cloud services and analytical tools, as well as their impact on the processes of collecting, processing and systematising information. The authors found that the use of digital solutions ensures faster data processing, greater accuracy of accounting information, the ability to integrate various information systems and expand analytical management functions, as well as facilitating the optimisation of document flow and the application of new technologies, in particular blockchain, for data protection and transparency. A comparison of traditional and digitised accounting systems was conducted by O. Yakubyshyn (2025); in particular, specialised software products, electronic document management and reporting services were characterised, and directions for the transformation of accounting processes under the influence of digital technologies were outlined. The findings indicated that digitalisation facilitates the automation of data processing, the generation of real-time reports, the integration of accounting systems with tax administration services, and an increase in the transparency and reliability of information; however, it is accompanied by cybersecurity risks, the need to modernise infrastructure, and rising demands on staff qualifications.

The growth in the volume of digital data is driving a transformation in approaches to the organisation of accounting and taxation, as explored by I. Balaniuk & T. Ivanyuk (2022). The paper explored the application of cloud technologies, artificial intelligence, blockchain, big data and the Internet of Things in accounting and taxation consultancy, as well as their impact on the automation of information processing and changes to accounting procedures. The study established those digital solutions reduce data processing time and minimise errors, whilst requiring the updating of professional competencies. Theoretical approaches to the digital transformation of accounting systems, as researched by O.L. Polyova *et al*. (2024), revealed the application of information technologies, automated solutions and software products for the collection, processing and analysis of financial and operational data, and identify directions for the integration of accounting systems with management processes. As a result, the study established that the use of digital technologies ensures an increase in the efficiency of accounting processes, a reduction in the time taken to process information, an improvement in the quality of financial reporting, and the integration of accounting and management systems, as well as creating conditions for the generation of analytical and predictive information in real time.

The need to transition to digital forms of accounting, reporting and taxation is determined by the growth in data volumes, the need to automate information processing and ensure the accuracy of financial indicators. The introduction of digital technologies, as identified by N. Brazil *et al*. (2023) in their study ensured the acceleration of information collection, processing and analysis, reduce the number of errors in reporting and automate routine operations, as well as facilitating the transition from paper documents to electronic formats, which enhances the efficiency of accounting systems and the transparency of interactions with regulatory authorities. At the same time, it has been established that digitalisation expands access to information, ensures data integration and improves compliance with tax requirements, including the use of electronic reporting and digital platforms for public services. The application of digital solutions in production and management processes, as identified by V. Lesiuk (2021), helped to reduce the number of operations, minimise paper-based document flow, decrease the number of errors and increase labour productivity, as well as enabling the use of innovative tools, in particular robotic systems, sensors and analytical models for management decision-making. The study also established that digitalisation encompasses both the automation of internal processes and the integration of technologies into production activities, which improves economic efficiency and competitiveness of enterprises.

The growing volume of financial information, the need to improve the accuracy of accounting data and to ensure the timely preparation of reports necessitate the use of digital technologies in business operations. The organisation of accounting in the agricultural sector, considering the impact of digital technologies, was studied by P. Nesenenko (2022), who examined the application of automated accounting systems, electronic document management and information platforms for processing financial data. The findings indicated that the use of digital solutions enhances the efficiency of accounting processes, ensures the timely preparation of reports, reduces labour costs associated with information processing, and strengthens control over financial transactions.

At the same time, further research is required into the integration of accounting and tax services, data consistency, the refinement of digital transformation methodologies, the assessment of the impact of technology, and the assurance of information security. This

study aimed to identify the specific features of the digitalisation of accounting and tax processes in agricultural enterprises and to determine their impact on financial results. To achieve this objective, the following tasks were set: to analyse approaches to the implementation of digital technologies in the accounting and tax processes of enterprises; to investigate tools for the automation of accounting operations and tax administration in agriculture; and to assess the impact of digitalisation on the financial results of Myronivsky Hliboproduct (MHP) and Kernel.

MATERIALS AND METHODS

The study was empirical in nature and covered the period 2021-2025, with additional data from January-February 2026. The chosen time frame was determined by the need to cover the period of implementation of digital solutions in the accounting and tax records of agricultural enterprises, including transformational changes after 2022, as well as the opportunity to track the dynamics of financial indicators and the development of digital services in the medium term; the inclusion of data for early 2026 has made it possible to reflect the current level of use of electronic services.

The study employed a systematic approach to analysing the organisation of accounting processes in agricultural enterprises, within which accounting was viewed as a set of interrelated processes determined by the specific nature of production and external operating conditions. The method of generalising scientific approaches was used to justify the feasibility of applying digital technologies and to identify directions for the transition to electronic data processing and remote control of business operations (Oleynikova & Dolzhenko, 2020). The analysis of the software products Business Automation Software (n.d.), MeDoc (2024a; 2024b) and SAP Business One (n.d.) was conducted using a descriptive-analytical research method to determine their functional capabilities, level of automation and compliance with tax regulation requirements. A functional-instrumental approach was used to study ERP systems, within the framework of which the integration of financial, managerial and tax accounting was assessed, as well as the possibilities for creating a unified information environment for the enterprise (Shyhun & Zhuravel, 2021).

The study analysed the use of digital tax administration services by Ukrainian enterprises in 2022-2024, identifying the mechanisms for taxpayers' interaction with the State Tax Service and the specific features of its electronic services. The analysis of the functioning of the electronic value-added tax administration system was conducted using the structural-logical analysis method, which addressed procedures for registering tax invoices and adjustment calculations, the mechanisms for monitoring compliance with the "first event" principle, as well as the processes of blocking and subsequently unblocking documents in the Unified Register of Tax Invoices. To assess the scale of blocking and the volume of value-added tax, the method of statistical analysis of open data was used, analysing the following indicators:

- number of taxpayers for whom the registration of tax invoices/adjustment calculations (TI/AC) has been blocked;
- total number of blocked tax invoices/correction notes;
- amount of value added tax (VAT) on blocked tax invoices/correction notes;
- proportion of blocked documents out of the total number submitted for registration;
- volume and proportion of unblocked tax invoices/credit notes;
- amount of VAT following the unblocking procedures;
- total amount of VAT submitted for registration in the Unified Register of Tax Invoices.

This has made it possible to describe the characteristics of how the electronic value-added tax administration system operates in tax administration practice (Potaeva, 2025). MHP (2021; 2022; 2023; 2024; 2025) was selected for the case study due to the scale of its operations, its vertical integration and its use of comprehensive digital systems. For MHP, the implementation of the SAP Suite 4 High-Performance Analytic Appliance (S/4HANA) system, which includes the Run Intelligent Sustainable Enterprise (RISE) model, was considered. The SAP Material Management (MM) and SAP Production Planning (PP) modules were analysed separately. Additionally, SAP SuccessFactors was considered in combination with the proprietary vZoo system using the functional analysis method, which can be used for investigation of the integration of production, financial and management processes. The dynamics of MHP's financial indicators (revenue, earnings before interest, taxes, depreciation and amortisation (EBITDA), operating profit, net profit, capital expenditure (CAPEX), net debt, Net Debt/EBITDA) for 2021-2025 were analysed based on consolidated financial statements.

For Kernel (2021; 2022; 2023; 2024; 2025), the implementation of Microsoft Dynamics NAV (Navision) 2018 and its integration with KernelEDocs, based on Microsoft SharePoint, were examined. The use of Microsoft Dynamics 365 Business Central in international divisions was analysed separately using the functional

analysis method, which was used the investigation of the digital integration of business processes. The automation of electronic consignment notes was analysed using the process analysis method, which addressed changes in settlement times with carriers, the accuracy of source documents, the workload on accounting departments, and document loss (Tarasovsky, 2026). The dynamics of Kernel's financial indicators (revenue, EBITDA, operating profit, net profit, net debt, Net Debt/EBITDA) for 2021-2025 were analysed based on financial statements using statistical analysis and the calculation of relative indicators (2021/2025, 2024/2025), which made it possible to assess changes in financial indicators over time.

Based on the results obtained, a generalisation method was applied to identify areas for improving the digitalisation of accounting and tax processes for MHP and Kernel, which was used for development of approaches to enhance the efficiency of financial information processing. A limitation of the study is that the analysis is based on open data and aggregated indicators of digital services, which limits the detail of the assessment of the enterprises' internal accounting processes.

RESULTS AND DISCUSSION

State of digitalisation in the accounting and tax functions of agricultural enterprises in Ukraine

The operations of agricultural enterprises are characterised by dependence on natural and climatic conditions, the seasonal nature of production, and a significant volume of business transactions, which create specific conditions for the organisation of accounting processes. Such activities are accompanied by a heightened level of risk and require the processing of large volumes of diverse information, which complicates the preparation of reliable financial and tax figures. The specific features of agricultural production necessitate the accounting for biological assets, land resources, as well as a significant number of settlement transactions related to tax liabilities and state regulation. Under these conditions, the organisation of accounting processes requires constant updating of information, prompt processing, and ensuring consistency between different types of data. As noted by L. Oleynikova & I. Dolzhenko (2020), the digitalisation of accounting involves a transition to processing information in electronic format, which was used for accounting operations to be conducted in real time, increases management flexibility, and can be used for remote monitoring of financial and economic activities. The use of digital solutions helps streamline accounting processes, reduce the labour intensity of information processing and improve the reliability of the data.

In Ukraine, localised software products adapted to the requirements of national legislation and the specific features of tax regulations are used for accounting purposes. The most widely used systems are Business Automation Software (n.d.), which is used for recording transactions, settlements with counterparties, inventory management, payroll and the preparation of statutory reports, as well as MeDoc (2024a; 2024b), which provides electronic document management, registration of tax invoices and submission of reports to regulatory authorities. For medium and large enterprises, SAP Business One (n.d.) is used, combining financial accounting, logistics, inventory management and analytical tools within a single ERP system. In particular, as noted by M. Shyhun & A. Zhuravel (2021), the use of SAP facilitates the creation of a unified enterprise information environment, the synchronisation of financial, management and tax accounting, as well as the standardisation of accounting processes and the expansion of analytical capabilities, enabling the use of accounting data for management decision-making. Alongside this, Ukrainian software products have become widespread, notably Dilovod (n.d.), MASTER (n.d.) and Debet Plus (n.d.a; n.d.b), which provide financial accounting, processing of source documents, inventory management, settlements with counterparties and the preparation of statutory and tax reports in accordance with current regulatory requirements. Bookkeeper (n.d.), Navkolo (n.d.) and SMARTFIN.UA (n.d.) are also used to automate accounting procedures, including sales accounting, payroll calculation, determination of tax liabilities and preparation of reports for regulatory authorities.

These systems differ in terms of functionality, architecture and level of automation, as well as their focus on different user categories – ranging from sole traders and small businesses to medium-sized and large companies. They support integration with electronic document management, banking services and other information systems, ensuring data exchange, reconciliation of financial information and reduced transaction processing times. Additionally, they provide for the generation of analytical reports, control of financial flows and adaptation to changes in legislation through the updating of functional modules. Due to restrictions on the use of Russian software, businesses are transitioning to the use of BAS and Ukrainian solutions, whilst large companies are implementing international systems with localisation, in particular SAP (Human capital management software, n.d.) or Odoo (n.d.). The functional capabilities of such systems cover the automation of core accounting processes, including the processing of source documents, inventory management, payroll calculation, tax calculations and

the preparation of financial statements. In particular, these systems provide for the automatic generation of balance sheets, income statements, and declarations for value-added tax, income tax and the unified social contribution, as well as supporting electronic signatures and the submission of reports via integrated modules. The use of electronic document management involves the creation, signing and exchange of source documents in electronic form in accordance with current legislation, which reduces the time taken to process information and minimises errors.

