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Адреса редакції:
Поліський національний університет
10008, б-р Старий, 7, м. Житомир, Україна
E-mail: info@sciencehorizon.com.ua
https://sciencehorizon.com.ua/uk

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Editors office address:
Polissia National University
10008, 7 Staryi Bvld., Zhytomyr, Ukraine
E-mail: info@sciencehorizon.com.ua
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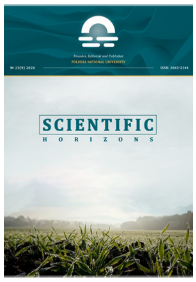

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Technology of manufacture and efficacy of obstetric pessaries for preventive therapy in cows

Svitlana Huralska*
Doctor of Veterinary Sciences, Professor
Polissia National University
10008, 7 Stary Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0001-7383-1989

Liudmyla Yevtukh
PhD in Veterinary Sciences, Associate Professor
Polissia National University
10008, 7 Stary Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0003-3116-3980

Hennady Hryshchuk
PhD in Veterinary Sciences, Associate Professor
Polissia National University
10008, 7 Stary Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0001-7092-2412

Volodymyr Honcharenko
PhD in Veterinary Sciences, Associate Professor
Polissia National University
10008, 7 Stary Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0002-2183-8828

Vyacheslav Zakharin
PhD in Veterinary Sciences, Associate Professor
Polissia National University
10008, 7 Stary Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0002-4157-644X

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Abstract. The relevance of this study lies in the need to develop new, effective means of preventive therapy for retained placenta in cows, a common issue in veterinary medicine. Retained placenta can lead to serious complications, highlighting the necessity for the implementation of effective therapeutic solutions. This study aimed to develop the composition and manufacturing technology of polyethylene oxide-based pessaries incorporating the uterine β-adrenoreceptor blocker, anapriline, and to assess their efficacy in the preventive treatment of retained placenta in cows. The

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**Corresponding author*

pessaries were produced by casting into moulds, using polyethylene oxide with molecular weights of 400 and 1500 in a ratio of 1:9, with the addition of anapriline to the base. The study was conducted on four groups of cows: a control group, which did not receive obstetric pessaries, and three experimental groups, in which pessaries with different compositions containing anapriline were tested. The manufactured pharmaceutical compositions were investigated immediately after calving by introducing them into the space between the placenta and chorion. The results of the study demonstrated that the use of pessaries containing anapriline significantly improved the efficiency of placental separation. In particular, compositions No. 2 and No. 3 showed the best performance, reducing the average time of placental separation by 6.8 and 5.6 hours, respectively, compared with the control group. The proposed pessaries proved effective in the prevention of retained placenta. The findings also suggest potential for the development of an industrial manufacturing technology for these pessaries, facilitating their widespread use in cattle farming to enhance animal productivity and reduce economic losses. The practical value of this article lies in the fact that the developed pharmaceutical compositions can be employed in veterinary practice for the preventive therapy and treatment of retained placenta in cows

Keywords: cattle; reproductive health; retained placenta; prevention of obstetric pathology; postpartum period

INTRODUCTION

In the context of the post-war recovery of Ukraine's agricultural sector, the effective reproduction of the dairy cattle population is of particular importance. The decline in livestock numbers caused by military actions significantly complicates the stabilisation and development of the dairy industry. Addressing the challenges associated with improving the reproductive capacity of dairy herds requires a thorough scientific approach and the search for effective preventive and therapeutic measures to reduce the incidence of postpartum complications, particularly obstetric and gynaecological pathologies. One of the most common disorders in the postpartum period is retained placenta, which negatively impacts the overall health of the animals, their productivity, and subsequent reproductive function.

O. Kotykova *et al.* (2024) emphasise that cattle hold a significant place in the agricultural sector of many countries, ensuring the production of milk, meat, and other products. Their importance is not limited to productivity alone, as these animals play a key role in ensuring food security for the population and supporting agriculture. Overcoming the challenges related to the recovery of the dairy industry and ensuring the health of cattle is a priority for veterinary medicine in the current climate. S. Sidashova *et al.* (2024) note that veterinary professionals face the crucial task of minimising the negative impact on dairy herd reproduction, particularly by reducing the incidence of gynaecological diseases in cows.

Numerous scientific studies have highlighted the crucial role of the postpartum period in ensuring cow health and productivity. Notably, K. Macmillan *et al.* (2020) underscored the importance of complete involution of the reproductive organs after calving, which dictates the subsequent reproductive cycle and level of milk yield. V. Vlizlo *et al.* (2024) examined the interrelationship between postpartum disorders and reduced overall cow productivity. R. Schmitt *et al.* (2023) emphasised that postpartum stress and hormonal changes exacerbate the risk of obstetric complications, which subsequently lead to reduced fertility.

Retained placenta is one of the most frequent complications of the third stage of labour in cows, requiring particular attention to ensure the future health and productivity of the animals. C. Luo *et al.* (2024) state that retained foetal membranes in dairy cows is a common reproductive disorder resulting from the firm attachment of maternal and foetal placental tissues. F. Mahnani *et al.* (2021) analysed the multifactorial nature of retained placenta, identifying housing conditions and the physiological and pathological states of the animals as key contributing factors. Among the primary causes of this complication, researchers identify age, parity, hormonal peculiarities, heredity, uterine hypotony and atony, adhesions between the maternal and foetal parts of the placenta, slowed involution, subclinical endometritis, as well as impaired uterine selfcleaning and increased turgor of the caruncles and cotyledons. Additional factors contributing to retained placenta include errors in feeding pregnant cows, lack of exercise, uterine overstretching, inflammatory processes in the placenta, and mechanical obstructions.

In turn, the application of modern approaches to the therapy of such pathologies, particularly the use of innovative agents like polyethylene oxide-based pessaries with the beta-blocker anaprilin, allows not only for addressing the cause of retained placenta but also promotes the normalisation of reproductive system functions. Thus, in the context of rehabilitating the livestock sector in Ukraine, there is a growing need for effective measures for the prevention and treatment of obstetric and gynaecological diseases in cows, which underscores the relevance of developing new veterinary solutions. This study aimed to investigate the efficacy of using intravaginal pessaries based on polyethylene oxide with the beta-blocker anaprilin for the prevention and treatment of retained placenta in dairy cows.

LITERATURE REVIEW

In their studies, S. Sidashova *et al.* (2024) established that, compared to healthy cows in the main dairy herd, a significantly higher prevalence of chronic subclinical endometritis symptoms was observed in the culled group, averaging around 34%. A significant prevalence of multi-organ gynaecological pathology was also detected, particularly chronic adhesive salpingitis. Among culled cows, this indicator increased by almost 31%, indicating the chronicity of prolonged inflammatory processes in the endometrium and the ciliated epithelium of the oviducts, which can lead to chronic, irreversible infertility.

Z. Rodriguez *et al.* (2023) note that the postpartum period involves the transition from pregnancy and parturition to lactation and preparation for a new gestation. During this time, the resistance of the cow's body is reduced, requiring specific management and feeding regimes that promote complete involution of the reproductive organs, high levels of lactation, and the proper functioning of all organs and systems. According to S. Washaya *et al.* (2025), cows enter a period of sexual inactivity after calving, the duration of which can vary significantly. This is due to factors such as inadequate feeding, the suckling process, hormonal imbalances, and the effects of stress.

In the context of modern intensive livestock farming, lactating cows genetically predisposed to high milk yields experience metabolic stress during the postpartum period. As highlighted by I. Hryshchuk *et al.* (2021) and R. Mylostyvyi *et al.* (2021), the transition period from pregnancy to lactation is a critical phase accompanied by significant physiological, metabolic, and inflammatory changes. Successful lactation is largely dependent on the efficiency of adaptation during the postpartum period. Consequently, challenges in lactation adaptation have been the subject of intensive research in dairy farming over the past 50 years. However, as underscored by S. Huralska and V. Olishevskyi (2024) and V. Vlizlo *et al.* (2024), the postpartum period continues to be critical for animal welfare, farm profitability, and stable milk production.

Diseases of the reproductive organs in cattle represent a significant challenge in modern veterinary obstetrics and gynaecology, as they are a primary cause of prolonged infertility in cows, leading to reduced milk yield, cessation of lactation, and premature culling. Such diseases result in profound structural changes in the endometrium and myometrium, manifesting as uterine hypotony, oedema of the serous and muscular membranes, diffuse infiltration of the endometrium by lymphoid elements, necrosis, and shedding of the superficial layer. As Matamala *et al.* (2021) emphasise, opportunistic microflora plays a significant role in the development of pathology, particularly through increased virulence and the number of drug-resistant strains, as well as the high incidence among pregnant animals. H. Beiranvand *et al.* (2024) report that an unfavourable intrauterine environment during pregnancy can cause long-lasting structural and physiological changes in foetal development, which may lead to health problems and reduced productivity in adulthood. Clinical conditions accompanying multiple pregnancies in cows include retained placenta, metritis, mastitis, lameness, and disorders of the digestive and respiratory systems.

Retained placenta in cows is a common postpartum complication that typically disrupts the reproductive cycle. As A. Mahnani *et al.* (2021) point out, subsequent conception can be delayed by 2-6 months, which in turn increases the calving interval, alters the timing of the next calving, raises the risk of uterine infections and infertility, negatively affects cyclicity, and reduces milk yield, thereby lowering the overall economic efficiency of production and the productivity of the industry. Furthermore, retained placenta can prolong uterine involution and provoke the development of cystic ovarian degeneration, chronic endometritis, pyometra, and other conditions. Despite treatment, this pathology significantly increases the risk of reduced productivity and the occurrence of reproductive disorders in cows. According to J. Rajoriya *et al.* (2024), this leads to a decrease in the number of offspring that could be obtained in a calendar year and negatively impacts the economic performance of farms of various ownership types. Based on the research results of Y. Amin *et al.* (2021), cows with retained placenta are at high risk of developing postpartum metritis. S. Boudelal *et al.* (2022) indicate that with complications such as retained placenta, the risk of developing diseases of various aetiologies increases.

Thus, researchers are paying particular attention to studying the characteristics of the postpartum period in cows, analysing its impact on animal health, productivity, and reproductive function, as well as preventive measures. R. Schmitt *et al.* (2023) demonstrate that the use of flunixin meglumine in the early postpartum period helps reduce inflammation, lowers the risk of metritis in heifers, improves the metabolic profile in cows, and decreases pain manifestations in all animals. F. Magata *et al.* (2021) in their studies indicate that the efficacy of using oxytocin for the prevention of retained foetal membranes (RFM) in dairy cows remains debatable. The physiological characteristics of animals during calving can influence the body's reaction to oxytocin. At the same time, the authors note that the effect of oxytocin varies depending on the course of calving. Administering the drug in the early postpartum period can reduce the risk of RFM development and mitigate the negative impact of obstetric intervention during calving on subsequent reproductive function. According to the research results of Y. Amin *et al.* (2023), the combination of prostaglandin F2α with α-chymotrypsin is an effective method for treating retained placenta. This treatment ensures effective placental separation, promotes rapid uterine involution, reduces the likelihood of postpartum metritis, and improves reproductive performance.

Therefore, early diagnosis and preventive measures are crucial for minimising the risks of obstetric and gynaecological pathology. These actions help reduce economic losses and ensure effective treatment, which contributes to improving the reproductive health of cows and the overall productivity of farms.