The agricultural sector utilises specialised configurations, notably Business Automation Union (n.d.) and Debet Plus (n.d.a), which address specific features of accounting for biological assets, production processes in crop and livestock farming, as well as the seasonal nature of these activities. Such systems facilitate the recording of harvests, land cultivation costs, animal movements, the generation of analytical data by crop and production unit, as well as the automation of tax calculations, covering specific tax regimes. Depending on the organisation's needs, both cloud-based and on-premises solutions are used. Cloud services provide real-time access to accounting data and do not require on-premises infrastructure, whereas on-premises systems provide full control over data and are predominantly used by large organisations. In practice, it is common to combine different solutions, in particular the use of on-premises accounting systems alongside cloud-based e-reporting services, which ensures a complete cycle of financial and tax information processing.

Businesses in Ukraine made extensive use of the State Tax Service's digital services between 2022 and 2024 to automate reporting, monitor payments and conduct tax transactions, including the Taxpayer's Electronic Account, the electronic VAT administration system and electronic cash registers (e-Receipt) (Main Department of the..., 2019), which were integrated with accounting systems such as BAS, SAP and MeDoc. The Electronic Taxpayer's Office served as the central tool for real-time interaction with tax authorities and facilitated the submission of returns, the exchange of messages, access to register data and the monitoring of the status of settlements with the budget.

The electronic VAT administration system ensured the registration and verification of tax invoices and adjustment calculations, monitored compliance with the "first event" principle, and tracked registration limits. In 2024, on average, the registration of tax invoices and adjustment calculations was blocked each month for approximately 24,000 taxpayers, accounting for around 15% of those submitting tax invoices/adjustment calculations for registration. In total, around 2.33 million tax invoices and adjustment calculations were blocked over the year, amounting to nearly UAH 54 billion in VAT. At the same time, taxpayers subsequently confirmed the right to register 1.75 million tax invoices and adjustment calculations (around 71% of those blocked), corresponding to a VAT amount of approximately UAH 40 billion (74% of the blocked volume). Of these, 1.66 million tax invoices/correction calculations were unblocked by State Tax Service commissions, accounting for approximately 95% of the documents submitted for review. The total value of VAT submitted for registration in the Unified Register of Tax Invoices in 2024 amounted to approximately UAH 2,744 billion, of which approximately UAH 54 billion was blocked, and following the unblocking procedures – approximately UAH 14 billion, which corresponded to roughly 0.5% of the total VAT amount (Potaeva, 2025).

MeDoc (2024a; 2024b) served as a key tool for electronic reporting and document management, facilitating the registration of tax invoices in the VAT Electronic Administration System, the exchange of source documents, and the submission of reports. The volume of electronic document flow through this system grew: the number of documents sent stood at 34.5 million in 2022 and 73 million in 2023, and in 2024 exceeded 82 million, which is 13% more than in 2023. In 2024, businesses submitted approximately 10 million tax returns, with over 98% of returns for legal entities and sole traders being submitted electronically. In particular, in January-February 2026, 347,620 returns were filed in the Lviv region, 98% of which were submitted electronically (Main Department of the..., 2026). The total volume of electronic documents also included over 80 million source documents in electronic document management systems. In January-February 2025, the rate of tax returns submitted electronically remained stable at around 98% for both legal entities and individuals. At the same time, the proportion of electronic tax returns submitted by citizens rose from 77% in January-February 2025 to 82% for the same period in 2026. The digitalisation of tax administration has also influenced the organisation of tax control. In 2024, 3,242 audits were planned, of which over 60% were conducted in the form of documentary analysis using digital data without visiting the taxpayer. In the first nine months of 2024, 5,483 documentary audits of sole traders were carried out, a 26% decrease compared with 2023, resulting in additional tax assessments of approximately UAH 10 billion (Prasad, 2024).

A comparison revealed that L. He *et al*. (2024) and the present study both examined the impact of digital technologies on agricultural enterprises, albeit with different focuses. This study focused on the digitalisation

of accounting and tax administration, specifically process automation, electronic document management and integration with State Tax Service (STS) services. In contrast, L. He *et al*. analysed the impact of digital finance on "green" innovations and the role of corporate social responsibility. The common feature was that digitalisation was viewed as a factor in increasing efficiency, reducing information asymmetry and improving management. At the same time, the differences lie in the methods and level of analysis: this study employed a descriptive-analytical approach using statistical indicators of system performance, whereas L. He *et al*. utilised econometric modelling of panel data.

A similar line of reasoning was evident when comparing this study with that of X. Gao & R. Gao (2024), although the focus shifted from internal processes to the functioning of the agricultural supply chain. Whilst in this study digitalisation ensured the consistency of accounting and tax data, X. Gao & R. Gao (2024) viewed digital financial inclusion as a factor of resilience, influencing access to financial resources and the ability of entities to withstand external risks. What remained common was the perception of digitalisation as a mechanism for optimising information flows and access to resources. However, the level of analysis differed: the micro-level of the enterprise versus the meso-level of the sectoral chain, which also necessitated the use of different research tools.

Extending this comparative framework using the findings of W. Li *et al*. (2025) highlighted another dimension of digitalisation: innovation. Whilst in this study digital solutions ensured the accuracy of accounting data and the automation of reporting, W. Li *et al*. (2025) linked digital financial inclusion to an increase in enterprises' innovative activity, by overcoming financial constraints and stimulating investment in research and development. The convergence lay in the recognition of the role of digital technologies in enhancing efficiency and access to resources, whilst the differences manifested in the focus of the analysis and the methods employed – ranging from describing the functioning of digital services to identifying causal relationships based on panel data. In the study by Y. Liu *et al*. (2024), the focus shifted even further – to assessing the performance of enterprises in a foreign trade context. In contrast to the analysis of internal accounting processes, the authors investigated the impact of digital transformation on the quality and safety of agricultural exports, emphasising the role of digital platforms and technologies in ensuring product standards. The common thread remained the idea of increasing efficiency and improving data management; however, the difference lay in the shift from the internal organisation of information to the assessment of the results of enterprises' activities using econometric methods.

A comparison with the study by S. Jin & Z. Zhong (2024) revealed yet another level of generalisation – the macroeconomic level. Whilst this study viewed digitalisation as a tool for organising accounting and tax administration, S. Jin & Z. Zhong (2024) analysed the impact of digital financial inclusion on the total factor productivity of agriculture, covering sectoral integration and rural development. Both approaches recognised the role of digital technologies in improving resource efficiency but differed in scale: from the analysis of internal enterprise processes to the quantitative assessment of productivity based on econometric models. The operations of agricultural enterprises were subject to specific requirements regarding the organisation of accounting, which necessitated the use of digital tools to process large volumes of data. The use of accounting systems and STS services ensured the automation of accounting and tax processes, as well as the integration of financial information. Statistical indicators show the dominance of electronic reporting and significant volumes of electronic document flow. At the same time, during the tax administration process, there were instances of tax invoices being blocked, which required additional action on the part of taxpayers to confirm transactions.

Assessment of the impact of digital technologies on accounting and tax processes

MHP operates as a vertically integrated agro-industrial holding, within which crop production, livestock farming and processing are combined into a single production and logistics chain, which imposes specific requirements on the organisation of accounting and tax processes (MHP considers the EU…, 2025). This structure necessitates the processing of significant volumes of data relating to the production of raw materials, their transformation into finished products and their sale on domestic and foreign markets, where exports account for approximately 55% of total sales.

Digitalisation of accounting processes at MHP has been implemented using the unified ERP system SAP Suite 4 High-Performance Analytic Appliance (S/4HANA), which integrates financial, management and production accounting within a corporate framework. The system covers all of the company's business processes, including finance, logistics, procurement, human resources and production, and can be used for parallel financial and tax accounting in real time. Using the RISE with SAP model combines infrastructure, accounting processes and analytical tools within a single environment, covering both the company's Ukrainian and European assets. The organisation of accounting within

the SAP system involves the automation of key areas, including inventory management, payroll, cost accounting and production processes. In particular, the SAP MM module handles inventory, procurement and warehouse operations with integration into production processes; SAP SuccessFactors automates HR accounting and payroll processing with the relevant tax calculations; whilst the Financial Accounting/Controlling modules handle financial accounting, budgeting, cost allocation and reporting. Production accounting is implemented via the SAP PP module in conjunction with the company vZoo system, which integrates data on production, resource usage and product quality into a single accounting system ("MHP" implements a system..., 2021).

The consolidation of accounting data at MHP is implemented centrally via SAP S/4HANA, which ensures the automatic integration of financial, operational and production information from various departments and legal entities. The use of the SAP Master Data Governance module standartises master data before processing, ensuring consistency of information at the group level. This approach eliminates the need for manual data aggregation and can be used for generation of consolidated reports in real time. The tax function in MHP is integrated into a single ERP system and implemented as a component of financial accounting. The automation of tax processes covers the calculation of tax liabilities, the preparation of tax returns and the verification of business transactions against tax legislation. Due to the integration of accounting and tax accounting, tax figures are generated automatically based on source data, reducing the need for additional data processing and ensuring consistency between financial and tax data. MHP's digital infrastructure forms a unified information environment within which accounting, control and data processing are conducted at all stages of the production cycle. The summary of MHP's financial and investment indicators for 2021-2025 is based on the company's consolidated financial statements, enabling an assessment of changes in the scale of operations, profitability, investment activity and debt burden. The trends in these indicators reflect the recovery of operational activities following 2021 and the subsequent expansion of the business (Table 1).

Table 1. *Trends in MHP's financial and investment indicators for 2021-2025*

Indicator	2021	2022	2023	2024	2025	2021/2025, %	2024/2025, %
Revenue, million USD US	1,647	1,876	2,294	2,262	2,635	160	116
EBITDA, million USD US	519	275	329	437	455	88	104
Operating profit, million USD US	416	176	247	346	313	75	90
Net profit, million USD US	377	-269	122	141	215	57	152
CAPEX, million USD US	92	106	150	180	210	228	117
Net debt, million USD	1,164	1,186	1,050	950	900	77	95
Net Debt/EBITDA	2.09	2.94	3.19	2.17	1.98	95	91

Source: *compiled by the author based on MHP (2021; 2022; 2023; 2024; 2025)*

Table 1 show that between 2021 and 2025, MHP expanded the scale of its operations whilst simultaneously restructuring its financial profile. Revenue increased from USD 1,647 million to USD 2,635 million (+60%), whilst EBITDA decreased from USD 519 million to USD 455 million (-12%), reflecting the impact of external factors in 2022 and the subsequent recovery of operating activities. Capital expenditure rose from USD 92 million to USD 210 million (+128%), indicating an expansion of investment activity and the implementation of technological solutions. At the same time, net debt decreased from USD 1,164 million to USD 900 million (-23%), and the Net Debt/EBITDA ratio decreased from 2.09 to 1.98, reflecting an improvement in financial stability. In 2025, compared with 2024, revenue grew by 16%, whilst EBITDA increased by 4% and net profit increased by 52%.