MATERIALS AND METHODS

The studies were conducted between 2022 and 2023 at the private agricultural enterprise Savertsi in the Popilnia District of the Zhytomyr Region, on Holstein Friesian cows aged 3-5 years. To determine the efficacy of the therapeutic action of the manufactured moulded pessaries, four groups of cows with a history of the complete retained placenta during previous calvings were selected: a control group (without the use of obstetric pessaries) and three experimental groups: the first treated with obstetric pessaries of composition No. 1, the second with composition No. 2, and the third with composition No. 3. For the studies, a suppository base comprising polyethylene oxide with a molecular weight of 400 and polyethylene oxide with a molecular weight of 1500 in a 1:9 ratio was chosen for the manufacture of pessaries weighing 10.0 g each. During the studies, the principles of the "General Ethical Principles of Experiments on Animals" (Reznikov, 2003), which comply with the requirements of the Law of Ukraine No. 3447-IV (2006), the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986), and the Universal Declaration on Animal Welfare (2007), were observed.

Pessaries were manufactured using a moulding method according to the techniques described in the patents (Utility model patent No. 152703, 2023; Utility model patent No. 152953, 2023). The process involved the following steps: at the preparatory stage, incoming analysis of anaprilin, polyethylene oxide 400, and polyethylene oxide 1500 was carried out to ensure compliance with the current State Pharmacopoeia of Ukraine (SPhU) (2015), after which all components were weighed. Next, solutions of anaprilin in polyethylene oxide 400 were prepared (Table 1). The manufactured medicinal compositions in the form of pessaries were tested immediately after calving by introducing them into the space between the placenta and the chorion.

***Table 1**. Composition of pessaries*

Composition	Component characteristics, g		
	Anaprilin	Polyethylene oxide 400	Polyethylene oxide 1500
No. 1	0.01	0.6	9.19
No. 2	0.02	0.8	8.58
No. 3	0.03	1.0	7.97

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

The process continued with setting the temperature of a water bath within the range of +40°C to +50°C. A suitable vessel (a chemical beaker made of neutra l glass) was placed in the bath, and the weighed polyethylene oxide 1500 substance was added to it. This was heated until it melted, and while maintaining the temperature and constant stirring, the solution of anaprilin in polyethylene oxide 400 was added. The resulting melted suppository mass was poured into moulds at 10 g per mould and cooled to a temperature between +1°C and +20°C until solidified. Next, to release the suppositories (sticks) from the moulds, the outer layer of each pessary was melted by heating and simultaneously rotating the mould with the pessary around its axis in a stream of hot air from a spirit lamp. The pessaries were then immediately pushed out of the moulds. The manufactured pessaries were wrapped in strips of paraffin paper. The average mass of the pessaries was 10.0 ± 0.32 g, and all manipulations were documented in the patents (Utility model patent No. 152703, 2023; Utility model patent No. 152953, 2023).

Sufficiently studied methods for reducing tissue hydration in caruncles and cotyledons involve the use of osmotically active medicinal compositions. For instance, known soft dosage forms in the shape of sticks weighing 5-50 g include gelatin-glycerine gel, which possesses a complex of osmotically active, bacteriostatic, absorbent, and evacuative properties and is capable of maintaining the endometrial mucin layer due to its properties. Its composition includes 5%-50% gelatin, and 1%-75% glycerine, with the remainder being water. To enhance the absorbent properties of the pessaries, finely dispersed siliceous organic adsorbent Enterosgel was introduced into the melted gelatin-glycerine base. Additionally, to enhance the tonic effect on the myometrium, anaprilin, a non-selective uterine beta-adrenoceptor blocker, was added to the gelatin-glycerine suppository base. This results in increased tonic cholinergic influences on uterine contractions. Particular attention was paid to increasing the shelf life of the pessaries. Concurrently, the feasibility of using suppository bases comprising an alloy of polyethylene oxide 1500 with polyethylene oxide 400 in a 9:1 ratio was investigated. It was established that such bases exhibit more pronounced osmotic and antiseptic properties. Consequently, they were concluded to be suitable for the treatment of obstetric and gynaecological complications in cows (Utility model patent No. 152703, 2023; Utility model patent No. 152953, 2023). The manufactured sticks complied with the requirements of the SPhU and were used in clinical trials (Table 2).

***Table 2**. Characteristics of pessary components*

Component name	Composition, No.	Weight, g	Influence of parameter on product quality
Anaprilin	1	0.01	Lower limit – insufficient tonic effect on uterine contractions
	2	0.02	Optimal content – sufficient tonic effect on uterine contractions
	3	0.03	Upper limit – excessive tonic effect on uterine contractions, risking cervical spasm
Polyethylene oxide 400	1	0.60	Lower limit – insufficient osmotic action and permeability into the interstitial space
	2	0.80	Optimal content – sufficient osmotic action and permeability into the interstitial space
	3	1.00	Upper limit – stick loses hardness
Polyethylene oxide 1500	1	9.19	Upper limit – unacceptable brittleness of the stick
	2	8.58	Optimal content – sufficient osmotic action of the substance and rheological properties of the stick
	3	7.97	Lower limit – stick hardness is lost

***Note:** the manufactured sticks complied with the requirements of the SPhU*
***Source:** developed by the authors*

Statistical analysis of the obtained results was performed using Statistica 6.0 software (StatSoft Inc., USA). Fisher's F-test was used to assess significance. Differences between indicators were considered statistically significant at $P < 0.05$.

RESULTS AND DISCUSSION

Based on the study results, retained placental expulsion was observed in 2 cows in the control group. In the remaining cows, the placenta was expelled spontaneously, with an average time of 10.31 ± 4.13 hours (Fig. 1).

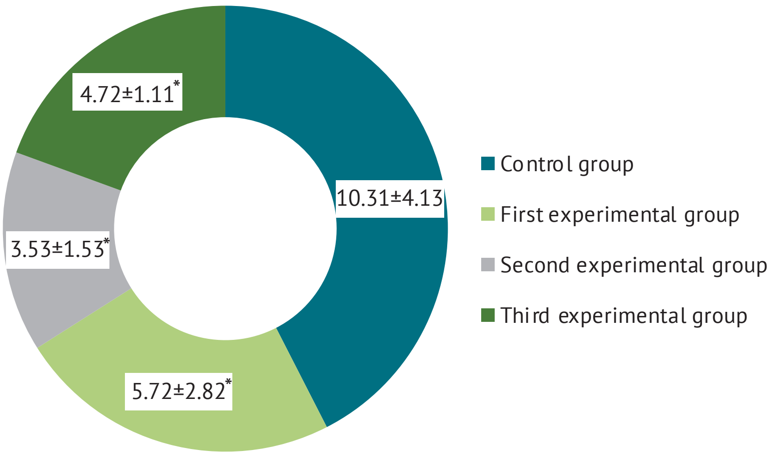

***Figure 1**. Time of placenta expulsion, hours*

***Note:** * – $P < 0.05$ compared to the control group*
***Source:** developed by the authors*

Pessaries of composition No. 1 (Table 1), with the minimum content of active substances, were administered to 10 experimental cows. Trials showed satisfactory therapeutic action, with complete retention of the foetal membranes for over 12 hours observed in one cow, representing 10% of the total number of experimental animals. The average time for placental detachment significantly decreased by 1.8 times ($P < 0.05$) compared to the control, amounting to 5.72 ± 2.82 hours. Trials of the pessaries manufactured according to composition No. 2 (Table 1), with a medium content of active substances, demonstrated high therapeutic efficacy. No cases of placenta retention were diagnosed in this experimental group. The average time for detachment of the foetal portion of the placenta was 3.53 ± 1.53 hours, which was 2.9 times shorter ($P < 0.05$) compared to the analogous indicator in the control group cows. Trials of the pessaries manufactured according to composition No. 3 (Table 1), with the maximum permissible content of active substances, showed their sufficiently high therapeutic action; no cases of placenta retention were observed, and the average time for their detachment was 4.72 ± 1.11 hours.

Thus, the comparative analysis showed that the use of the manufactured medicinal compositions in the form of sticks on an osmotically active base comprising an alloy of polyethylene oxide with molecular weights of 400 and 1500 and the active substance anaprilin, for preventive therapy, ensures the detachment of the foetal placenta from the maternal part 4.6, 6.8, and 5.6 hours earlier than in the control group cows (which received no therapeutic intervention during the third stage of labour). During the analysis of the postpartum period in the control group of cows, subinvolution of the uterus was diagnosed in three animals, necessitating appropriate treatment. Oestrus was observed in 5 cows within the first 30 days postpartum and in another 3 by day 40. Purulent-catarrhal endometritis was detected in 2 cows, for which appropriate therapeutic measures were implemented.

According to the livestock management system at the research farm, the first oestrus in cows is not used for service to allow for the completion of involutionary processes in the reproductive organs; artificial insemination is performed at the second oestrus. In the control group, 7 cows exhibited a second oestrus cyclically (19-21 days after the first), while a prolonged oestrous cycle was diagnosed in three. Following artificial insemination, taking into account the treatment administered, the conception rate at first service in the control group cows was 50%. In the experimental groups, the involution of the reproductive organs proceeded without complications. Oestrus was recorded within 30 days postpartum, and the second oestrus was characterised by cyclicity. The conception rate at first service was significantly higher than in the control group: 70% in the first experimental group, 80% in the second, and 90% in the third. This confirms the high efficacy of the developed and applied preventive therapy. The obtained results indicate the advisability of using the proposed therapeutic approaches for the prevention of postpartum complications, which allows for timely uterine involution, improves the reproductive performance of animals and optimises breeding processes on farms.

The high prophylactic and therapeutic efficacy of the proposed medicinal products is attributed to the biological and physicochemical properties of each component in the composition, as well as the environment of the uterine cavity during calving and the postpartum period. An important factor is the preservation of the endometrial mucin layer, which provides optimal conditions for the restoration of the reproductive system. Key characteristics of this layer include its ability to absorb moisture, optimal viscosity, and low shear stress values, which promote effective placental detachment and the prevention of complications. The sufficient efficacy of local prophylactic and therapeutic agents formulated with water, oxidising agents, surfactants, coagulants, and astringents is hindered by their capacity for irritation and tissue denaturation; the destruction of cells, which become a nutrient medium for pathogenic microflora after losing morphological integrity; insufficiently active penetration to accumulations of causative agents of purulent-inflammatory processes deep within tissues; insufficiently intensive absorption from the surface of the endometrial mucous membrane; and the destruction of the endometrial mucin layer, which possesses a complex of beneficial properties (ensuring sufficient cell hydration; absorbing pathogens with subsequent evacuation from the uterine cavity; significantly reducing shear stress, thereby creating conditions for placental slippage) (Utility model patent No. 152703, 2023; Utility model patent No. 152953, 2023).

Several authors, such as Y. Li *et al.* (2022), have described the efficacy of using various interventions in the postpartum period, including pharmacological preparations, immunostimulants, osmotically active compositions, and other therapeutic solutions aimed at improving the involution of the reproductive organs and the prevention and treatment of gynaecological diseases in cows. Notably, L. Cui *et al.* (2021), in their studies, used meloxicam, a non-steroidal anti-inflammatory drug, to reduce pain and control inflammatory processes in cows with metritis. The results showed that meloxicam effectively reduces inflammation and prevents the growth of pathologically altered tissues, playing a key role in reducing the clinical manifestations of the disease.

H. Li *et al.* (2024) draw attention to the importance of selenium (*Se*) as a key trace element that influences animal growth and development, as well as rapid endometrial recovery. The researchers established that *Se* promotes the regeneration of the endometrial epithelium and restores the natural protective barriers of the uterus, allowing cows to return to normal reproductive cyclicity more quickly. The authors studied the effect of *Se* on the proliferation of endometrial epithelial cells in cows and concluded that *Se* can reduce their damage and stimulate cell proliferation and migration *in vitro* by increasing the expression of growth factor genes.

According to K. Jiang *et al.* (2024), interferon-tau (*IFN-τ*) is an innovative type of interferon that plays a key role in regulating inflammatory processes. *IFN-τ* is capable of protecting endometrial epithelial cells from inflammatory damage. According to the authors, this opens up new horizons in understanding the molecular mechanisms that underpin the anti-inflammatory action of *IFN-τ* in cattle endometrial tissues and provides a theoretical basis for further investigation of its *in vivo* application for the prevention of negative consequences of endometritis. Such studies underscore the importance of a comprehensive approach to the therapy and prevention of gynaecological diseases in cows during the postpartum period using innovative agents and technologies. Comparative analysis indicates a shared trend in both human and veterinary medicine towards the implementation of innovative polymeric drug formulations to prevent pathological processes, which confirms the relevance and potential of further developments in this area. In this context, the results of the study by M. da Cunha Vieira *et al.* (2024), which demonstrate a positive clinical effect from the use of anaprilin, warrant attention.

The proposed medicinal compositions in the form of pessaries possess a unique biotechnological feature: they contain ingredients that do not disrupt the mucin layer, thereby ensuring their therapeutic and prophylactic action. Based on the results of the current studies, the use of these agents promotes the detachment of the foetal placenta on average 5.7 hours earlier compared to cows that did not receive the corresponding therapeutic intervention. The high efficacy of the developed agents is attributed to the optimal biological and physicochemical properties of the components, which preserve the integrity of the endometrial mucin layer, thus contributing to reduced shear stress and improved placental detachment. Calving, like parturition in other mammals, is a complex and stressful process for cows. Prolonged or complicated labour, delayed birth, or the need for difficult obstetric assistance for calf delivery can negatively impact the health, behaviour, and productivity of cows, and also increase the risks of calf morbidity and neonatal mortality. Therefore, ensuring a physiological course of calving is key to improving the welfare of both the cow and her offspring (Matamala *et al.,* 2021). There is a significant body of scientific research concerning the prevalence of infertility in cattle. Researchers such as P. Sklyarov *et al.* (2023) note that this indicator in cows ranges from 20% to 90%. The main causes of infertility include individual and age-related characteristics of the animals, as well as feeding, housing, and management conditions (Kraievskyi *et al.,* 2020; Bondarenko *et al.,* 2020; Hryshchuk & Huralska, 2022).

The postpartum period in cows is characterised by complex physiological processes that significantly influence the state of the reproductive organs and the overall health of the animal. As S. Bors & A. Bors (2020) point out, it is during this period that uterine involution, endometrial regeneration, and the restoration of reproductive system functions occur. P. Skljarov and O. Zubkov (2020) express a similar view, emphasising the importance of this stage for the animal's subsequent productivity. According to the research results of M. Zhelavskyi *et al.* (2020), the negative impact of factors such as feeding and housing conditions during the last month of gestation can cause the development of pathological changes. In particular, this often leads to retained placenta after calving, which becomes a cause of inflammatory processes in the endometrium and requires timely diagnosis.

Inflammatory processes in the uterus and oviducts are a key factor in symptomatic infertility. This opinion is shared by S. Fedorenko and L. Kuraksina (2021) and A. Channo (2022), who emphasise the need for further research into the pathogenesis of infertility to develop effective means and methods for its prevention. As F. de Lima (2020) indicates, uterine diseases negatively affect the development of oocytes, follicles, and embryos, and the uterine environment has a prolonged impact on fertility. Uterine-origin pathologies that arise at the start of lactation affect not only the uterine tissues but also the ovaries, which significantly reduces the probability of pregnancy.

R. Chebel (2021) notes that studies predicting the risk of retained foetal membranes (RFM) and metritis development in dairy cows based on pre-calving haemograms, as well as immune and metabolic status assessment, allow for accurate identification of animals likely to develop uterine diseases after calving. The author also emphasises that identifying cows at low risk of uterine pathologies avoids the need for intensive postpartum monitoring. P. Nyabinwa *et al.* (2020) state that endometritis, a postpartum uterine infection in dairy cows, can lead to significant productivity losses, including reduced milk yield, milk discarded during treatment, and increased veterinary costs. To minimise milk yield losses and reduce economic damage, it is advisable to conduct timely diagnosis and effective treatment of such diseases.

According to R. Cocco *et al.* (2021), systematic review and meta-analysis (*SR-MA*) is a powerful tool for quantitatively assessing parameter variations using comparative data. This contributes to maximising productivity and ensuring animal welfare. For example, changes in the rumination activity of dairy cows before or immediately after calving can be considered as early markers of postpartum diseases. Such studies aimed to assess, using *SR-MA*, whether rumination time recorded during the pre- and postpartum periods would be a consistent and reliable early indicator of metritis in dairy cows. Retained foetal membranes in farm animals are a significant factor contributing to the development of inflammatory processes in the reproductive system. In such cases, the main general approach to treatment is the use of antibiotics, as supported by the research data of C. Hanzen and H. Rahab (2024). According to the results of the current study, obstetric pessaries with anaprilin demonstrated high efficacy in the prevention and treatment of retained placenta in cows. For instance, in the control group, the average time for placental detachment was 10 hours, whereas with the use of pessaries of composition No. 1, this indicator significantly decreased to 5 hours. Similar results were observed by V. Zakharin *et al.* (2024), who reported a significant reduction in the time for placental detachment when using pessaries with anaprilin. Specifically, in their study, the average time for placental detachment was approximately 7 hours. Thus, the obtained results indicate the high biotechnological efficacy of pessaries with anaprilin in the treatment of retained placenta in cows, leading to a reduction in the duration of retention and a decreased risk of complications compared to traditional treatment methods.

CONCLUSIONS

The proposed medicinal compositions in the form of pessaries consist of components that do not disrupt the mucin layer covering the endometrium, thereby ensuring their therapeutic and prophylactic action. Pessaries containing anaprilin, based on an alloy of polyethylene oxide 400 with polyethylene oxide 1500, have significantly longer shelf lives compared to using a gelatinglycerine gel. The use of anaprilin in a polyethylene oxide suppository base, owing to its osmotic activity, more effectively reduces the hydration of endometrial cells compared to a gelatinglycerine base and exerts a better antiseptic effect on the protective mucin layer covering the endometrium. The application of anaprilin within pessaries on osmotically active polyethylene oxide bases, after their insertion into the uterine cavity of cows in the space between the placenta and the chorion, significantly improves and shortens the time of placental expulsion, thus preventing the development of complications.

Obstetric pessaries containing anaprilin in medicinal compositions of formulations No. 2 and No. 3 proved effective for the preventive therapy of retained placenta in cows, as evidenced by the reduction in the average time for its detachment. The medicinal compositions of pessaries No. 2 and No. 3 demonstrated potential for further development of industrial production technology and implementation in veterinary practice. Specifically, in the control group, the average time for placental detachment was 10.31 ± 4.13 hours, while with the use of pessaries of formulation No. 1, this indicator decreased to 5.72 ± 2.82 hours ($P < 0.05$), in formulation No. 2 – to 3.53 ± 1.53 hours ($P < 0.05$), and in formulation No. 3 – to 4.72 ± 1.11 hours. The obtained results indicate the advisability of using the proposed therapeutic approaches for the prevention of postpartum complications, which allows for timely uterine involution, improves the reproductive performance of animals and optimises breeding processes on farms. In the future, the development of a technology for manufacturing pessaries with serratiopeptidase and the investigation of their clinical efficacy in obstetric practice for the prevention and treatment of postpartum complications in cows are planned.

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CONFLICT OF INTEREST

None.

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Технологія виготовлення та ефективність акушерських песаріїв для превентивної терапії корів

Світлана Гуральська
Доктор ветеринарних наук, професор
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0001-7383-1989
Людмила Євтух
Кандидат ветеринарних наук, доцент
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0003-3116-3980
Геннадій Грищук
Кандидат ветеринарних наук, доцент
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0001-7092-2412
Володимир Гончаренко
Кандидат ветеринарних наук, доцент
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0002-2183-8828
В'ячеслав Захарін
Кандидат ветеринарних наук, доцент
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0002-4157-644X

Анотація. Актуальність роботи полягає у необхідності розробки нових, ефективних засобів превентивної терапії затримання посліду у корів, яке є поширеною проблемою у ветеринарії. Затримання посліду може спричинити серйозні ускладнення, що підкреслює необхідність впровадження ефективних терапевтичних рішень. Метою роботи була розробка складу, технології виготовлення та вивчення ефективності песаріїв на поліетиленоксидній основі з використанням β-блокатора адренорецепторів матки анаприліна для превентивної терапії затримання посліду у корів. Песарії виготовляли методом виливання у форми, використовуючи поліетиленоксид з молекулярною масою 400 і 1500 у співвідношенні 1:9 з додаванням анаприліну, який вводився до основи. Дослідження проводили на чотирьох групах корів: контрольній, в якій акушерські песарії не застосовували та трьох дослідних, на яких тестували песарії різного складу з анаприліном. Виготовлені лікарські композиції досліджували безпосередньо після отелення шляхом їх введення у проміжок між плацентою і хоріоном. Результати дослідження показали, що застосування песаріїв з анаприліном значно покращує показники ефективності відділення посліду. Зокрема, склад № 2 та № 3 продемонстрували найкращі показники, скорочуючи середній час відділення посліду на 6,8 і 5,6 годин відповідно у порівнянні з контрольною групою. Запропоновані песарії виявилися ефективними у профілактиці затримання посліду. Отримані результати також відкривають перспективи для розробки промислової технології виготовлення песаріїв, що забезпечить їх широке використання в скотарстві для підвищення продуктивності тварин та зниження економічних витрат. Практична цінність роботи полягає в тому, що розроблені лікарські композиції можуть використовуватися у ветеринарній практиці для превентивної терапії та лікування затримання посліду у корів

Ключові слова: велика рогата худоба; репродуктивне здоров'я; затримання посліду; профілактика акушерської патології; післяотельний період

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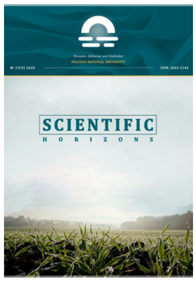

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Application of robotics in automation of livestock feeding and farm management

Ihor Garasymchuk*

PhD in Technical Sciences, Associate Professor

Higher Educational Institution "Podillia State University"

32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine

https://orcid.org/0000-0002-4304-4447

Oleksandr Dumanskyi

PhD in Technical Sciences, Associate Professor

Higher Educational Institution "Podillia State University"

32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine

https://orcid.org/0000-0002-1750-5844

Yurii Pantsyr

PhD in Technical Sciences, Associate Professor

Higher Educational Institution "Podillia State University"

32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine

https://orcid.org/0000-0003-2969-1936

Pavlo Potapskyi

PhD in Technical Sciences, Associate Professor

Higher Educational Institution "Podillia State University"

32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine

https://orcid.org/0000-0003-4792-8992

Mykola Vusatyi

Assistant

Higher Educational Institution "Podillia State University"

32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine

https://orcid.org/0000-0003-3070-9283

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Abstract. The study aimed to assess the impact of automated feeding on the physiological state, productivity and conditions of livestock. The study analysed the effect of automated feeding systems on physiological parameters, stress levels, cattle productivity and sanitary conditions in the feeding area. The experiment was conducted on 200 dairy cows and 150 beef bulls, divided into control (traditional feeding) and experimental (automated feeding) groups. Body temperature, heart and respiratory rates, stress levels, disease incidence, milk yield, average daily weight gain and microclimate parameters were measured. The study results demonstrated that the