The expansion of MHP's operations between 2021 and 2025 was accompanied by an increase in the volume of financial and tax transactions, reflected in a 60% rise in revenue and a more than twofold increase in capital expenditure. The increasing complexity of the business structure, in particular the integration of production segments and the implementation of investment projects, necessitates the maintenance of parallel accounting and tax records, cost accounting by responsibility centres, and the monitoring of investment flows. The dynamics of EBITDA and the Net Debt/EBITDA ratio reflect the changing demands on the financial management system and the need for analytical data processing to monitor liquidity and debt obligations. In such circumstances, the use of integrated ERP systems, in particular SAP S/4HANA, ensures the automation of accounting processes, the consistency of financial and tax information, and the generation of reports in real time, reflecting the changing role of digital technologies in the accounting and tax functions of the enterprise.

Kernel (2021; 2022; 2023; 2024; 2025) utilises a centralised model for the digitalisation of accounting and tax functions, based on a single Microsoft Dynamics NAV 2018 ERP system implemented for the management company and key subsidiaries, including Kernel Trade. This system provides integrated management of financial, operational and accounting processes, including procurement, sales, inventory management, cash flow and intercompany settlements. The system architecture is complemented by integration with the KernelEDocs electronic document management platform based on Microsoft SharePoint, which can be used for automation of the creation, approval, signing and storage of source documents, as well as supporting the use of qualified electronic signatures. For international divisions, Microsoft Dynamics 365 Business Central is used with data synchronisation to the central system, forming a connected hybrid information infrastructure. The implementation of the ERP system has led to changes in the parameters of accounting and tax processes, resulting in a reduction in the time taken to prepare financial statements by an average of 5 days, as well as a reduction in audit costs due to built-in control mechanisms. Centralised verification of counterparties using integrated services has reduced the number of transactions with high-risk partners by approximately half, which has had an impact on tax and financial risk parameters. The automation of cash flow management ensures liquidity and cash flow planning based on data from the accounting system. The digitisation of procurement and document management processes has accelerated the processing of transactions with grain suppliers by an average of three times, whilst also ensuring transparency in mutual settlements and monitoring of contractual obligations within trading operations. The ERP system implements full tracking of inventory costs, eliminating situations where, before the system's implementation, approximately 20% of costs were not automatically reflected in accounting and planning. Built-in BI tools can be used to generate financial and management reports online, providing access to analytical information for decision-making at various management levels (The results of the implementation…, 2024).

As part of the digitalisation of its logistics and accounting processes, Kernel has scaled up the use of electronic consignment notes (e-TTN), integrating around 1,000 partner haulage companies, 6,000 drivers, and over 400 dispatchers and weighbridge operators into a single digital system. The introduction of e-waybills facilitated the transition from paper-based document flow to an electronic format for primary documents used in accounting and tax records. As a result, the time taken to settle accounts with carriers has been reduced: whereas previously payment took 5-7 days due to the need to process paper documents, this process takes place much more quickly following the introduction of the digital system. In addition, the time taken to verify the accuracy of primary documents has been reduced by approximately 80%, reflecting the automation of control procedures and a reduction in the workload on accounting departments. The use of e-TTN has also eliminated document losses that occurred with paper-based document flow: in a single season, the company generates around 240,000 waybills when moving agricultural products between internal warehouses. The integration of e-TTN into the digital infrastructure, particularly in conjunction with the Microsoft Dynamics NAV 2018 ERP system and the KernelEDocs electronic document management platform, ensures the automatic generation of source documents, their approval, signing with a qualified electronic signature, and subsequent use for tax reporting. Thus, the digitalisation of logistics operations is directly integrated into the accounting and tax systems, ensuring data consistency, reducing information processing times and improving the controllability of business transactions (Tarasovsky, 2026).

Overall, Kernel's digital transformation encompasses accounting, tax processes, document management and management analytics, creating a unified information environment for processing financial data. The use of the Microsoft Dynamics NAV ERP system, combined with integrated services, ensures the consistency of accounting data, the automation of calculations, control over financial flows, and support for management decision-making processes. The financial statements reflect the dynamics of Kernel's financial indicators for 2021-2025, which characterise changes in the scale of operations, the structure of financial flows and the company's debt burden (Table 2).

Table 2. *Trends in Kernel's financial indicators for 2021-2025*

Indicator	2021	2022	2023	2024	2025	2021/2025, %	2024/2025, %
Revenue, million USD US	5,647	5,332	3,455	3,581	4,115	73	115
EBITDA, million USD US	929	220	544	381	466	50	122
Operating profit, million USD US	792	677	753	604	361	46	60
Net profit, million USD US	513	-41	299	168	238	46	142

Table 2, Continued

Indicator	2021	2022	2023	2024	2025	2021/2025, %	2024/2025, %
Net Debt, million USD US	836	1,488	595	281	143	17	51
Net Debt/EBITDA	0.9	6.8	1.1	0.7	0.3	33	43

Source: *compiled by the author based on Kernel (2021; 2022; 2023; 2024; 2025)*

Table 2 show that between 2021 and 2025, Kernel's operations were characterised by significant fluctuations in financial results, accompanied by a reduction in debt levels and a transformation in the structure of cash flows. Revenue decreased from USD 5,647 million to USD 4,115 million (-27%), reflecting changes in logistics conditions and export volumes, whilst EBITDA decreased from USD 929 million to USD 466 million (-50%), indicating rising costs and instability in the operating margin. In 2022, the company recorded a loss (USD -41 million), followed by a recovery in profitability to USD 238 million in 2023-2025. At the same time, the most significant changes occurred in debt management: net debt fell from USD 836 million in 2021 to USD 143 million in 2025 (-83%), and the Net Debt/EBITDA ratio decreased from 0.9 to 0.3. In 2022, this ratio rose to 6.8, reflecting a sharp deterioration in financial stability; however, it subsequently decreased rapidly, indicating active management of liquidity and cash flows.

Changes in the scale of operations, high volatility in financial results, and significant volumes of transactions involving inventory, export contracts and financial instruments necessitate an integrated approach to accounting and tax reporting. The use of a single Microsoft Dynamics NAV 2018 ERP system centralises data on procurement, sales, cash flow and settlements with counterparties, enabling the generation of consistent financial and tax information. Integration with the KernelEDocs electronic document management system and the use of built-in BI tools ensure the automation of source document processing, control of tax liabilities and the ability to generate analytical reports promptly.

A 49% reduction in net debt in 2024-2025 alone, as well as a reduction in the Net Debt/EBITDA ratio to 0.3, demonstrates the use of digital tools for liquidity management, cash flow planning and financial risk control. At the same time, the 15% growth in revenue and 22% growth in EBITDA in 2025 were accompanied by increased demands on data processing speed and the synchronisation of accounting processes across departments. Thus, the dynamics of Kernel's financial indicators in 2021-2025 reflect a transition to a model in which the digitalisation of accounting and tax functions ensures the integration of financial flows, the automation of accounting procedures and real-time control of operations in a changing external environment.

An analysis of the interrelationships between approaches to the digitalisation of the agricultural sector revealed that its interpretation varied depending on the scope of the study, ranging from internal business operations to systemic transformations within the industry. In this study, digital solutions were viewed as a tool for streamlining accounting and tax processes, ensuring the consistency of financial data and improving the efficiency of its processing. At the same time, E.N. Sadjadi & R. Fernández (2023) interpreted digitalisation as a multidimensional phenomenon encompassing the infrastructure, technologies and socio-economic conditions of the agricultural sector's functioning. Thus, the convergence resided in the recognition of the impact of digital technologies on management and productivity, whilst the divergence manifested itself in the scale, from the applied level to a comprehensive overview analysis.

This difference in levels of analysis was also evident when compared with the findings of B. García-Cornejo *et al.* (2025); however, in this case, the focus shifted to assessing the efficiency of farms. Whilst in this study digitalisation ensured the accuracy and integration of accounting processes, B. García-Cornejo *et al.* linked it to the use of management accounting practices and Information and Communication Technologies as factors in improving productivity. Both approaches agreed on the role of information systems in improving resource management but differed in their methodology: a description of how the systems function versus a quantitative assessment of effectiveness.

The study by M. Černá & J. Pokorný (2024) proved to be more closely related in terms of subject matter, as it also analysed changes in accounting and tax processes under the influence of digital technologies. However, whilst this study focused on the practical application of digital tools by enterprises, M. Černá & J. Pokorný (2024) examined these processes through the prism of the regulatory environment and institutional changes. As a result, digitalisation emerged as a common subject of analysis, but with varying levels of detail – ranging from the applied level to the generalised institutional context. In the study by H. Fu & T. Ramayah (2025), digital transformation was explained through the behavioural and competency characteristics of enterprises. In contrast to the technology-oriented approach of this study, the authors linked the outcomes of digitalisation

to levels of financial literacy, digital orientation and organisational learning. In both cases, the impact of digital technologies on efficiency and management was acknowledged, but the differences lay in the explanatory mechanisms: technological integration versus behavioural-econometric analysis of transformation factors.

Further broadening of the comparison, based on the study by M. Sauvagerd *et al*. (2024), transitioned from enterprise level to that of agri-food systems. Whilst in this study digital technologies facilitated the optimisation of internal procedures, M. Sauvagerd *et al*. (2024) viewed them as the foundation for transforming market structures and platform-based interactions within the sector. Despite the different scales, both approaches converged in their interpretation of digitalisation as a tool for improving data management and process coordination, whilst the differences lay in the focus – internal operations versus systemic changes in the industry. In the study by Y. Yuan *et al*. (2024), digitalisation was linked not only to the organisation of processes but also to areas of business development, in particular "green" transformations. This created a logical transition from managerial aspects to strategic business outcomes. What remained common was the perception of digital technologies as a factor in improving efficiency and access to resources; however, the difference lay in the shift in emphasis from accounting procedures to economic and environmental outcomes, which were assessed using quantitative methods.

An analysis of two agribusiness companies has shown that the implementation of digital solutions in accounting and tax functions is linked to an increase in transaction volumes and a growing complexity of business processes between 2021 and 2025. Changes in revenue, EBITDA, investment activity and debt burden were accompanied by an increase in the number of financial and tax transactions, which required the automation of accounting procedures and the centralisation of data. The use of ERP systems ensured the integration of accounting, logistics and financial processes, the automatic generation of reports and data consistency across departments. This created the conditions for faster information processing, control of business transactions and management of financial flows in a changing external environment.

Areas for improving the digitalisation of accounting and tax processes

The enhancement of digitalisation in accounting and tax processes at MHP and Kernel involves the further development of data integration within the existing ERP systems and the expansion of their functionality in line with the growth in transaction volumes. At MHP, the use of SAP S/4HANA ensures the consolidation of financial, production and logistics data, whilst at Kernel, a centralised model based on Microsoft Dynamics NAV 2018 combines accounting, document management and analytics. Further improvements involve deepening the integration of these systems with external services, in particular tax platforms, using Application Programming Interfaces (APIs), which streamline the transfer of data to e-administration systems without duplication of information or manual intervention.

The development of digital solutions at MHP and Kernel should be viewed in the context of the transition to cloud-based architectures, which ensure the scalability of accounting systems and data synchronisation across departments. At MHP, this can be achieved through the continued use of the RISE with SAP model, which integrates Ukrainian and international assets into a single accounting environment, whilst at Kernel, the transition from Dynamics NAV to Dynamics 365 Business Central creates the conditions for the unification of accounting processes between the parent company and international divisions. This approach ensures real-time data processing and reduces dependence on local infrastructure, which is particularly relevant given the growth in financial flows and the geographical expansion of operations.