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*Corresponding author

body temperature in the experimental group was 0.3°C lower (38.6°C vs. 38.9°C in the control group), the heart rate decreased by 9% (60 ± 3 beats/min vs. 66 ± 4 beats/min), and the respiratory rate by 14.3% (24 ± 2 breaths/min vs. 28 ± 3 breaths/min). Stress levels, as measured by cortisol, decreased by 29.4% compared to traditional feeding. The incidence of gastrointestinal disorders decreased from 22.5% to 9.5%, and cases of metabolic disorders from 13.2% to 6.7%. Milk yields in the automated system increased by 19.1% (26.8 ± 1.1 litres/day vs. 22.5 ± 1.2 litres/day), and average daily weight gain in beef cattle increased by 23.2% (1.38 ± 0.05 kg/day vs. 1.12 ± 0.07 kg/day). The analysis of the microclimate in the feeding area determined a 22% reduction in ammonia levels, an improvement in humidity to the optimum 65-70% and a 17% increase in the cleanliness of the feeders. Comparisons with European farms demonstrated that automated feeding can reduce the gap between Ukrainian farms regarding animal productivity and sanitary conditions. The findings confirm the feasibility of introducing automated feeding systems to reduce morbidity, increase feeding efficiency and create more comfortable conditions for cattle

Keywords: physiological state; sanitary conditions; technological innovations; feed efficiency; feed management

INTRODUCTION

The research relevance is determined by the need to increase the efficiency of livestock production in Ukraine through the introduction of modern automated feeding technologies. The use of such systems can improve the physiological condition of animals, reduce stress, optimise the diet and increase the productivity of cattle. In developed countries, such as Germany, the Netherlands and Denmark, automated systems are actively used to ensure stable growth in milk yields and average daily weight gain. In Ukraine, the level of adoption of these technologies remains insufficient, which affects the efficiency of livestock farming and the conditions of livestock keeping. The problem of the study is that traditional methods of animal feeding often do not meet modern requirements for production efficiency. Uneven distribution of feed, high incidence of diseases, low productivity, and high levels of stress in animals are key challenges that can be addressed through automation. Insufficient adaptation of Ukrainian farms to the latest technologies makes it difficult to maintain optimal physiological parameters of animals and reduces their productivity (Misiuk & Zakhodym, 2023). Therefore, research into the impact of automated feeding systems on the health and productivity of cattle is necessary for the implementation of effective feeding management methods and the improvement of animal welfare in Ukraine.

According to a study by D. Chebotar (2024), artificial intelligence is substantial in optimising production processes in livestock farming, which reduces human intervention and improves feeding efficiency. Similar conclusions were drawn by O. Solona *et al.* (2023), proving the effectiveness of digital technologies in livestock production, emphasising their positive impact on the physiological state of animals and dietary stability. As noted by P. Lub *et al.* (2024), the use of information technology in agriculture contributes to better resource management, which has a direct impact on feeding efficiency and livestock comfort. At the same time, according to H. Dilaver and K.F. Dilaver (2024), the introduction of robotic systems in livestock production provides a stable feeding regime and reduces stress in animals, which has a positive effect on their productivity. A. Monteiro *et al.* (2021) investigated the principles of precision agriculture, including automated livestock management, and noted that the use of such technologies helps to increase animal productivity through optimal feed supply. Furthermore, A. Melak *et al.* (2024) analysed the impact of artificial intelligence on farm management, which increased the efficiency of automated feeding systems and optimised production processes.

Moreover, C. Tzanidakis *et al.* (2023) addressed the possibilities of using precision animal husbandry technologies for the maintenance of pasture animals, which increased the efficiency of feed distribution and reduced feed losses. In turn, D.E. Micle *et al.* (2021) investigated the impact of robotic process automation on dairy farming efficiency, emphasising the increase in productivity due to intelligent control systems. Furthermore, according to G.O. Uzedhe *et al.* (2023), the introduction of automated feeding systems reduced animal stress and improved sanitary conditions in the feeding area, which positively affected the overall productivity of livestock. At the same time, E. Romano *et al.* (2023) analysed the benefits of automated feeding systems at the farm level in Italy, highlighting the improvement of physiological parameters in cattle.

According to the analysis of R. García *et al.* (2023), autonomous computing systems are key in livestock production processes, providing stable feeding control and reducing dependence on the human factor. In addition, M. Dayoub *et al.* (2024) highlighted the prospects for the development of smart farming, where automated feeding systems are a key element in increasing productivity and improving animal welfare. Thus, the analysed studies confirmed the feasibility of automating cattle feeding as a tool for increasing productivity and improving animal health. The study aimed to assess the impact of automated feeding systems on the health and productivity of cattle and compare it with the practices of Germany, the Netherlands and Denmark.

MATERIALS AND METHODS

The study was conducted in 2024 between June and August at the Agro-Leader farm in Kyiv region (Ukraine). The region is characterised by a temperate continental climate, which includes warm summers with average daily temperatures ranging from +18°C to +27°C, as well as sufficient humidity for intensive livestock farming. Precipitation in summer averages 200-250 mm, which helps to maintain the natural moisture content of the fodder. The farm was chosen due to its modern infrastructure, the ability to use automated feeding systems and the presence of a large number of dairy and beef cattle. The objects of the study were dairy cows (Ukrainian Black-and-White breed) and Limousin beef bulls. The choice of these categories of cattle was justified by the need to assess the impact of automated feeding on different areas of livestock production – dairy and meat. The dairy productivity of cows largely depends on the stability of feeding and the absence of stress factors, which could be improved through automation. In the case of beef breeds, efficient feed intake and uniform weight gain were the key indicators to be analysed.

The experiment included two groups of animals: control (traditional feeding) and experimental (automated feeding). Each group consisted of 200 dairy cows and 150 beef bulls. The animals' diet consisted of 35 kg of silage, 8 kg of haylage, 6 kg of mixed fodder and 1.5 kg of mineral supplements per day. In the control group, feeding was conducted manually twice a day (at 6:00 and 18:00), while in the experimental group, an automated system Trioliet Triomatic T40 (Netherlands) was used to ensure uniform feed distribution six times a day (at 5:00, 9:00, 13:00, 17:00, 21:00 and 1:00). The following devices were used to measure physiological parameters: a digital veterinary thermometer Gimette VT-10 (France) to measure body temperature, an electronic stethoscope 3M Littmann 3200 (USA) to record heart rate, a portable gas analyser Dräger X-am 5000 (Germany) to measure ammonia levels in the feeding area. The concentration of cortisol in the blood was determined using a Mindray MR-96A enzyme-linked immunosorbent assay (China). A 3M Clean-Trace ATP digital microbiological analyser (USA) was used to analyse the purity of the feeders. All experimental studies were conducted in accordance with European convention for the protection of vertebrate animals used for experimental and other scientific purposes (1986).

To evaluate the effectiveness of automated feeding, physiological parameters, disease incidence, stress level, productivity, and microclimate in the feeding area were analysed and the productivity of Ukrainian animals was compared with European farms. Physiological parameters included measuring body temperature using a Gimette VT-10 thermometer (France), heart rate using a 3M Littmann 3200 (USA) and respiratory rate by direct observation for one minute. The incidence of diseases was analysed based on veterinary reports of gastrointestinal disorders, metabolic disorders and hoof pathologies. The level of cortisol in the blood of animals was determined by enzyme-linked immunosorbent assay (ELISA) using a Mindray MR-96A device (China). Behavioural reactions of animals were assessed by observing the frequency of aggressive interactions during feeding, the average time of feed consumption and the duration of rest, which were recorded using a Hikvision DS-2CD2043G0-I video surveillance system (China) with automatic analysis of animal activity. The microclimate in the feeding area was assessed using a Dräger X-am 5000 gas analyser (Germany) to determine ammonia levels, a Testo 835-T1 digital thermometer (Germany) to measure air temperature, and an Extech RH390 hygrometer (USA) to determine humidity. Farms in Germany, the Netherlands, and Denmark were selected for the comparison of animal productivity, as these countries have a high level of livestock automation, which provided reliable results on the impact of technology on productivity. In addition, these countries have different approaches to livestock feeding, which provides a wider range for comparative analysis. Statistical processing of the results was conducted by analysis of variance (ANOVA) in Statistica 12 software using Student's t-test to assess the significance of differences between groups.

RESULTS

Influence of automated feeding on physiological parameters and disease incidence in cattle. The body temperature of the animals receiving feed through the automated system fluctuated within the physiological norm (38.6 ± 0.2°C in cows and 38.7 ± 0.2°C in bulls). In the control group, greater deviations were recorded – 38.9 ± 0.3°C in cows and 39.0 ± 0.3°C in bulls. This indicates an increased thermal load on the animal body due to uneven feed intake, which is typical for traditional feeding methods. The heart rate of cows in the experimental group was 9% lower than in the control group (60 ± 3 beats/min vs. 66 ± 4 beats/min). This indicates a lower level of physiological stress and a general improvement in adaptation to the conditions of detention. Similarly, bulls in the control group had a heart rate of 70 ± 5 beats/min, while animals with automated feeding had a heart rate of 63 ± 3 beats/min. The respiratory rate was also lower in animals of the experimental group: 24 ± 2 breaths/min in cows and 27 ± 2 breaths/min in bulls, which is lower than in the control group (28 ± 3 breaths/min in cows and 32 ± 3 breaths/min in bulls). A decrease in respiratory rate may indicate a decrease in the stress load on animals, which is ensured by uniform feeding and better feeding organisation.

The level of cortisol in the blood – one of the key indicators of stress – was also different between the groups. In the control group, the average cortisol level was 5.1 ± 0.5 nmol/l, while in the experimental group, it was 3.6 ± 0.4 nmol/l, which indicates a 29.4% reduction in stress. Limousin bulls have a similar trend: 5.4 ± 0.5 nmol/l in the control group and 4.0 ± 0.4 nmol/l in the experimental group. The frequency of nutrition-related diseases was significantly lower among the animals of the experimental group. Disorders of the gastrointestinal tract (GIT) in dairy cows of the control group were recorded in 22.5% of cases, including acidosis – in 12.1% of animals and diarrhoea – in 6.4%. In the experimental group, the frequency of such disorders decreased to 9.5%. In bulls, the incidence of gastrointestinal diseases was even higher – 25.8% in the control group versus 11.3% in the automated feeding animals. Hoof diseases were also much less common among the animals in the experimental group. In dairy cows of the traditional group, were recorded in 18.2% of cases, while in the experimental group – 7.8%. In bulls, these figures were 20.1% in the control group and 9.0% in animals fed through the automated system. Metabolic disorders, such as ketosis and hypocalcaemia, were also much less common in the experimental group. In cows in the traditional group, the incidence of these diseases was 13.2%, while in animals fed through the automated system, this figure dropped to 6.7%. In bulls, the situation is similar: 10.4% in the control group and 5.9% in the experimental group (Table 1).

***Table 1**. Influence of automated feeding on physiological parameters and disease incidence in cattle*

Metric	Control cows (traditional feeding)	Experimental cows (automated feeding)	Control bulls (traditional feeding)	Experimental bulls (automated feeding)	Reduction (%)
Body temperature, °C	38.9 ± 0.3	38.6 ± 0.2	39.0 ± 0.3	38.7 ± 0.2	-0.8%
Heart rate, bpm	66 ± 4	60 ± 3	70 ± 5	63 ± 3	-9.0%
Respiratory rate, breaths/min	28 ± 3	24 ± 2	32 ± 3	27 ± 2	-14.3%
Blood glucose concentration mmol/l	3.9 ± 0.4	3.5 ± 0.3	4.2 ± 0.5	3.8 ± 0.4	-10.3%
Incidence of gastrointestinal diseases, %	22.5%	9.5%	25.8%	11.3 %	-57.9%
Hoof diseases, %	18.2%	7.8%	20.1%	9.0%	-58.2%
Metabolic disorders, %	13.2%	6.7%	10.4%	5.9%	-49.2%

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

Thus, automated feeding systems significantly improve animal health, and reduce stress levels and the incidence of diseases, which increases milk and meat production.

Assessment of stress levels and behavioural responses of livestock during traditional and automated feeding. One of the key parameters for assessing stress is the level of cortisol, which was significantly reduced in animals of the experimental group. The average level of cortisol in cows of the control group was 5.1 ± 0.5 nmol/l, while in cows of the experimental group – 3.6 ± 0.4 nmol/l, which indicates a 29.4% reduction in stress load. A similar trend was observed in bulls, where the level of cortisol decreased from 5.4 ± 0.5 nmol/l in the control group to 4.0 ± 0.4 nmol/l in the experimental group, which is a decrease of 25.9%.