The improved efficiency of accounting and tax processes in the companies studied is linked to the increased use of analytical tools. At MHP, the integration of SAP modules with production systems can be used for generation of detailed information on costs and operational performance, whilst at Kernel, the use of Business Intelligence reporting provides real-time access to financial indicators and liquidity monitoring. Further development involves the implementation of models for forecasting tax liabilities, analysing cash flows and assessing financial risks based on accumulated data, ensuring a transition from recording transactions to analytical management.

Advances in digitalisation are also linked to the automation of routine operations, which has already been partially implemented in both companies. At Kernel, the introduction of a "payment factory" and centralised approval procedures has accelerated the processing of financial transactions, whilst at MHP, the automation of accounting via SAP modules reduces the number of manual operations. Further development involves the use of robotic process automation (RPA) for processing source documents, verifying tax data and generating reports, which reduces the labour intensity of accounting procedures and improves the accuracy of calculations.

The integration of logistics processes with accounting and tax records is a distinct area of improvement,

which is particularly evident in Kernel through the implementation of electronic consignment notes. Scaling e-waybills to involve thousands of participants in the logistics process automatically records product movement transactions in the accounting system, reducing document processing time and ensuring data consistency. At MHP, a similar effect is achieved through the integration of SAP's production and logistics modules; however, further development may involve expanding the use of electronic source documents and their direct integration with tax systems.

Further improvements to digitalisation involve the development of data management systems, including the standardisation of reference data and accounting processes. At MHP, this is achieved using SAP Master Data Governance (n.d.), which ensures data consistency across departments, whilst at Kernel, centralised accounting can create a single information base for financial and tax reporting. Expanding these approaches reduces the number of errors, improves data quality and ensures consistency between different types of accounting.

From a modelling perspective, the effectiveness of digitalisation can be represented as a function of the relationship between transaction volume, the level of automation, and the time spent on data processing. In the case of MHP, a 60% increase in revenue in 2025 compared to 2021 was accompanied by a rise in the volume of accounting transactions, requiring a corresponding increase in the level of automation to maintain efficiency. At Kernel, where financial indicators were highly volatile, the use of an ERP system reduced debt levels and ensured liquidity control, which can be interpreted as the result of optimised financial data processing. Formalisation of these processes addressed the impact of digital solutions on the performance of accounting systems and justified further investment in their development.

A separate area of focus is the development of integration with government tax services, which involves the automatic exchange of data between ERP systems and the State Tax Service's platforms. The study shows that the volume of electronic document flow and reporting is increasing, creating the conditions for a transition to fully digital interaction with regulatory authorities. For MHP and Kernel, this means the ability to automatically generate tax figures based on accounting data and reduce the number of operations associated with reporting. Thus, the areas for improving digitalisation at MHP and Kernel are linked to deeper integration of ERP systems, the transition to cloud technologies, the use of analytical tools and automation, as well as the development of interaction with tax services. This ensures the consistency of financial and tax data, reduces information processing time and improves the efficiency of accounting process management as the scale of operations grows.

An analysis of the relationship between digitalisation and business performance revealed varying interpretations of this process. In this study, digitalisation was interpreted as a tool for streamlining accounting and tax procedures, ensuring the consistency of financial data and the automation of reporting, whereas K. Valaskova *et al*. (2025) shifted the focus to the strategic dimension, linking digital transformation to financial results through mechanisms of strategic alignment. Thus, the common thread remained the idea of improving management efficiency, although the level of analysis shifted from operational to strategic.

This difference in the scope of the analysis was also evident in the study by S. Nain *et al*. (2025), where digitalisation was viewed not as a technological solution, but as a combination of organisational and behavioural factors that shape business outcomes. In this context, the present study appeared more applied in nature, as it focused on specific tools – ERP systems and digital tax administration services. At the same time, both approaches converged in their interpretation of digital technologies as a means of optimising data processing and enhancing management transparency.

This broadening of the analytical perspective was further evident in the study by R.R. Shamshiri *et al*. (2024), where digitalisation extended beyond accounting processes and was linked to the transformation of production using the Internet of Things (IoT), drones and artificial intelligence. Whereas in this study, digital solutions streamlined financial flows and tax control, in the work of R.R. Shamshiri *et al*. (2024), they altered the very logic of agricultural production, focusing on productivity and sustainability. Nevertheless, in both cases, digitalisation served the function of processing large volumes of data and supporting decision-making.

Another avenue for the development of digital tools was presented in the study by Q.H. Pham & K.P. Vu (2024), in which digitalisation was integrated with innovative business models and digital forensic accounting. In contrast to this approach, the present study remained within the scope of regulatory and accounting functions, whereas Q.H. Pham & K.P. Vu (2024) viewed digital tools as a foundation for internationalisation and innovation. What remained common was the improvement in the quality of information and control; however, differences emerged in focus, ranging from operational support to strategic business development. N. Hendriyetty *et al*. (2022) interpreted digitalisation

at an even more generalised level, emphasising the transformation of the accounting profession itself and changes in taxation models within the digital economy. In this context, this study reflected the practical dimension of implementing digital solutions, whilst N. Hendriyetty *et al*. (2022) established the theoretical foundation for these changes. Despite the difference in approaches, both positions converged in their interpretation of digitalisation as a process that alters information processing mechanisms, enhances its accuracy, and transforms the financial data management system.

The digitalisation of accounting and tax processes at MHP and Kernel was enhanced through deeper integration of ERP systems, the expansion of their functionality, and interaction with external services. The transition to cloud architectures and the use of analytical tools ensured real-time data processing and improved the quality of financial information. The automation of operations, including the use of RPA and electronic document management, helped to reduce the labour intensity of accounting procedures and minimise errors.

CONCLUSIONS

A summary of the study results indicates that the digitalisation of accounting and tax functions in Ukraine's agricultural sector is accompanied by a shift towards integrated information systems, an increase in the volume of electronic document flow, and a higher level of automation in financial processes. The study found that the use of ERP solutions, the State Tax Service's electronic services and electronic document management systems can be used for processing of significant volumes of data, ensures the consistency of financial and tax information, and reduces the time required to prepare reports.

Statistics confirm the high level of digitalisation in tax administration. In 2024, over 98% of tax returns were submitted electronically, and the total number of electronic documents exceeded 80 million. The number of documents in the MeDoc system increased from 34.5 million in 2022 to over 82 million in 2024, reflecting the rapid growth of electronic document flow. At the same time, the VAT electronic administration system processed significant volumes of transactions: in 2024, tax invoices and credit notes totalling approximately UAH 2,744 billion were submitted for registration, of which around UAH 54 billion (approximately 1.97%) was initially blocked. However, following the unblocking procedures, the actual amount of blocked VAT was approximately UAH 14 billion, which corresponded to roughly 0.5% of the total amount.

An MHP's analysis showed that between 2021-2025, revenue growth from USD 1,647 million to USD 2,635 million (+60%) was accompanied by a shift in the dynamics of operating indicators, notably a decrease in EBITDA from USD 519 million to USD 455 million (-12%), which reflected the impact of external factors in 2022 and the subsequent recovery of operations. At the same time, the reduction in the Net Debt/EBITDA ratio from 2.94 to 1.98 reflects improved financial management efficiency, achieved through the integration of accounting and analytical functions into SAP S/4HANA. At Kernel, digitalisation was reflected in the optimisation of accounting and logistics processes: a reduction in reporting preparation times by 5 days, a reduction in document verification time by 80%, and the automation of processing up to 240,000 electronic consignment notes per season. The company's financial indicators also demonstrate this transformation: a reduction in net debt from USD 836 million in 2021 to USD 143 million in 2025 (-83%) and a decrease in the Net Debt/EBITDA ratio to 0.3 in 2025.

The further development of digitalisation involves the integration of ERP systems with tax services via APIs, the transition to cloud-based solutions, and the increased use of BI tools for forecasting tax liabilities and analysing cash flows. The automation of routine processes, the integration of logistics data (e-waybills) and the standardisation of data management ensure the consistency of accounting information and a reduction in processing time. Future research prospects involve broadening the scope of analysis, in particular by conducting a more in-depth assessment of the effectiveness of the digitalisation of accounting and tax processes based on a broader empirical foundation.

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Цифровізація бухгалтерського обліку та податкової функції для сільськогосподарських підприємств

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Анотація. Метою даного дослідження було визначення особливостей цифровізації бухгалтерського обліку та податкових процесів аграрних підприємств з оцінюванням її впливу на фінансові результати. У межах дослідження застосовано системний підхід, метод узагальнення, описово-аналітичний, структурно-логічний та статистичний методи для дослідження інформаційних систем підприємств і цифрових сервісів податкового адміністрування. Результати дослідження показали, що рівень цифровізації податкового адміністрування перевищує 98 % електронного подання звітності, а обсяг електронного документообігу зріс з 34,5 млн документів у 2022 році до понад 82 млн у 2024 році. У системі електронного адміністрування податку на додану вартість у 2024 році було оброблено податкові накладні на суму близько 2,744 млрд грн, з яких первинно заблоковано близько 54 млрд грн (приблизно 1,97 %), тоді як після процедур розблокування фактичний обсяг заблокованого податку на додану вартість становив близько 14 млрд грн, що відповідало приблизно 0,5 % від загальної суми. Аналіз діяльності компанії МХП засвідчив зростання виручки з 1,647 до 2,635 млн дол. США (+60 %) та капітальних інвестицій з 92 до 210 млн дол. США (+128 %) у 2021-2025 роках при одночасному зниженні чистого боргу з 1,164 до 900 млн дол. США. У компанії Kernel встановлено скорочення чистого боргу з 836 до 143 млн дол. США (-83 %), а також автоматизацію обробки до 240 тис. електронних товарно-транспортних накладних за сезон і скорочення часу перевірки документів на 80 %. Напрями вдосконалення передбачають інтеграцію облікових систем із податковими сервісами, використання хмарних технологій, аналітичних інструментів та автоматизацію обробки даних для підвищення узгодженості інформації і швидкості облікових процесів. Практичне значення дослідження полягає у можливості використання його результатів аграрними підприємствами для оптимізації облікових і податкових процесів, підвищення ефективності управління фінансовими потоками та зниження витрат

Ключові слова: автоматизація; документообіг; адміністрування; ефективність; контроль; аналітика

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The strategy for enhancing the competitiveness of local communities in the Black Sea economic region based on innovation

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Abstract. The current economic development, characterised by accelerated globalisation, digitalisation, and transformation of social relations, poses new challenges for local communities, while opening up opportunities for their innovative development, which makes it critically important to develop adapted strategies to increase competitiveness in the context of decentralisation reform and structural transformations in Ukraine. The purpose of the article was to develop an innovative strategy to enhance the competitiveness of territorial communities in the Black Sea economic region. The limitations of the traditional "triple helix" model ("university-government-business") for the Ukrainian context were analysed, and the necessity of implementing the "quadruple helix" approach, which includes civil society as a key element, are substantiated. An integrated innovation model consisting of five core components – innovation strategy, innovation ecosystem, innovation infrastructure, innovation culture, and innovation management system – was proposed. A comprehensive algorithm for implementing the innovation strategy, covering twelve sequential stages from comprehensive diagnostics to the institutionalisation of innovation activities, was presented. Special attention has been given to the development of territorial competence centres, mechanisms of adaptive strategic planning, and inter-territorial innovation alliances based on public-private partnerships. Specific proposals for implementing the innovation strategy in the short term (1-2 years) and long term (5-10 years), taking into account the unique characteristics of the region's local communities, are outlined. The research results confirmed that successful implementation requires systematic coordination among stakeholders, leadership from local self-government bodies, and flexible responses to changes in the external environment. The proposed approach is shown to provide comprehensive solutions to challenges in the

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field of innovation-driven development through the integration of strategic planning, institutional development, and the practical execution of implemented measures

Keywords: competitiveness; innovation strategy; innovation ecosystem; "quadruple helix" model of innovative development; strategic planning

INTRODUCTION

Contemporary global development is characterised by accelerated globalisation, digitalisation, and transformation of social relations, presenting territorial communities with new challenges whilst opening opportunities for advancement. Traditional approaches to regional development, predominantly based on macroeconomic indicators and sectoral policies, prove insufficient for ensuring sustainable and balanced development at the local level. Therefore, there is a need to develop strategy of the development of territorial communities, which require the application of innovative approaches to mechanisms for ensuring the development of territories and ensuring their competitiveness in the current conditions of transformation.

It is confirmed by the views of N. Gavkalova *et al*. (2023), who analysed territorial development effectiveness within Ukraine's regional policy framework, demonstrating that development prospects depend on strategies accounting for global digitalisation trends and innovation levels in developed economies. However, it has been scientifically proven that there are certain limitations and peculiarities in innovative development that need to be taken into account. P. Marques & K. Morgan (2021) critically examined the limitations of regional innovation concepts that rely too heavily on the experiences of advanced regions, arguing that such approaches neglect the realities of less-developed regions. They highlighted the importance of understanding formal institutional dynamics to avoid culturally deterministic explanations of underdevelopment, stressing that firm-level innovation alone is insufficient to generate regional growth. R. Chornyi *et al*. (2025) analysed the consequences of war for Ukraine's innovation-industrial regional development, identifying systemic technological lag and widening disparities between central and peripheral regions. Their study emphasised that enterprise relocation and industrial park development, supported by legislative improvements, foster diversification and competition. They concluded that effective state support mechanisms are essential to stimulate innovation diffusion, strengthen regional business environments, and enhance national resilience.

I. Tomashuk & I. Tomashuk (2023) examined the strategic foundations of innovation-driven territorial community development, emphasising entrepreneurship as the main catalyst of local economic transformation. Their study highlighted that a favourable business climate and integrated innovation structures, such as technology parks and incubators, are essential for fostering competitiveness and sustainable growth. F. Fidanoski *et al*. (2023) can be presented as a broader reflection on innovation development models. Their work illustrates how the Triple Helix framework (built on the interaction of academia, industry, and government) remains a milestone in knowledge-based economies, yet still faces efficiency challenges. This underscores the need for innovation models that not only stimulate technological progress but also integrate social participation, and institutional adaptability. Such perspectives reinforce the argument that territorial development strategies must evolve toward inclusive, resilient, and sustainable innovation systems, which include state, business and science. Meanwhile, analysing various views on the formation of the foundations of innovative development A. Zarichniak *et al*. (2025) investigated regional innovation models through comparative analysis of EU and US experiences, critically examined how concepts developed in advanced regions may inadequately address the realities of less-developed territories. The authors emphasised the need for context-sensitive approaches that account for local institutional dynamics and resource endowments rather than direct transfer of Western models.

Taken together, these scholarly perspectives confirmed that innovation-driven territorial development requires strategies that combine global trends with local realities, integrate entrepreneurship with institutional adaptability, and foster collaboration among government, business, and academia. This provides a strong rationale for applying the Triple Helix model as the foundation for designing an innovation strategy that enhances the competitiveness of territorial communities in Ukraine. However, most studies either focus on general innovation models in advanced economies or analyse Ukraine's territorial development in broad terms, without tailoring innovation strategies to the unique challenges of coastal and border regions, such as uneven resource distribution, infrastructural gaps, and external shocks. Furthermore, there is limited

integration of the Triple Helix model into practical mechanisms for strengthening competitiveness at the community level, particularly in regions undergoing transformation and recovery. This study aimed to develop an integrated innovation strategy for enhancing the competitiveness of territorial communities in the Black Sea economic region.

MATERIALS AND METHODS

The research employed a comprehensive methodological approach combining theoretical analysis, empirical investigation, and strategic planning techniques. The study focused on territorial communities within the Black Sea economic region of Ukraine, selected due to their strategic importance and diversity of development characteristics. The analytical framework integrated several methodological approaches. Comparative analysis examined the applicability of international innovation models, particularly the triple and quadruple helix concepts, to Ukrainian conditions. Systems analysis facilitated understanding of interactions among different components of the territorial innovation system and their collective impact on competitiveness. The strategy for enhancing the competitiveness of local communities based on innovation was developed through a systematic multi-stage procedure.

The case study method was employed to examine practical applications of innovation helix models in territorial development contexts Theoretical framework analysis – critical examination of existing innovation models (triple helix, quadruple helix) and their applicability to Ukrainian territorial communities, including assessment of structural differences between Western and post-socialist innovation ecosystems. Stakeholder identification – systematic identification of key actors in territorial innovation systems: government bodies, educational and scientific institutions, business sector, and civil society, with analysis of their roles, capacities, and interaction patterns. Component definition – determination of essential elements for the integrated model including: innovation strategy formulation mechanisms, innovation ecosystem architecture, innovation infrastructure requirements, innovation culture development approaches, and innovation management systems. Integration mechanism design – development of coordination and cooperation mechanisms ensuring synergistic interaction among model components, including adaptive planning procedures, partnership frameworks, lobbying and coordination structures, joint financing schemes, and monitoring systems. Priority area selection – identification of key sectors for innovation implementation (education, medicine, infrastructure, social protection, social programs) was based on territorial specificities and community development needs. Implementation algorithm development – formulation of a twelve-stage sequential implementation process through iterative consultation with practitioners, local government representatives, and academic experts, ensuring practical applicability whilst maintaining theoretical rigour. Temporal perspective differentiation – development of short-term (1-2 years) and long-term (5-10 years) implementation scenarios with specific measures, timelines, resource requirements, and expected outcomes for each perspective. Validation through expert consultations. Strategic planning methodology incorporated scenario development for long-term perspectives, participatory planning techniques involving stakeholder engagement, and adaptive planning approaches allowing for flexibility in responding to environmental changes. The participatory approach included workshops and consultations with representatives from local self-government bodies, business associations, educational institutions, and civil society organisations.

Data collection methods included semi-structured interviews with key stakeholders in territorial communities conducted between March and June 2025 with a total of 220 respondents representing 21 territorial communities of the Black Sea economic region, including Vasylivska, Nechaianska, Chohodarivska, Dolynska, Kochubeiivska, Borozenska, Halytsyn'ivska, Stepivska, Uspenivska, Shyriaiivska, Novoolesk'sandrivska, Tiahynska, Yelanetska, Veselynivska, Vylkivska, Ovidiopilska, Vysokopilska, Chornobaiivska, Kryvoozierska, Tarutynska, and Bilozierska, with 10 to 12 respondents per community. By occupational profile, the sample was distributed across five broad sectors: the education sector (teachers, educators, lecturers, and school directors) accounted for 54 respondents (24.5%); the business and commercial sector (entrepreneurs, construction workers, retail workers, accountants, farmers, and pharmacists) for 64 respondents (29.1%); the public administration sector (civil servants and directors of municipal enterprises) for 28 respondents (12.7%); healthcare (physicians and nurses) for 16 respondents (7.3%); and other categories, including pensioners, unemployed persons, military personnel, and security guards, for the remaining 58 respondents (26.4%). This broad occupational diversity reflects the heterogeneous social structure of the surveyed communities and ensures a representative range of perspectives on local innovation capacity and development needs.

Case Study Selection. Two international cases were selected for comparative analysis using a purposive selection protocol based on three criteria: documented application of triple or quadruple helix

models in a territorial development context; availability of published peer-reviewed assessments of both outcomes and limitations; and contrasting institutional environments to maximise analytical diversity. The Berlin-Adlershof Science City (Germany) was selected as a benchmark case of a well-resourced, government-driven triple helix implementation in a mature market economy, widely cited in helix model literature and subject to critical evaluation regarding resource asymmetries among stakeholders. The Flottsund Bridge project (Uppsala, Sweden) was chosen as a contrasting case in which triple helix collaboration explicitly failed due to inadequate civil society engagement, thereby illustrating the rationale for transitioning to a quadruple helix framework. Both cases are drawn from leading scholarly publications and provide complementary empirical evidence directly relevant to the Ukrainian context analysed in this study. The synthesis of theoretical frameworks with empirical findings enabled development of an integrated innovation model specifically adapted to the characteristics of Ukrainian territorial communities, addressing the structural limitations identified in the comparative analysis while leveraging constitutional provisions regarding civil society's role in governance.

RESULTS

International experience demonstrates both the potential and limitations of helix innovation models in territorial development contexts, providing critical insights for Ukrainian territorial communities. The Berlin-Adlershof Science City in Germany exemplifies successful triple helix implementation in a well-resourced environment, where by 2016 the science and technology park hosted over 1,000 companies and scientific institutions, attracting 15,996 employees and 6,524 students. Success factors included sustained government financial support from project inception, establishment of WISTA as a public-private partnership entity managing park operations and technology centres, and long-term strategic planning fostering linkages among universities (Humboldt University), industry, and government structures (Alhowaily, 2021). However, even in this successful case, significant challenges emerged: stakeholder interactions remained resource-dependent, with Humboldt University's participation constrained by limited financial and recruitment capacities compared to industrial actors, and absence of an independent fusion organisation at the intersection of the three helices hindered autonomous operation (Taratori *et al.*, 2021). These limitations in a developed German context foreshadow even greater challenges in resource-constrained Ukrainian settings.

The Flottsund Bridge renovation project in Uppsala, Sweden, illustrates the critical importance of civil society integration from early planning stages. Originally designed following the triple helix model with collaboration among the Regional Development Office, academic researchers, and renewable energy technology developers, the project ultimately failed to achieve its innovation commercialisation objectives due to late and ineffective citizen engagement (Garcia-Teran & Skoglund, 2019). Open meetings intended for dialogue devolved into one-way communications, with residents feeling excluded from decision-making processes (Taratori *et al.*, 2021). This case underscores fundamental limitations of triple helix approaches that treat citizens merely as end-users rather than active co-creators, validating the necessity of quadruple helix frameworks incorporating civil society as a foundational pillar rather than a supplementary element – a lesson particularly relevant for Ukrainian communities where constitutional principles emphasise citizens as sovereignty bearers.

Analysis reveals significant limitations in directly applying the traditional triple helix model to Ukrainian territorial communities, validated by the challenges observed even in successful Western implementations like Berlin-Adlershof. Each element of the model operates under different paradigms compared to highly developed Western countries where the concept originated. Regarding universities, Western institutions represent financially robust entities providing not only educational services but engaging extensively in scientific and technical practices. They possess resources to attract foreign specialists with relevant expertise, significantly accelerating innovation development timelines, and to recruit students through merit-based selection supported by substantial scholarships (Miller *et al.*, 2016; Machado *et al.*, 2024). The resource asymmetries observed in Berlin-Adlershof, where even Humboldt University faced participation constraints, magnify exponentially in Ukrainian contexts. Ukrainian educational institutions, whilst maintaining strong academic traditions, operate under different systemic conditions. Rather than "university" as the sole innovation generator, the Ukrainian context requires considering "education" more broadly as the foundation encompassing secondary education, vocational training, higher education institutions, National Academy of Sciences establishments, research institutes, and other scientific organisations conducting fundamental and applied research.