The assessment of livestock behavioural reactions demonstrated a decrease in the frequency of aggressive interactions between animals when using automated feeding systems. In the control group, 23% of cows and 27% of bulls had conflicts overfeeding, which manifested themselves in the form of pushing, displacement of rivals from feeders and minor fights. In the experimental group, these indicators decreased significantly the frequency of aggressive behaviour in cows decreased to 8%, and in bulls to 11%, which is almost three times lower than in the control group. Animals of the experimental group showed longer feed consumption time, which is an important indicator of the calm state of animals. In the control group, the average feed intake time was 25 ± 4 minutes in cows and 22 ± 3 minutes in bulls, while in the experimental group, this figure increased to 30 ± 3 minutes in cows and 28 ± 2 minutes in bulls. Increasing the time of feed consumption improved digestion and reduced the risk of acidosis and other gastrointestinal diseases.

A significant increase in the total time spent by animals at rest was also recorded. Cows in the control group were observed lying down for an average of 10.8 ± 1.3 hours per day, while in the experimental group, this figure was 12.5 ± 1.2 hours, which is 15.7% more. In bulls, similar indicators were 9.9 ± 1.2 hours in the control group and 11.4 ± 1.1 hours in the experimental group. A longer rest period restores the body, improves metabolic processes and optimises body weight gain. Another important indicator was a decrease in the frequency of social conflicts related to feeding. In the control group, 21% of cows and 25% of bulls recorded episodes of active displacement of rivals from feeders, while in the experimental group, this figure dropped to 6% in cows and 9% in bulls, indicating a significant improvement in social stability in the herd. The results of the study also demonstrated a decrease in the time that animals spent standing without eating feed, which can be a marker of discomfort or anxiety. In the control group, this figure was 35% in cows and 38% in bulls, while in the experimental group, it decreased to 22% in cows and 24% in bulls (Table 2).

Table 2. *Assessment of stress level and behavioural reactions of livestock during traditional and automated feeding*

Metric	Control cows (traditional feeding)	Experimental cows (automated feeding)	Control bulls (traditional feeding)	Experimental bulls (automated feeding)	Reduction (%)
Cortisol level, nmol/l	5.1 ± 0.5	3.6 ± 0.4	5.4 ± 0.5	4.0 ± 0.4	-29.4%
Frequency of aggressive behaviour, %	23%	8%	27%	11%	-65.2%
Average feed consumption time, min	25 ± 4	30 ± 3	22 ± 3	28 ± 2	+20%
Rest time, h/day	10.8 ± 1.3	12.5 ± 1.2	9.9 ± 1.2	11.4 ± 1.1	+15.7%
Number of social conflicts per day (blows, oustings), %	21%	6%	25%	9%	-71.4%
Frequency of standing without feed intake, %	35%	22%	38%	24%	-36.5%

Source: *compiled by the authors*

Thus, automated feeding systems significantly reduce animal stress levels by distributing feed evenly, reducing competition and improving overall health. This has a direct impact on the productivity of dairy cows and beef bulls, contributing to higher milk yields, better weight gain and overall animal welfare. Automation of the feeding process improves livestock conditions and optimises the production performance of Ukrainian farms.

Comparison of cattle productivity with traditional and automated feeding. The average daily weight gain of bulls was significantly higher in the experimental group compared to control animals. The bulls fed by the traditional method had an average weight gain of 1.12 ± 0.07 kg per day, while in the experimental group, this figure reached 1.38 ± 0.05 kg per day. This indicated an increase in weight gain by 23.2%, which was the result of a stable feed intake, its uniform distribution throughout the day and the absence of competition between animals.

A similar situation was observed in beef cows. In the control group, the average daily weight gain was 0.92 ± 0.06 kg, while in cows fed through automated systems, this figure increased to 1.17 ± 0.04 kg. The weight gain in this group increased by 27.2%, which was due to better feed digestibility, improved metabolism and the absence of stress factors associated with uneven feeding. The milk yield of dairy cows also demonstrated a significant increase when using automated systems. The average daily milk yield in the control group was 22.5 ± 1.2 litres, while in the experimental group, it increased to 26.8 ± 1.1 litres. This indicated a 19.1% increase in productivity. The main reasons for this increase were stable feed intake, improved digestive efficiency and reduced stress levels (Lutsenko & Popkov, 2024).

Another important indicator that influenced animal performance was the feed digestibility rate. This parameter determined the efficiency of the use of nutrients supplied by the feed. In the control group, the feed digestibility rate was 64%, while in the experimental group, it increased to 72%, indicating a more efficient use of nutrients. The higher feed digestibility rate reduced feed losses and also reduced the burden on the animals' digestive system (Verzhykhovsky & Nedoseko v, 2024). An increase in the average duration of feed consumption was also recorded. In animals of the control group, this figure was 25 ± 4 minutes, which indicated rapid feed intake and possible risks of incomplete assimilation. In animals of the experimental group, the average feed intake time increased to 30 ± 3 minutes, which enusred even digestion of food and prevention of acidosis, rumen disorders and other digestive disorders (Fig. 1).

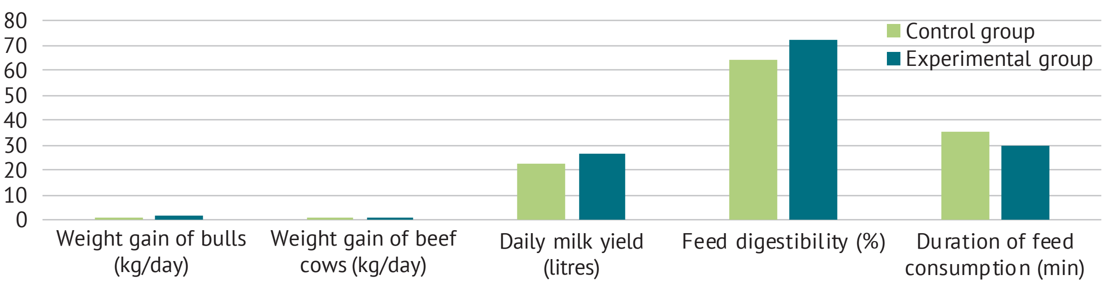

Figure 1. *Comparison of cattle productivity with traditional and automated feeding*
Source: *compiled by the authors*

Thus, the data obtained confirmed that the introduction of automated feeding systems is an important factor in improving the efficiency of cattle breeding. They increased average daily weight gain, higher milk yields, improved nutrient absorption and reduced stress in animals. The air temperature in the feeding area was critical for the health of the cattle, as overheating or hypothermia could hurt the productivity and body condition of the animals. In the control group, where the traditional feeding system was used, the average temperature was 18.5°C, which could cause discomfort for the cattle, especially in high-density conditions. In the experimental group, where automated feeding systems were used, the average temperature in the feeding area dropped to 16.8°C, which contributed to a more comfortable environment and prevented overheating of the animals.

The impact of automation on the microclimate in the feeding area. Humidity levels in the feeding area also differed between groups. In the control group, the air humidity was 72%, which exceeded the optimum levels for comfortable cattle keeping and contributed to the development of pathogenic microflora. In the experimental group, the humidity level dropped to 65%, which corresponded to the recommended parameters for cattle. This improvement was attributed to more uniform feed consumption and less spilt water due to the automated feed mixtures. One of the key indicators of microclimate quality was the level of ammonia in the air, which was formed as a result of the decomposition of organic matter and could adversely affect the respiratory system of animals (Montayeva *et al.*, 2023). In the control group, the ammonia concentration reached 15 ppm, which posed a risk of mucosal irritation and respiratory diseases. In the experimental group, this figure decreased to 8 ppm, indicating a significant improvement in the air environment. This was caused by a reduction in feed residues and more efficient air circulation around the automated feeders.

Feeder cleanliness was one of the most important factors affecting animal health and performance (Yakubchak *et al.*, 2018). In the control group, the average cleanliness level of the feeders was 68%, indicating frequent accumulation of feed residues and contamination caused by mechanical food distribution. In the experimental group, the cleanliness of the feeders increased to 89%, which significantly reduced the risk of microbial contamination of feed and the development of pathogenic bacteria. The quality of the feed also improved with the automated feeder. In the control group, the average feed score was 75%, indicating a certain decrease in quality due to the possibility of oxidation of feed residues and contamination with dust or litter. In the experimental group, this figure increased to 92%, which ensured better nutrient absorption and reduced the risk of foodborne diseases (Fig. 2).

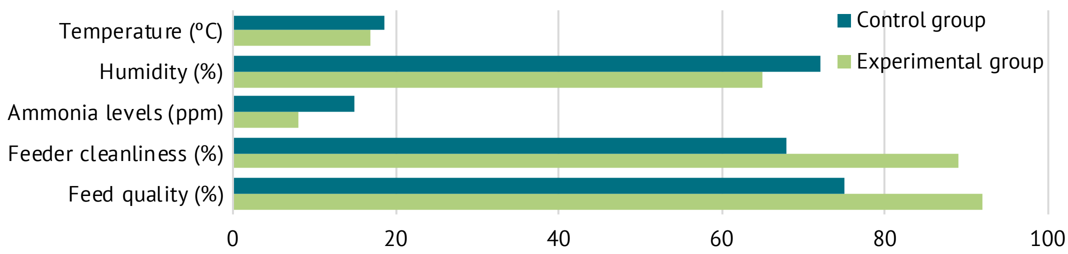

Figure 2*. The impact of automation on the microclimate in the feeding area*
Source: *compiled by the authors*

Thus, the results of the study confirmed that the automation of the feeding process not only increased the efficiency of feed use but also significantly improved the microclimate parameters in the feeding area. This made automated feeding systems an appropriate method for ensuring comfortable conditions for cattle in modern farms.

Comparison of cattle performance in Ukraine and Europe. Physiological parameters of cattle differed significantly between Ukrainian and European farms. The average body temperature of cattle in Ukraine was 38.9°C, while on farms in Germany, the Netherlands and Denmark this figure was lower and was within 38.6°C, indicating more comfortable conditions for the animals. The heart rate of cows on Ukrainian farms was 66 ± 4 beats/min, while in Germany, the Netherlands and Denmark this figure was lower – 62 ± 3 beats/min, indicating a lower level of physiological stress. Similarly, the respiratory rate was higher on Ukrainian farms (28 breaths/min versus 25 breaths/min in the above European countries), which also indicated the influence of stress factors.

The incidence of nutrition-related diseases in Ukraine was significantly higher than in Germany, the Netherlands and Denmark. Gastrointestinal disorders were recorded in 22.5% of animals in Ukraine, while in European countries this figure was 12.3%. Hoof diseases, which are often the result of an unbalanced diet and unsatisfactory housing conditions, occurred in 18.2% of cases on control Ukrainian farms, while on farms in Germany, the Netherlands and Denmark, the frequency was much lower at 9.1%. Metabolic disorders (ketosis, acidosis) were also more common in Ukraine (13.2%), while on European farms this figure was only 6.4%, indicating better feed quality and more effective nutrition management. The stress levels of the animals also differed significantly. In Ukraine, cattle blood cortisol levels averaged 5.1 nmol/l, while in Germany, the Netherlands and Denmark, this figure did not exceed 3.8 nmol/l. This was due to more stable housing conditions, lack of competition for feed and the use of automated feeding systems on most European farms. In addition, in Germany, the Netherlands and Denmark, cattle spent more time resting (12.8 hours per day on average, compared to 10.8 hours in Ukraine), which contributed to better recovery and improved productivity.