The business component demonstrates even more pronounced differences. Western business evolved systematically over centuries, developing from small

entrepreneurial structures to transnational corporations, with founders often graduating from the same prestigious academic institutions (Todeva & Panayiotis, 2017). This historical continuity facilitated organic integration between education and business, with corporations investing in research activities and participating in educational institution governance boards (Hasche *et al.*, 2019). Ukrainian business remained relatively passive regarding personnel training and modern innovation development within domestic educational institutions, preferring to adopt foreign technologies. Economic difficulties and population decline, particularly in peripheral territories, resulted in closure of financially unsustainable rural schools and reduction of social infrastructure networks – challenges absent from successful Western triple helix implementations. Government structures in countries where the triple helix functions effectively, exemplified by the United States, demonstrate sophisticated integration between education, business, and policy-making. Elite institutions like Yale University (founded 1701, endowment 42 billion USD) and Harvard University (founded 1636, endowment 50 billion USD) have prepared numerous American presidents and political leaders (Stiglitz *et al.*, 2013). Ukrainian government institutions lack comparable historical experience and financial resources, failing to create conditions enabling highly educated youth to access prestigious institutions, establish institutional-level cooperation between business and universities, or position themselves as primary customers and promoters of innovations.

Given these structural limitations observed in Ukrainian contexts and validated by challenges encountered even in successful Western triple helix implementations, this research advocates implementing the quadruple helix model, incorporating civil society as the fourth element (Fig. 1). The Flottsund Bridge case demonstrated that excluding citizens from early planning stages undermines project success even in well-resourced Swedish contexts; this risk intensifies in Ukrainian communities where citizen engagement can compensate for governmental and business sector weaknesses. The Constitution of Ukraine (1996) established that "the bearer of sovereignty and the sole source of power in Ukraine is the people", making civil society's role fundamentally important and providing unique constitutional legitimacy absent in Western contexts where civil society functions as supplementary rather than foundational. Citizens simultaneously serve as primary creators, promoters, and users of innovations (Carayannis & Evangelos, 2016), positioning them as the determining element in the innovation development model.

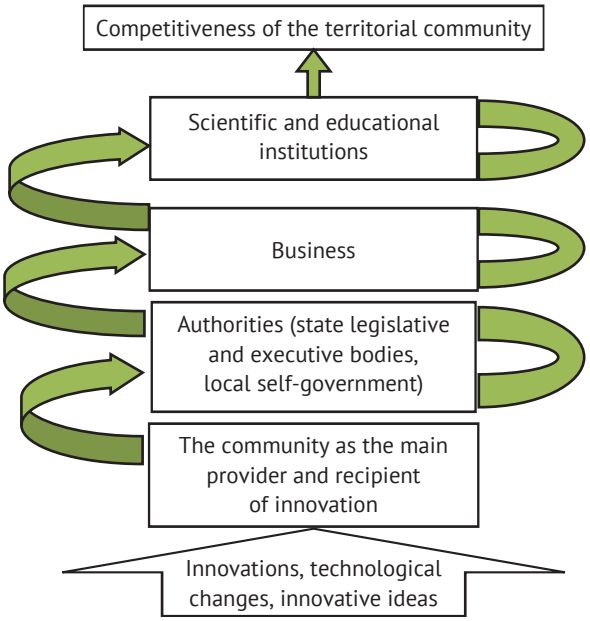

Figure 1. *The innovative foundations of the socioeconomic development of territorial communities*
Source: *compiled by the authors*

The innovation approach to territorial development must encompass not only traditional economic linkages but a broad spectrum of interactions among different territorial stakeholders: business, scientific institutions, educational establishments, public organiiations, and government bodies (Morawska *et al.*, 2024). These relationships manifest as industrial clusters, innovation ecosystems, enterprise networks, scientific-production complexes, and creative industries. Contemporary productive relations focus not exclusively on material goods production but also on knowledge generation, information processing, cultural value creation, and social innovations. The research proposes an integrated innovation model for socio-economic development of territorial communities based on systematic approaches and considering interconnections among different innovation types, stakeholders, and management levels. The model comprises five key components working in synergy (Fig. 2). The innovation strategy component includes long-term community development vision, strategic priorities, goals and objectives, indicator systems comprising specific key performance indicators (KPIs) such as: the number of newly registered startups per year (target: 5-10 per community annually); the volume of investment in research and development as a percentage of the community's budget (target: 2-3%); the number of joint university-business innovation projects implemented (target: at least 3 per year); the proportion of residents engaged in innovation-related

educational programmes (target: 10% of working-age population); and the number of patents and intellectual property objects registered by community-based entities (target: 2-5 per year), and monitoring mechanisms. Critical elements involve identifying unique competitive advantages and their purposeful development. Strategy formulation requires comprehensive auditing of community potential, including human resources, material-technical base, financial capabilities, and distinctive territorial advantages.

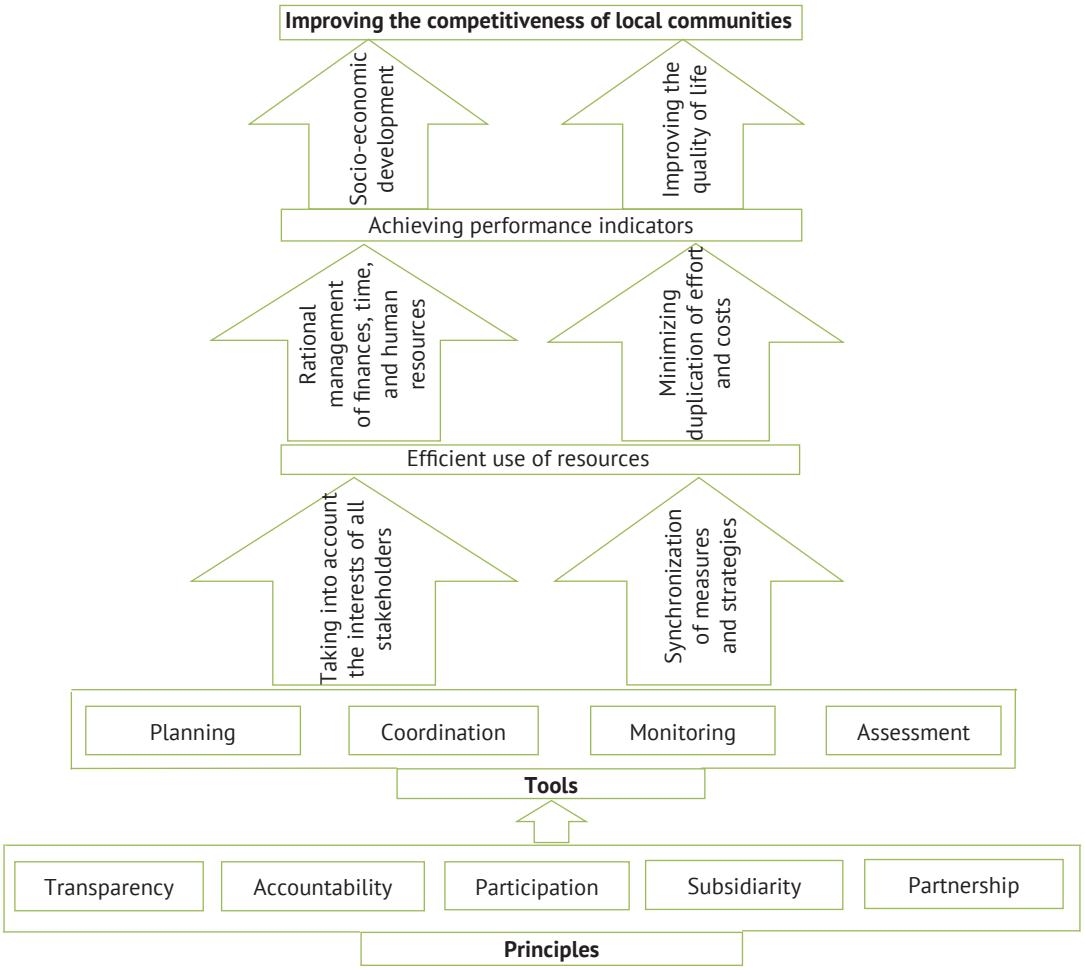

Figure 2. *The principles of implementing the mechanism for the socio-economic development of territorial communities based on innovation*

Source: *compiled by the authors*

The innovation ecosystem encompasses the network of interactions among community functioning participants: government bodies, business, educational and scientific institutions, public organisations, and citizens. Effective implementation requires establishing cooperation platforms as permanently operating structures ensuring coordination of different actors' activities, information exchange, and joint project planning and implementation. These platforms function both in traditional forms (councils, commissions, working groups) and digital formats (online platforms, mobile applications). Innovation infrastructure includes physical and virtual resources necessary for innovation development and implementation: business incubators, coworking spaces, technology parks, administrative service centres, digital platforms, and communication and information systems. Development involves creating territorial competence centres specialising in developing unique sectoral skills and knowledge, where each community concentrates efforts on 2-3 key directions best corresponding to its natural, historical, and human resources.

Innovation culture encompasses the system of values, norms, and attitudes promoting innovation generation and implementation. This requires special training programmes, experience exchange mechanisms, and systematic efforts to develop entrepreneurial thinking among the population. Practical implementation includes organising educational seminars and trainings

on innovation entrepreneurship, digital literacy, and participation in public initiatives. The innovation management system covers structures, processes, and instruments ensuring planning, coordination, implementation, and evaluation of innovation projects. Essential elements include creating specialised departments or development agencies responsible for innovation activities in the community, establishing procedures for assessing and selecting innovation initiatives, and forming special innovation development funds financed from various sources including state programmes, donor funds, and community internal reserves. Successful implementation requires a systematic algorithm encompassing twelve sequential stages, each building upon previous achievements whilst maintaining flexibility for adaptation to changing conditions (Fig. 3).