A comparison of productivity demonstrated a significant gap between Ukrainian and European farms. In dairy farming, the average daily milk yield in Ukraine was 22.5 litres, while in Germany, the Netherlands and Denmark it was 29.4 litres, which is 30.7% higher. This was determined by better livestock genetics, efficient feed management and the use of modern automated technologies. In the beef cattle sector, the average daily weight gain of bulls in Ukraine was 1.12 kg, while on European farms – it was 1.42 kg, indicating more efficient feed intake and higher quality of food additives. Sanitary conditions in the feeding area also varied significantly (Karatieieva *et al.*, 2024). In Ukraine, the level of cleanliness of feeders was estimated at 68%, while in Germany, the Netherlands and Denmark this figure reached 85%, indicating a better organisation of the cleaning and control system. Similarly, the quality of feed in European countries was estimated at 92%, which was significantly higher than in Ukraine (75%). This affects nutrient absorption, disease rates and livestock productivity (Fig. 3).

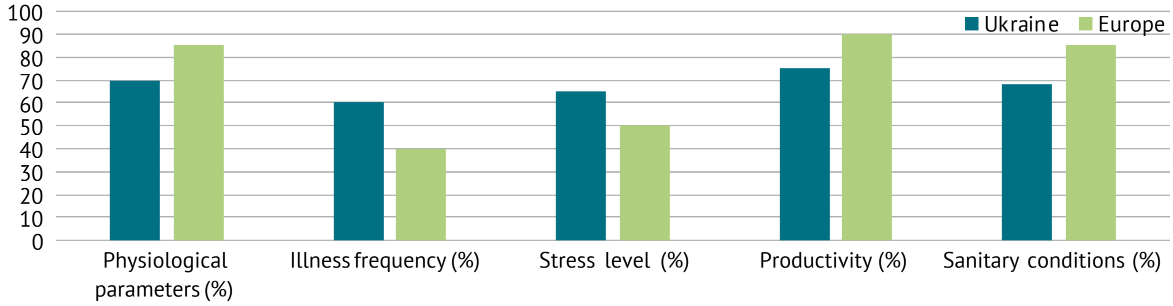

Figure 3*. Comparison of cattle performance in Ukraine and Europe*
Source: *compiled by the authors*

Thus, the analysis of indicators between Ukraine and countries such as Germany, the Netherlands and Denmark pointed to significant advantages for European farms. Improved sanitary conditions, efficient feeding strategies, and the wider use of automated systems contributed to lower stress and disease levels in animals, increased productivity, and optimised costs. These findings highlighted the need to implement similar approaches in Ukraine to improve the efficiency of livestock production.

DISCUSSION

The results of the study confirmed that automated feeding has a positive effect on the physiological state, productivity and stress level of cattle. The study determined that the animals in the experimental group had more stable physiological parameters, a lower level of diseases and increased average daily weight gain. The automated systems ensured an even distribution of feed, which reduced competition among animals and improved nutrient absorption. The data obtained are consistent with the results of European studies in terms of improved milk yields and feed efficiency. A comparison with farms in Germany, the Netherlands and Denmark showed that automated feeding systems contribute to a stable metabolism and increased milk yield, which confirms their effectiveness. An analysis of sanitary conditions showed that automation reduced contamination of feeders and improved the microclimate, which is an important factor for livestock health.

As confirmed by U. Kaur *et al.* (2023) and M.M. Mijwil *et al.* (2023), the use of automated systems in livestock production contributes to increased milk yields and efficient feed use through uniform distribution and minimisation of food losses. These conclusions are fully consistent with the results of this study, which also established an increase in milk yield in dairy cows and weight gain in bulls due to an improved feeding regime. At the same time, the study by U. Kaur *et al.* analysed mainly dairy breeds, while this study also covered the meat sector, which improves the assessment of the benefits of automation in various aspects of animal husbandry. M.M. Mijwil *et al.* conducted a general overview, while the current study provided specific empirical indicators of the impact of automated technologies on animal productivity and health.

As noted by S. Morrone *et al.* (2022) and J. Bae *et al.* (2023), the introduction of Industry 4.0 technologies and autonomous feeding systems improved farm management, ensuring the stability of physiological parameters and improving the absorption of feed nutrients. These authors also confirmed the reduction of competition for feed due to the automated mode. Their findings are consistent with the results of this study, in particular concerning improved physiological conditions and animal performance. At the same time, this study additionally analysed the sanitary conditions in the feeding area and the microclimate, which were understudied by S. Morrone *et al.* and J. Bae *et al.* As a result, this study provides a more comprehensive analysis of the impact of automation. A. Singh *et al.* (2022) and M. Kraft *et al.* (2022) confirmed that the use of smart technologies in livestock farming can reduce physiological stress and ensure the stability of the feeding regime. The authors emphasised the importance of stable livestock conditions, which also corresponds to the results of this study. However, the study by A. Singh *et al.* did not sufficiently cover the impact of automation on livestock productivity, while M. Kraft *et al.* mainly analysed the management aspects of technology. The present study comprehensively considered the physiological, productive and sanitary aspects of automation, which provided a more complete picture of the impact of modern feeding systems on the conditions of housing, health and productivity of cattle.

As confirmed by A. Kumar *et al.* (2024) and P.A. Vlaicu *et al.* (2024), automation of livestock feeding processes increases the physiological comfort of animals, reducing stress factors and optimising feed management. These studies determined an improvement in cattle productivity due to the precise distribution of feed and the stability of diets, which fully coincides with the results of this study. At the same time, Kumar *et al.* emphasised the role of artificial intelligence technologies in optimising management processes, while P.A. Vlaicu *et al.* addressed welfare and sustainability aspects. This study extended these findings by adding empirical results on the impact of automated systems on the incidence of diseases and sanitary conditions, which the authors of the above works did not consider in detail.

As noted by M.A. Hayden *et al.* (2022) and C. Cheng *et al.* (2023), the introduction of automation on livestock farms improved worker safety, reduced physical activity and increased the accuracy of feeding operations. M.A. Hayden *et al.* emphasised that automation helps to reduce the number of injuries and improves overall production safety. C. Cheng *et al.* additionally emphasised the technical advantages of robotic systems, such as improved feeding accuracy. The results of this study also confirmed the benefits of automation, but it takes a deeper look at the direct impact of automated systems on animal physiology and the microclimate in the feeding area, which improved the comprehensiveness of the results. At the same time, M.A. Hayden *et al.* and C. Cheng *et al.* did not cover the physiological and sanitary aspects, which are discussed in detail in this study.

As emphasised by G. Attard (2023) and R. Sparrow and M. Howard (2021), robotic technologies in agriculture increase the efficiency of feeding management and reduce the impact of the human factor, which ensures the stability of animal conditions. G. Attard indicated that robots improve livestock welfare by reducing competition for feed and stable distribution of rations, which coincides with the results of this study. R. Sparrow and M. Howard additionally emphasises the ethical aspects of robots, such as reducing stress and improving animal welfare. This study also determined a positive impact of automation on physiological parameters, disease incidence, and stress levels. However, G. Attard, R. Sparrow and M. Howard analysed general theoretical aspects, while this study empirically confirmed the specific benefits of automation in the case of cattle in Ukraine.

According to L.F.P. Oliveira *et al.* (2021) and M.A. Alanezi *et al.* (2022)., the use of modern technologies, in particular unmanned aerial vehicles (UAVs) and robotic systems in livestock production, optimising the control and feeding processes, reducing resource consumption and improving the accuracy of operations. M.A. Alanezi *et al.* highlighted the remote monitoring of livestock, while L.F.P. Oliveira *et al.* emphasised the importance of introducing robots for precise feed distribution. These conclusions correlate with the study, but this study analyses in depth the impact of automation on physiological parameters and stress levels in animals, which is lacking in the above-mentioned authors. Thus, this study complements the results of these authors by revealing a wider range of the impact of automation on livestock health.

According to C.R. Eastwood *et al.* (2022) and T. Martin *et al.* (2022), the use of robotic technologies in dairy farming improved working conditions, livestock welfare and farm productivity through a sound and responsible approach to implementation. C.R. Eastwood *et al.* emphasised the importance of systematic design of robots for dairy farms, while T. Martin *et al.* analysed changes in farm labour organisations under the influence of robotics. Compared to these studies, the present study addresses the physiological and sanitary aspects of automated feeding, including disease rates and feed quality, which were not analysed in detail by the above-mentioned authors. As a result, this study has the advantage of being more comprehensive and specific in its analysis of the impact of automation on livestock welfare.

As noted by E.S. Mohamed *et al.* (2021) and K.B. Yılmaz (2024), the use of smart technologies and automated systems in animal husbandry contributes to sustainable development, efficient resource management and improved physiological performance of animals. E.S. Mohamed *et al.* analysed the general benefits of implementing smart technologies to reduce stress, and K.B. Yılmaz emphasised the importance of integrated automated herd management systems. Compared to the results of these authors, the present study is more empirical in nature and includes an analysis of specific changes in physiological parameters, morbidity, microclimate and animal productivity. As a result, the results are more practically oriented and improve the accuracy of assessment of the benefits of automation on farms in Ukraine. Automated feeding improves the physiological state of livestock, reduces stress and increases productivity, which is confirmed by various studies. Contrary to other studies, this study comprehensively analysed the physiological, productive and sanitary aspects of automation in Ukrainian livestock production.

CONCLUSIONS

The study determined that the use of automated cattle feeding systems improved physiological parameters, animal productivity and the sanitary condition of the feeding area. The study included 200 dairy cows and 150 beef bulls, which were divided into a control group (traditional feeding) and an experimental group (automated feeding). The analysis of changes in the physiological state of the animals included an assessment of body temperature, heart rate and respiration rate, stress level and morbidity. Animal productivity was also studied in terms of average daily weight gain and milk yield, as well as changes in microclimatic conditions in the feeding area.

The study demonstrated that the body temperature of animals fed through automated systems was 0.3°C lower compared to traditional feeding, indicating a stable physiological state and less stress on the body. The heart rate in the experimental group decreased by 9% and the respiratory rate – by 14.3%, which confirmed the reduction of stress on the animals. The incidence of gastrointestinal disorders was more than halved, and cases of metabolic disorders decreased by 49.2%. Animal productivity under automated feeding has increased significantly: the average daily weight gain of bulls has increased by 23.2%, and the milk yield of dairy cows – by 19.1%. These results confirmed that stable feed distribution, optimised ration composition and the absence of competition for food contribute to better nutrient absorption and overall productivity. The study also demonstrated improved sanitary conditions in the feeding area. Ammonia levels were reduced by 22%, which had a positive impact on the general condition of the cattle and reduced the risk of respiratory diseases. Air humidity has stabilised at 65-70%, and the cleanliness of the feeders has improved by 17%, which has also reduced the risk of spreading infectious diseases. Comparison with European farms demonstrated that feeding automation can reduce the gap between Ukrainian farms in terms of key indicators of animal productivity and health. It was found that the use of modern technologies significantly improves livestock conditions, reducing stress and morbidity. A limitation of the study was that the experiment was conducted on a single farm, which may limit the generalisability of the results for different climatic zones and farm types. Further research should cover the long-term impact of automated feeding systems on livestock reproductive performance and their economic efficiency in different regions.

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CONFLICT OF INTEREST

None.