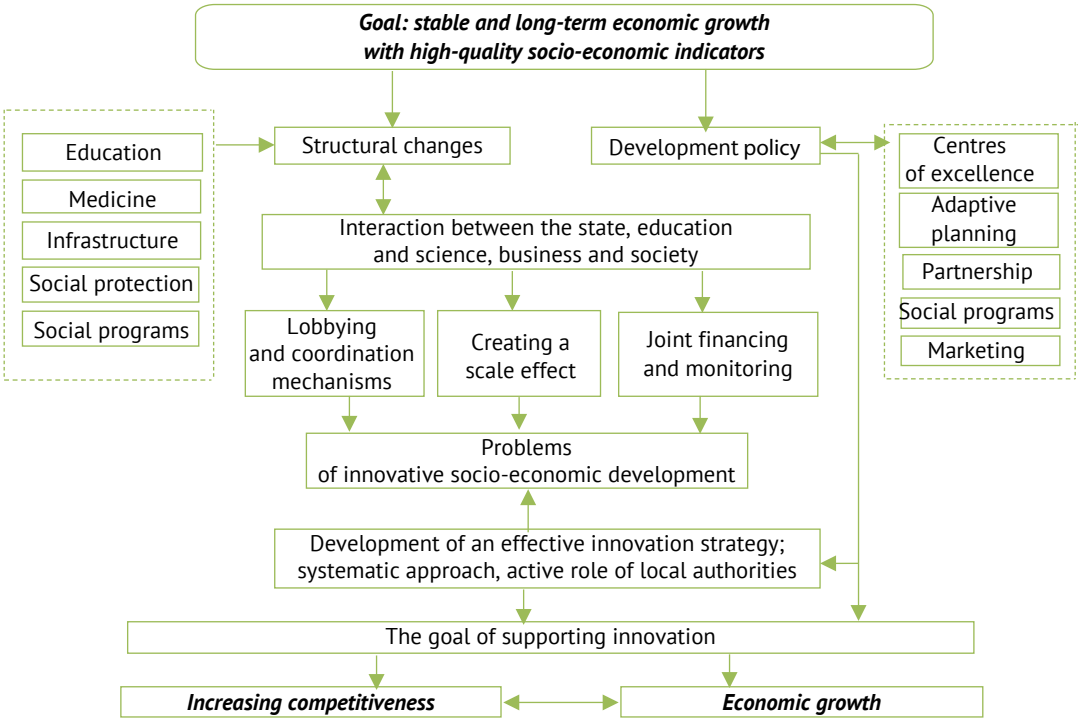

Figure 3. *Strategy for enhancing the competitiveness of local communities based on innovation*
Source: *compiled by the authors*

Stage one involves conducting comprehensive diagnostics of the territorial community's innovation potential, including analysis of available resources, infrastructure, human capital, and existing innovation practices. This stage encompasses SWOT analysis of the innovation environment, identification of key stakeholders, and determination of baseline competitive advantages, with particular attention to assessing readiness levels among local government, business, and civil society for innovation transformations. A SWOT analysis of the innovation environment of territorial communities in the Black Sea Economic Region, conducted as part of this diagnostic stage, is presented in Table 1. The analysis reveals that whilst the region possesses significant structural advantages – including its strategic coastal location, established higher education institutions, and an active civil society sector – these are counterbalanced by persistent weaknesses such as insufficient university-business linkages, underdeveloped innovation infrastructure, and limited local budget autonomy. At the same time, the growing availability of international reconstruction funding represents tangible opportunities, whilst ongoing armed conflict and widening intra-regional disparities between big cities and peripheral communities remain critical threats requiring strategic attention. Stage two focuses on formulating strategic vision for community innovation development considering global trends and national priorities. The strategic planning process must base itself on participatory principles, engaging broad circles of interested parties including business representatives, scientific community, public organisations, and active residents. The outcome should clearly define long-term innovation development goals and main directions for their achievement. Stage three develops a detailed implementation plan with specific tasks, execution timelines, necessary resources, and success indicators. The plan includes creating institutional

architecture supporting innovation activities, particularly forming specialised structural subdivisions within local self-government bodies, establishing advisory councils on innovations, and developing partnership networks. An important plan component involves designing stimulus and support systems for innovation initiatives, including financial mechanisms, tax preferences, and administrative services.

Table 1. *SWOT Analysis of the innovation environment of territorial communities in the Black Sea economic region of Ukraine*

Strengths	Weaknesses
➥ Strategic location on the Black Sea coast enabling cross-border trade, logistics, and access to EU and Near East markets; ➥ Presence of higher education institutions with R&D potential; ➥ Diverse natural and agricultural resources creating niches for agro-innovation and eco-tourism; ➥ Active civil society organisations and NGO sector engaged in community development; ➥ Decentralisation reform expanding local self-governance authority and financial resources; ➥ Established port infrastructure in Odesa and Mykolaiv providing logistical foundation for trade-oriented innovation clusters; ➥ Rich cultural and historical heritage offering comparative advantage for creative industries and cultural tourism innovation; ➥ Presence of vocational training institutions and secondary specialised schools forming a pipeline for technically skilled workforce	➥ Significant population decline and brain drain, especially from peripheral communities; ➥ Limited financial autonomy of local budgets and weak investment climate; ➥ Insufficient university-business linkages; low business investment in R&D and innovation; ➥ Underdeveloped innovation infrastructure (absence of technology parks, incubators); ➥ Low digital literacy and innovation culture among the general population; ➥ Fragmented governance and insufficient inter-community coordination, limiting the scale of jointly implemented innovation initiatives; ➥ Weak intellectual property protection mechanisms and limited awareness of patent procedures among local innovators and entrepreneurs; ➥ Absence of systematic monitoring and evaluation frameworks for innovation policy effectiveness at the community level
Opportunities	**Threats**
➥ Access to international reconstruction and innovation funding (EU, USAID, World Bank) supporting post-war recovery; ➥ Ukraine's EU accession process driving alignment with European innovation policies and standards; ➥ Growing national interest in smart specialisation and cluster development as tools for regional competitiveness; ➥ Digital transformation initiatives providing opportunities for e-governance and remote innovation collaboration; ➥ Post-war return migration creating a potential entrepreneurial workforce; ➥ Reconstruction-driven demand for innovative construction materials, energy-efficient technologies, and smart urban planning solutions; ➥ Expansion of remote work and distributed innovation models reducing geographic disadvantages of peripheral communities; ➥ Potential to develop renewable energy projects (wind and solar) along the Black Sea coast, attracting green technology investment	➥ Ongoing armed conflict causing infrastructure destruction, population displacement, and economic instability; ➥ Risk of continued brain drain and loss of skilled human capital essential for innovation ecosystems; ➥ Widening disparities between large urban centre and peripheral communities in access to resources and innovation support; ➥ Institutional instability and frequent changes in regulatory environment reducing investor confidence; ➥ Limited administrative capacity of small communities to design and implement complex innovation strategies without external support; ➥ Dependence on centralised state funding with high vulnerability to budget cuts and shifting national priorities during wartime; ➥ Cybersecurity threats and risks of digital infrastructure attacks undermining e-governance and innovation platform operations; ➥ Growing competition from other regions and countries for international grant funding and qualified innovation personnel

Source: *compiled by the authors*

Stage four establishes innovation infrastructure encompassing physical, informational, and institutional components. Physical infrastructure involves creating technology parks, business incubators, coworking spaces, and technology transfer centres. Informational infrastructure must ensure access to modern digital technologies, high-speed internet, and specialised information resources. Institutional infrastructure includes forming networks of organisations providing consulting, educational, and financial services to innovators and entrepreneurs. Stage five develops human capital as the primary driver of innovation activity. This process includes education system modernisation considering innovation economy needs, developing continuous learning and qualification improvement programmes, and creating mechanisms for attracting and retaining talented specialists within community territory. Particular attention requires forming entrepreneurial culture and developing innovation thinking skills among the population through educational programmes, trainings, and mentoring initiatives.

Stage six activates research activities at the territorial level through creating local research centres, supporting applied research oriented toward solving specific community problems, and developing partnership relations with academic institutions. An important component involves forming systems for ordering research work from local self-government bodies and local enterprises, ensuring demand for innovation developments and stimulating their practical implementation. Stage seven creates favourable regulatory environment for innovation activities through improving local

normative acts, simplifying administrative procedures for enterprises conducting innovation activities, and establishing mechanisms for rapid response to innovators' needs. This stage also includes developing monitoring and evaluation systems for regulatory policy effectiveness with possibilities for prompt adjustments upon identifying deficiencies or emergence of new challenges. Stage eight develops financial support for innovation activities through diversifying financing sources, including budgetary funds, private investments, grant financing, and crowdfunding. Particular attention requires creating local innovation support funds, developing microcrediting for startups, and attracting business angels and venture investors. An important component involves forming guarantee and insurance systems for innovation projects to reduce investor risks. Stage nine advances innovation commercialisation systems through creating technology transfer centres, patent agencies, intellectual property consulting services, and marketing agencies specialising in innovation product promotion. This stage also envisions forming cooperation networks between developers and potential innovation consumers, including organising exhibitions, conferences, and business meetings.

Stage ten integrates the territorial community into regional, national, and international innovation networks through participation in joint projects, experience exchange, engagement in international cooperation programmes, and creating partnership relations with other innovation territories. This facilitates access to new knowledge, technologies, and sales markets, significantly enhancing local innovation competitiveness. Stage eleven establishes monitoring and evaluation systems for innovation strategy effectiveness through developing key indicators, regular analysis of achieved results, and strategy correction corresponding to external environment changes. The monitoring system must include both quantitative indicators and qualitative measures reflecting social and ecological aspects of innovation development. Stage twelve institutionalises innovation activities through consolidating achieved results in local strategic documents, creating permanently operating innovation support mechanisms, and forming continuous improvement culture. This ensures sustainability of territorial community innovation development and its capacity to adapt to future challenges and opportunities.

The short-term perspective (1-2 years) aims to create fundamental foundations of the integrated innovation model through simultaneous development of all key components. Initial efforts focus on comprehensive audit of community potential, establishing coordination councils for innovation development, creating basic physical and virtual resources for supporting innovation activities, and organising educational programmes for population capacity building. This period emphasises implementing 2-3 demonstration projects simultaneously engaging all innovation model components, serving as success stories motivating further resident participation in innovation processes. The long-term perspective (5-10 years) directs efforts toward full-scale implementation of the integrated innovation model ensuring systematic territorial community transformation. The innovation strategy evolves into a dynamic strategic management system based on continuous monitoring of external environment changes and automatic priority adjustment. Created analytical centres grow into foresight research centres focusing on future development scenario forecasting rather than retrospective analysis. Strategic decisions utilise big data and complex analytical models ensuring high planning accuracy.

The innovation ecosystem in strategic perspective transforms into a sustainable cooperation network spanning multiple territorial communities and integrating into national and international innovation networks. Cooperation platforms acquire inter-regional character, ensuring resource, knowledge, and best practice exchange among different territories. Within the economic region, joint research centres, inter-community investment funds, and mutual learning systems emerge, enabling the community to become an active centre for diffusion of innovation solutions and technologies to other regions and countries. Innovation infrastructure evolves into comprehensive technology parks, business incubators, and technology transfer centres, with territorial competence centres integrating educational, scientific, and production activities, ensuring preparation of highly qualified personnel at regional and national levels. The created network of specialised laboratories and research centres serves multiple regions' needs. Innovation culture becomes an integral part of community residents' thinking, with small and medium businesses forming foundations for further innovation activities and job creation. Participatory budgeting of innovations significantly expands, with bonus systems for stimulating innovation more broadly integrated into various aspects of public life. The innovation management system evolves into professional territorial development services applying modern project management methods for optimising decision-making processes. Multi-level coordination systems ensure coherence of actions at local, regional, and national levels, facilitating integration of economic efficiency, social justice, and ecological responsibility through interaction of all five innovation model components,

ensuring sustainable competitiveness and high quality of life for residents in long-term perspective.

Considering common characteristics among territorial communities in the Black Sea economic region, ensuring coordination of their innovation development proves essential. This realises through creating inter-territorial innovation alliances uniting communities around joint development projects, formed according to geographic, sectoral, or thematic principles and directed toward solving common challenges or implementing large-scale initiatives. Alliance advantages include possibilities for joint project financing, enhanced social engagement, coordinated efforts for innovation commercialisation, and lobbying common interests at higher management levels, creating scale effects for small territorial communities. The social component of the innovation strategy for ensuring competitiveness implements through loyalty programme systems stimulating resident participation in community innovation projects, aligned with the Presidential Decree of Ukraine No. 487/2021 (2021). Citizens may receive benefits or bonuses for participating in solving local problems, implementing rationalisation proposals, and innovation activities, usable for obtaining discounts on utilities, participating in educational programmes, or purchasing local goods and services. This system integrates with participatory innovation budgeting principles, where portions of community budget funds direct toward financing projects selected by residents through public voting systems, ensuring openness and government accountability to the public. The marketing aspect of the proposed innovation strategy includes creating territorial innovation brands based on unique community characteristics and achievements (Oleksiuk *et al.*, 2021). Each territory develops its own identification system for innovation products and services created or improved within its territory, integrating with the "innovation tourism" concept. The latter envisions attracting external parties to participate in territorial innovation projects through volunteer and grant programmes, participation in scientific research, and testing new products and services, creating additional opportunities for innovation financing and forming positive community image.