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Застосування робототехніки для автоматизації годування худоби та управління фермами

Ігор Гарасимчук
Кандидат технічних наук, доцент
Вищий навчальний заклад «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0002-4304-4447

Олександр Думанський
Кандидат технічних наук, доцент
Вищий навчальний заклад «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0002-1750-5844

Юрій Панцир
Кандидат технічних наук, доцент
Вищий навчальний заклад «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0003-2969-1936

Павло Потапський
Кандидат технічних наук, доцент
Вищий навчальний заклад «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0003-4792-8992

Микола Вусатий
Асистент
Вищий навчальний заклад «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0003-3070-9283

Анотація. Метою дослідження було оцінити вплив автоматизованого годування на фізіологічний стан, продуктивність і умови утримання худоби. У дослідженні проаналізовано вплив автоматизованих систем годування на фізіологічні показники, рівень стресу, продуктивність великої рогатої худоби та санітарні умови в зоні годівлі. Експеримент проведено на 200 коровах молочної породи та 150 бичках м'ясної породи, розділених на контрольну (традиційне годування) та експериментальну (автоматизоване годування) групи. Виміряно температуру тіла, частоту серцевих скорочень і дихання, рівень стресу, частоту захворювань, надої молока, середньодобові прирости маси та параметри мікроклімату. Результати показали, що температура тіла в експериментальній групі була нижчою на 0,3 °C (38,6 °C проти 38,9 °C у контрольній), частота серцевих скорочень знизилася на 9 % (60 ± 3 уд./хв проти 66 ± 4 уд./хв), а частота дихальних рухів – на 14,3 % (24 ± 2 вдихи/хв проти 28 ± 3 вдихи/хв). Рівень стресу, оцінений за показниками кортизолу, зменшився на 29,4 % у порівнянні з традиційним годуванням. Захворюваність на шлунково-кишкові розлади знизилася з 22,5 % до 9,5 %, а випадки метаболічних порушень – з 13,2 % до 6,7 %. Надої молока в автоматизованій системі зросли на 19,1 % (26,8 ± 1,1 л/добу проти 22.5 ± 1.2 л/добу), а середньодобові прирости маси у м'ясної худоби збільшилися на 23,2 % (1,38 ± 0,05 кг/добу проти 1,12 ± 0,07 кг/добу). Аналіз мікроклімату в зоні годування показав зниження рівня аміаку на 22 %, покращення вологості до оптимальних 65-70 % і підвищення рівня чистоти годівниць на 17 %. Порівняння з європейськими фермами продемонструвало, що автоматизоване годування дозволяє скоротити відставання українських господарств у продуктивності тварин та санітарних умовах утримання. Отримані висновки підтверджують доцільність впровадження автоматизованих систем годування для зниження рівня захворюваності, підвищення ефективності годівлі та створення комфортніших умов для великої рогатої худоби

Ключові слова: фізіологічний стан; санітарні умови; технологічні інновації; ефективність годівлі; кормовий менеджмент

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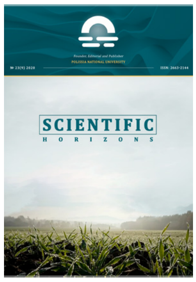

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Influence of sowing dates on the ecological stability, plasticity, and adaptability of lablab bean (*Dolichos lablab* L.)

Iryna Bobos
PhD in Agricultural Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0001-5193-7192

Oleksandr Komar*
PhD in Agricultural Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0001-7511-4190

Ivan Fedosiy
PhD in Agricultural Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-5044-9960

Natalia Iliuk
PhD in Agricultural Sciences
Open International University of Human Development "Ukraine"
03115, 23 Lvivska Str., Kyiv, Ukraine
https://orcid.org/0000-0002-3296-4790

Olena Siedova
Assistant
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0003-4869-1560

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Abstract. Understanding the effects of soil and climatic conditions on agricultural crops forms the basis for developing and implementing innovative technologies and strategies aimed at minimising negative impacts on farming systems and agriculture as a whole. This study aimed to examine the impact of different sowing dates on lablab beans in order to expand the crop's cultivation potential in the conditions of the Right-Bank Forest-Steppe of Ukraine. The following methods were employed to investigate

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**Corresponding author*

this issue: field trials to study the interaction of the research subject with biotic and abiotic factors and statistical analysis to evaluate the research results and determine the adaptability parameters of the lablab bean. It was established that the highest yield of green pods (2.1 t/ha)was achieved when sowing took place in the first ten-day period of May, which exceeded the control variant (the third ten-day period of April – 1.8 t/ha) by 0.3 t/ha (16.7%). The lowest yield (1.5 t/ha) was recorded when sowing occurred in the first ten-day period of June. The study also revealed that yield was influenced by the length of the growing season (r = 0.68), the sum of active temperatures (>10°C) (r = 0.72), and total precipitation (r = 0.74). A strong positive correlation was established between lablab bean yield and general adaptability (r = 0.99), plasticity (r = 0.67), homeostasis (r = 0.91), and breeding value (r = 0.71). Conversely, a negative correlation was observed between yield and the coefficient of variation (r = –0.75) as well as relative stability (r = –0.50). The relative yield stability (Sgi) ranged from 1.45% to 3.74%. The coefficient of variation in yield varied between 11.11% and 17.64%, depending on the sowing date. Under the agro-climatic conditions of the study, high plasticity was demonstrated in the sowing variants from the third ten-day period of April (control) to the third ten-day period of May. A low bi value was observed only when sowing took place in the first ten-day period of June, indicating that the lablab bean exhibited low ecological plasticity. The highest breeding value of the genotype (BVGi = 1.09 1.33) was recorded for sowings in the third ten-day period of April (control) and the first ten-day period of May, while the lowest value (BVGi = –0.275) occurred with sowing in the first ten-day period of June

Keywords: climatic factors; genotype; yield; food security; legumes

INTRODUCTION

The impact of climate change on agriculture has serious consequences for crop production, food security, and people's livelihoods (Huang *et al.*, 2020). Recent research suggests that a projected global average temperature rise of 1.8-4°C by the year 2100 is likely to lead to highly unpredictable precipitation patterns. It is also expected to significantly increase the frequency of extreme weather events, such as severe droughts, heat waves, cold spells, and floods (Bhattacharjee *et al.*, 2020). In 2010, it was estimated that out-of-season precipitation, hail, and floods caused damage across approximately 2.1 million hectares (González-Villagra *et al.*, 2023).

Changing climate conditions create favourable environments for the spread of pests and diseases, encourage the growth of weeds, and disrupt the balance of soil microorganisms. As noted by A. Shahzad *et al.* (2021), extreme weather events, particularly droughts, frosts, and heavy rainfall, place additional stress on plants, leading to reduced yields. Furthermore, the effects of climate change on agricultural productivity are not uniform across different geographical locations. Some regions are predicted to experience declines in yield, while others may see increases. As highlighted by T. Adamopoulos and D. Restuccia (2022), countries located in lower latitudes are more vulnerable to the negative impacts of climate change.

In this context, studying the agricultural potential of underutilised legume crops is particularly important. J. Minde *et al.* (2021) emphasise that growing lablab beans more widely could be a key factor in improving food and nutritional security, given their high nutritional value and ability to adapt to various climate conditions. According to P. Shashank *et al.* (2024), this versatile crop can be used as food in the form of immature seeds and pods, as well as a leafy vegetable. At the same time, lablab beans show significant environmental benefits, notably through their ability to fix atmospheric nitrogen within their own plant matter. As demonstrated in the research by L. Hernández-Herrerías *et al.* (2022), in mixed farming systems, lablab beans are often used as a cover crop alongside maize or sorghum. This helps to reduce water loss, improve soil fertility, and lower the risks of soil erosion.

In academic discussion, it is becoming increasingly accepted that climate change is a factor that encourages the development of innovative technologies and management approaches. O. Zavadska *et al.* (2021) and E. Elahi *et al.* (2022) highlight the need to put adaptive strategies in place to reduce the vulnerability of the agricultural sector to the challenges posed by the changing climate. Furthermore, the results of modelling carried out by I. Fedosiy *et al.* (2022) and A. Aboltins *et al.* (2024) suggest that adjusting farming schedules – particularly the timing of sowing and harvesting – is an effective way to adapt to climate change. Using data on crop development over two decades, X. Cui and W. Xie (2022) show that both sowing dates and the length of the growing season are significantly influenced by current temperature and precipitation levels. Their calculations indicate that adjusting the growing season could lead to sowing dates being shifted by 2-6 days and the growing season being shortened by 3-6 days by the end of this century. These changes could offset up to 9% of the yield losses associated with climate change.

The growth and potential yield of agricultural crops are determined by the environmental conditions experienced throughout the growing season. A lack of sufficient understanding about how lablab bean plants interact with their environment limits the ability to achieve maximum yields, as practical results show. To optimise the positive effects of environmental factors on the growth and yield of the lablab bean, information on the best sowing time is needed. This research aimed to analyse the impact of different sowing dates for lablab beans in order to identify the best farming practices for expanding its cultivation in the Right-Bank Forest-Steppe region of Ukraine.

MATERIALS AND METHODS

The experimental research was carried out over three years (2016-2018) at the National University of Life and Environmental Sciences of Ukraine (NULES, Ukraine). The soil at the research site is classified as dark grey podzolic soil with a medium level of leaching and a light loamy texture, with a soil pH of 6.1. The humus-rich topsoil layer was 24-28 cm deep. The research area is characterised by a low humus content, ranging from 1.5% to 2.2%, a medium nitrogen content of 26 to 38 mg/kg, phosphorus levels of 43 to 61 mg/kg, and potassium levels of 28 to 34 mg/kg.

During the period of 2016-2018, precipitation was distributed very unevenly throughout the year, ranging from 881 mm in 2018 to 939 mm in 2016 (Fig. 1). The period from November to March is considered the coldest time of the year. This is because temperatures often drop below 0°C during this time. In the colder months (November-March), 38.5%-44.5% of the total annual precipitation occurred. The highest monthly precipitation during the cold period reached 190.4 mm (December 2017), while the lowest was 24.8 mm (March 2017). The coldest months of the year were January (-4.3°C) and February (-1.5°C). Based on observations, the minimum air temperature recorded was −18.8°C on 4 January 2016 at 08:00, 2016. Air temperatures crossed the 10°C mark in the first ten-day period of April and the 15°C mark in the first ten-day period of May. Analysis of temperature data from 2016-2018 shows that the duration of the period with positive temperatures above 5°C was 217-241 days, above 10°C was 173-195 days, and above 15°C was 128-149 days. The total accumulated temperature above 5°C was 2,494°C-2,754°C, above 10°C was 1,475°C1,714°C, and above 15°C was 709°C-860°C. An extremely high temperature of +34.6°C was recorded on 17 July 2016 at 14:00.