Lobbying common interests at higher management levels represents a strategic mechanism for resource and influence consolidation, enabling small territorial communities to achieve synergetic scale effects in innovation development and competitiveness contexts. This approach must base itself on network governance concepts envisioning formation of horizontal and vertical linkages among different government levels and civil society (Vasiuk & Haievska, 2023). Small territorial communities with individually limited resources and political influence achieve significantly greater effectiveness through creating coalitions and alliances, alongside public control over management decision adoption and implementation. Lobbying effectiveness increases through developing comprehensive communication strategies including preparing analytical materials, presentations, and proposals demonstrating potential advantages of developing and implementing innovation goods and services for entire regions or the state. Important aspects include engaging scientists, educators, enterprises, and public organisations, providing additional legitimacy and scientific substantiation to initiatives advanced by government bodies and local self-government, alongside creating favourable normative-legal environments stimulating small and medium business development, innovations and entrepreneurship, strengthening leadership potential in communities, and preparing qualified specialists capable of effectively representing alliance interests at various government levels.

DISCUSSION

The findings of this research reveal fundamental systemic differences between innovation ecosystems in developed Western economies and Ukrainian territorial communities, necessitating conceptual adaptation rather than direct model transfer. While Western innovation models have evolved within stable institutional environments characterised by mature market mechanisms, well-established financial infrastructure, and robust regulatory frameworks, Ukrainian territorial communities operate under fundamentally different conditions. These conditions are shaped by ongoing institutional transformation, significant resource constraints, limited administrative capacity at the local level, and the unprecedented challenges posed by wartime realities. The divergence manifests across multiple critical dimensions of ecosystem architecture, including stakeholder capabilities and roles, resource availability and allocation mechanisms, governance structures and decision-making processes, innovation culture and entrepreneurial mindset, as well as patterns of inter-institutional collaboration. Consequently, successful innovation development in Ukrainian contexts requires not merely adjusting implementation parameters of Western frameworks, but reimagining their foundational assumptions to account for specific local capabilities, institutional peculiarities, historical development trajectories, and the unique governance structure emerging from decentralisation reforms.

Responding to these contextual specificities, the results of this study present an integrated innovation

model for the socio-economic development of territorial communities in Ukraine's Black Sea Economic Region, encompassing five synergistic components – innovation strategy, ecosystem, infrastructure, culture, and management – implemented through a twelve-stage algorithm with short- and long-term perspectives. This model extends the quadruple helix framework by integrating civil society as a foundational element, overcoming structural asymmetries in the Ukrainian context compared to Western triple helix examples (Fritsch & Wyrwich, 2021), such as resource constraints in education, business passivity, and governmental integration gaps observed in cases like Berlin-Adlershof and Flottsund Bridge. Unlike traditional approaches, it emphasises inter-territorial alliances, loyalty programs aligned with national civil society strategies, and marketing through innovation brands, promoting resilience amid wartime disruptions and decentralisation (Roman & Fellnhofer, 2022; Stephens, 2025).

The centrality of civil society in this adapted framework finds strong empirical support in recent scholarship. P. González-Martinez *et al*. (2023) and highlighted that civil society acts as a fundamental mediator in regional innovation systems, shaping the effectiveness of science, technology, and innovation policies. Their findings confirmed that greater citizen involvement and strong human capital significantly enhance innovation outcomes, highlighting the influential role of local governments and communities in fostering sustainable development. Building upon these theoretical foundations, several recent studies have validated and extended elements of the proposed approach. O. Kushnerov *et al*. (2025) applied the Quadruple Helix to form target indices for 1,469 territorial communities in Ukraine, training a neural network on socio-economic and security data. Results demonstrated high synergy efficiency among government, business, science, and civil society, validating ecosystem and monitoring (stage 11) with predictive accuracy. This work considers this approach valid for management digitalisation, but differ with sequential 12-stage algorithm adapted to wartime realities, as opposed to their neural network model.

Expanding the theoretical scope further, Kravchenko (2025) substantiated Triple/Quadruple/Quintuple Helix as the foundation for community innovation development, analysing their applicability to decentralisation. The author noted that the Quintuple Helix integrates an ecological dimension, validating innovation culture and long-term perspective (5-10 years). This aligns with stakeholder emphasis, but this work expands it with practical alliances and loyalty programs, addressing gaps in their theoretical base. E. Samara *et al*. (2023) applied a system dynamics approach to the development of a Regional Innovation System (RIS). Their methodology highlights the importance of viewing RIS as a complex, interconnected structure composed of multiple subsystems and measurable factors, where innovation emerges from dynamic interactions among institutions and policies. This systemic perspective aligns with current approach to building an innovation model: both emphasised that competitiveness and regional development cannot be explained by isolated actions, but require an integrated framework that captures the interdependencies between government, business, academia, and society.

Geographic specificity also emerges as a critical consideration in model adaptation. M. Cybulska (2024) tested spiral cooperation within the dualism of centre and periphery, finding that peripheral municipalities value state-business ties most for growth. This peripheral orientation corresponds to the proposed individual regional consideration of the Black Sea economic region (stage 1), which expands in successive stages absent from their analysis. Furthermore, Ukrainian scholarship on network governance provides conceptual alignment. N. Vasiuk & L. Haievska (2023) examined the essence of network management as horizontal coordination among state, business, NGOs, and citizens, highlighted public authorities' role in facilitating trust and resource exchange. Unlike their purely theoretical approach lacking practical implementation frameworks, current model innovates with a 12-stage algorithm integrated into the quadruple helix for territorial communities, tailored to wartime realities and Black Sea decentralisation, while extending their ideas through concrete innovation infrastructure and loyalty mechanisms.

Translating these theoretical insights into practical application, the quadruple helix approach addresses concrete challenges in Ukrainian communities. Government capacity limitations can be compensated through active civil society engagement in innovation identification, priority setting, and implementation monitoring. Business sector passivity may be overcome through citizen initiatives, social entrepreneurship, and cooperative models. Educational institution resource constraints can be supplemented through community-based learning initiatives and knowledge-sharing platforms. The research provides actionable frameworks for territorial community leaders and policymakers. The integrated model and implementation algorithm offer concrete guidance moving beyond abstract discourse to specific operational steps. Recognition that successful strategies require cultural transformation alongside institutional change informs capacity-building priorities. Inter-territorial cooperation mechanisms demonstrate that resource-constrained communities can enhance

competitiveness through strategic alliances, challenging deficit-focused narratives and highlighting opportunities for collective action and mutual benefit. These results contribute to emerging scholarly discourse on context-specific innovation model development in transition economies, particularly those experiencing simultaneous challenges of structural transformation, decentralisation reform, and geopolitical disruption.

CONCLUSIONS

This research demonstrated that implementing innovation strategies for ensuring territorial community competitiveness represents a complex multi-stage process requiring systematic approaches and coordinated efforts from all interested parties. The proposed integrated innovation model responds to systemic gaps through five synergistic components. The innovation strategy component ensured alignment between territorial aspirations and available resources through comprehensive auditing. The innovation ecosystem addressed coordination failures through permanent cooperation platforms functioning in traditional and digital formats. Innovation infrastructure through territorial competence centres represents strategic response to resource scarcity, with communities concentrating on key directions rather than attempting comprehensive coverage. Innovation culture development addresses fundamental challenges that institutional changes prove insufficient without corresponding shifts in values and attitudes. The innovation management system provides operational structures for planning, coordination, and evaluation.

Implementation success requires adaptive strategic planning based on continuous monitoring and flexible priority adjustment, particularly relevant given current challenges facing Ukraine. Inter-territorial collaboration through innovation alliances creates synergistic effects, enabling resource sharing, experience exchange, and coordinated advocacy at higher governance levels. The twelve-stage implementation algorithm provides practical guidance from initial diagnostics through institutionalisation, ensuring systematic progress whilst maintaining flexibility for local adaptation. Short-term and long-term perspectives outline concrete pathways from establishing foundational elements to achieving full-scale transformation into innovation-driven communities. The proposed approach ensures comprehensive solutions for innovation development challenges through combining strategic planning, institutional building, and practical implementation of specific measures. This enables territorial communities not merely to adapt to contemporary challenges but to form their own competitive advantages based on innovation potential and effective utilisation of available resources, ultimately contributing to enhanced quality of life and sustainable development in the Black Sea Economic Region. Future research should examine conflict management mechanisms among stakeholders, relationships between innovation strategy and social equity outcomes, and comparative studies in other post-socialist economies. Quantitative metrics need refinement beyond economic indicators to capture social, cultural, and environmental dimensions.

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CONFLICT OF INTEREST

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Стратегія підвищення конкурентності територіальних громад Причорноморського економічного району на інноваційних засадах

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Анотація. Сучасний економічний розвиток, що характеризується прискореною глобалізацією, цифровізацією та трансформацією соціальних відносин, ставить перед територіальними громадами нові виклики, водночас відкриваючи можливості для їх інноваційного розвитку, що робить критично важливим розроблення адаптованих стратегій підвищення конкурентоспроможності в умовах реформи децентралізації та структурних трансформацій в Україні. Метою статті було розроблення інноваційної стратегії для підвищення конкурентоспроможності територіальних громад у Причорноморському економічному районі. Проаналізовано обмеження традиційної моделі «потрійної спіралі» («університет-уряд-бізнес») для українських умов та обґрунтовує необхідність впровадження підходу «четверної спіралі», що включає громадянське суспільство як ключовий елемент. У дослідженні запропоновано інтегровану інноваційну модель, що складається з п'яти основних компонентів: інноваційної стратегії, інноваційної екосистеми, інноваційної інфраструктури, інноваційної культури та системи управління інноваціями. Представлено комплексний алгоритм реалізації інноваційної стратегії, що охоплює 12 послідовних етапів від комплексної діагностики до інституціоналізації інноваційної діяльності. Особлива увага приділена розвитку територіальних центрів компетенції, механізмів адаптивного стратегічного планування та міжтериторіальних інноваційних альянсів на основі державно-приватного партнерства. У статті викладено конкретні пропозиції щодо реалізації інноваційної стратегії в короткостроковій (1-2 роки) та довгостроковій (5-10 років) перспективі з урахуванням унікальних характеристик територіальних громад району. Результати дослідження підтвердили, що для успішної реалізації необхідна систематична координація між зацікавленими сторонами, лідерство з боку органів місцевого самоврядування та гнучке реагування на зміни в зовнішньому середовищі. Запропонований підхід забезпечує комплексні рішення для викликів у сфері інноваційного розвитку шляхом інтеграції стратегічного планування, інституційного розвитку та практичної реалізації конкретних заходів

Ключові слова: конкурентоспроможність; інноваційна стратегія; інноваційна екосистема; модель «четверної спіралі» інноваційного розвитку; стратегічне планування

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