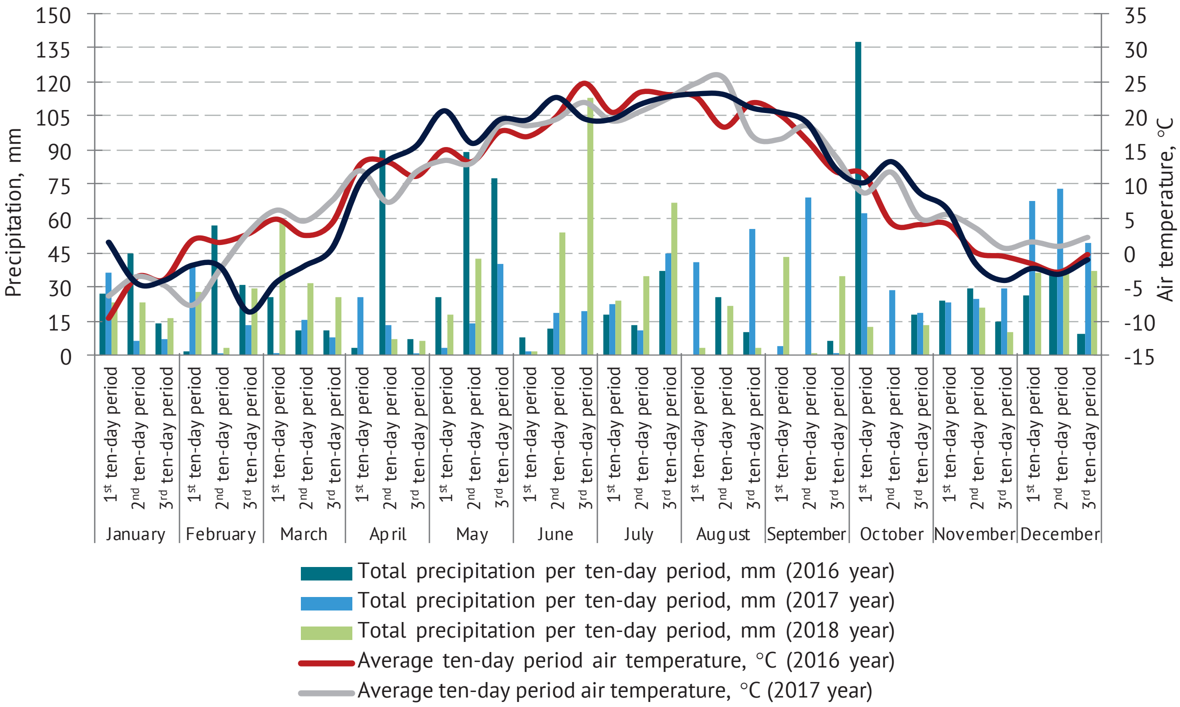

***Figure 1**. Dynamics of air temperature and precipitation, 2016-2018*
***Source:** compiled by the authors based on the conducted research*

The average monthly temperature in April was 12°C, with precipitation of 50.7 mm, which is 5.6% of the average annual amount. May was characterised by warm weather, with an average air temperature of 16.4°C. During this month, precipitation was highest for the period with positive temperatures, reaching 103.3 mm, or 11.4% of the average annual total. In June, the average monthly temperature noticeably increased, reaching 20.4°C. Simultaneously, 76 mm of precipitation, represents 8.4% of the average annual amount. July had an average temperature of 21.5°C, with 90.7 mm of precipitation, which is 10.1% of the average annual total. August was the hottest month across all the years of observation, with an average temperature of 22.0°C. The total precipitation for August was 52.8 mm, accounting for 5.9% of the average annual average. September had moderate weather with an average temperature of 16.6°C. Precipitation amounted to 53.0 mm, which is 5.9% of the average annual rainfall. October saw a significant drop in temperature, reaching 8.6°C. At the same time, 96.5 mm of precipitation, represents 10.7% of the average annual total.

The Department of Vegetable Crops at the National University of Life and Environmental Sciences of Ukraine studied four sowing dates for lablab bean (*Dolichos lablab* L. or *Lablab purpureus* (L.) Sweet) during the years 2016-2018: A) the third ten-day period of April; B) the first ten-day period of May; C) the third ten-day period of May; and D) the first ten-day period of June. The third ten-day period of April was used as the control sowing date. For all experimental groups, the same planting pattern was used – 70 × 20 cm, which resulted in a plant density of 71,000 plants per hectare. Seeds were sown at a depth of 2-3 cm. Each plot measured 5 square metres. Within these plots, 10 plants were selected for detailed study. The space allocated to each plant was controlled by the number of plants in a row, and the distance between rows was the same for all treatment groups. The width of the buffer zones was the same as the width of the plot on both sides of each experimental area.

The experimental design involved three replicates in the field, meaning three identical plots for each treatment, and three replicates over the three years (2016, 2017, and 2018). The field replicates allowed for a more comprehensive representation of the variability within the experimental site for each treatment, leading to more stable and accurate average results. The replicates over time established the influence, interaction, or carry-over effects of the factors being studied under different weather conditions. Overall, this resulted in a sample size of 36 observations (4 treatments × 3 repetitions per field × 3 repetitions over time). To ensure optimal quality, the green pods were harvested at the appropriate stage of maturity. This period is characterised by the pods reaching a typical size and the seeds developing a tender texture (Fig. 2). Harvesting was done manually when the pods in the plot reached harvest maturity (BBCH 77-79) (Meier *et al.*, 2009).

Figure 2*. Simultaneous flowering and fruiting of lablab bean plants*
Source: *authors' photo*

The assessment of general and specific adaptive capacity was based on studying the genetic type (n) in different environments (m) with several experimental repeats (c). Thus:

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

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

The following constraints were applied to the components of the model:

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

Effects of specific adaptive capacity:

$$SAC_i = V_i = X_i - u. \tag{3}$$

The parameters for the species' adaptability were as follows:

$$\sigma^2\ SAC_i = \frac{1}{m-1} * \sum_R (d_R + Vd_{iR})^2 - \frac{m-1}{m} * \sigma^2. \tag{4}$$

$$\sigma\ SAC_i = \sqrt{\sigma^2\ SAC_i}. \tag{5}$$

To compare the variability of different characteristics of lablab across different environments, the relative stability index Sgi was used:

$$S_{gi} = \frac{\sigma_{SAC_i}}{U+GAC} * 100\%. \tag{6}$$

The regression coefficient b_i was used to determine the response of the lablab bean to improvements in environmental conditions:

$$b_i = \frac{\sum x_{iR} * d_R}{\sum_R d_R^2}. \tag{7}$$

To identify the optimal sowing dates for lablab beans that combine productivity and stability, the breeding value of the genotype was used:

$$BVG_i = U + GAC_i - p\sigma_{SAC_i}. \tag{8}$$

The application of the Growing Degree Days method allowed for the determination of the cumulative effective air temperatures during the interphase development period of the lablab bean based on actual temperature data:

$$\sum t_{eff} = (t_{avg} - B) * n, \tag{9}$$

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

Statistical analysis of the research data was performed using the Statistica 13.1 software package (StatSoft, Inc., Tulsa, OK USA). Differences between the treatments were determined using Tukey's test, with significance considered at $p < 0.05$ (with Bonferroni correction applied). To establish the direction and strength of the relationship between the studied variables, the correlation coefficient was calculated (Nageswara, 2018). The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS

A box plot, shown in Figure 3, is a useful tool for visualising the distribution of output data, particularly for identifying outliers, the median, and quartiles. The current study gives a clear picture of the distribution of green pod yield over the period 2016-2018. The box itself represents the interquartile range, which contains 50% of the middle values. The bottom edge of the box shows the first quartile (the 25th percentile), and the top edge shows the third quartile (the 75th percentile). In the current case, the majority of yields for sowing in the third ten-day period of April (control) were between 1.65 and 1.90 t/ha, for the first ten-day period of May between 1.82 and 2.30 t/ha, for the third ten-day period of May between 1.53 and 1.94 t/ha, and for the first ten-day period of June between 1.31 and 1.74 t/ha. The line inside the box represents the median, which is the value that exactly divides the data into two equal halves. In the context of this study, the median yield was found to be around 1.78 t/ha for the third ten-day period of April (control), 2.06 t/ha for the first tenday period of May, 1.58 t/ha for the third ten-day period of May, and 1.40 t/ha for the first tenday period of June. The mode is defined as the value that appears most frequently within a dataset. In this study, it is worth noting that all values are unique, as each value occurs only once. The absence of any number appearing more often than others indicates that there is no mode.

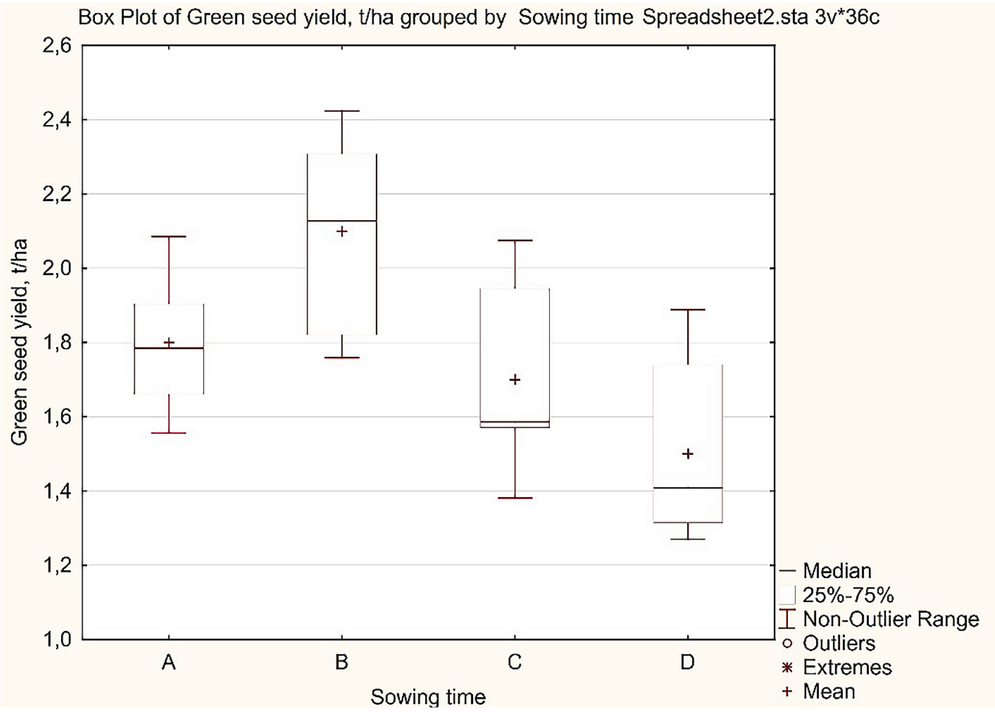

***Figure 3**. Box plot illustrating the yield of green pods of lablab bean*
***Note:** the x-axis represents the sowing date, where A) the third ten-day period of April (control); B) the first ten-day period of May; C) the third ten-day period of May; D) the first ten-day period of June (2016-2018)*
***Source:** developed by the authors based on the conducted research*

As shown in the graph, the mean value is indicated by a "+" symbol. This symbol was located within the box plot, which represents the interquartile range. A high yield of green pods of lablab bean (2.1 t/ha) was obtained when sown in the first ten-day period of May, an increase of 0.3 t/ha or 16.7% compared to the control. The worst yield results for the lablab bean were seen with sowing in the first ten-day period of June, resulting in a decrease of 0.3 t/ha or 16.7% compared to the control. It is worth noting the sowing date in the third ten-day period of May, where the yield was similar to the control (1.7 t/ha). For the control sowing date in the third ten-day period of April, a green pod yield of 1.8 t/ha was recorded.

On the graph, the whiskers outline the boundaries of the main body of the data and represent the entire range of values, excluding any outliers. For the control group (third ten-day period of April), the lower limit indicated by the whisker was approximately 1.56 t/ha, and the upper limit was 2.08 t/ha. Accordingly, for the other sowing dates, the ranges are as follows: first ten-day period of May – 1.76-2.42 t/ha, third ten-day period of May – 1.38-2.07 t/ha, and first ten-day period of June – 1.27-1.89 t/ha. Outliers are defined as data points that fall outside the whiskers. These points suggest the presence of anomalies or extreme values. The occurrence of outliers can be linked to various factors, including specific weather conditions, pest or disease infestation, or unique characteristics of the location. In the context of this research, no such deviations were identified. Therefore, based on the box plot, it can be concluded that the distribution of green pod yield in the experimental groups did not contain any outliers. The mean and median values are located at different points within the distribution. Yield is the most agronomically important element of a plant's phenotype, resulting from the interaction between genotype, environment, and cultivation technology. Physiological principles and agricultural data indicate that the duration, rate of growth, and maturation of the pods are the key factors determining the yield of lablab beans. From a physiological perspective, variations in the length of the growing season are most often linked to variations in the duration of the different phenological stages of growth and development. Statistical analysis showed a direct correlation ($r = 0.68$) between the length of the growing season and the yield of green pods (Fig. 4). This correlation coefficient indicates a strong relationship between the two studied variables. The regression equation, based on the data, allows for the prediction of yield dynamics with changes in the growing season's length. For example, an increase of 10 days in the growing season is predicted to lead to an increase in green pod yield of 207.3 kg/ha.

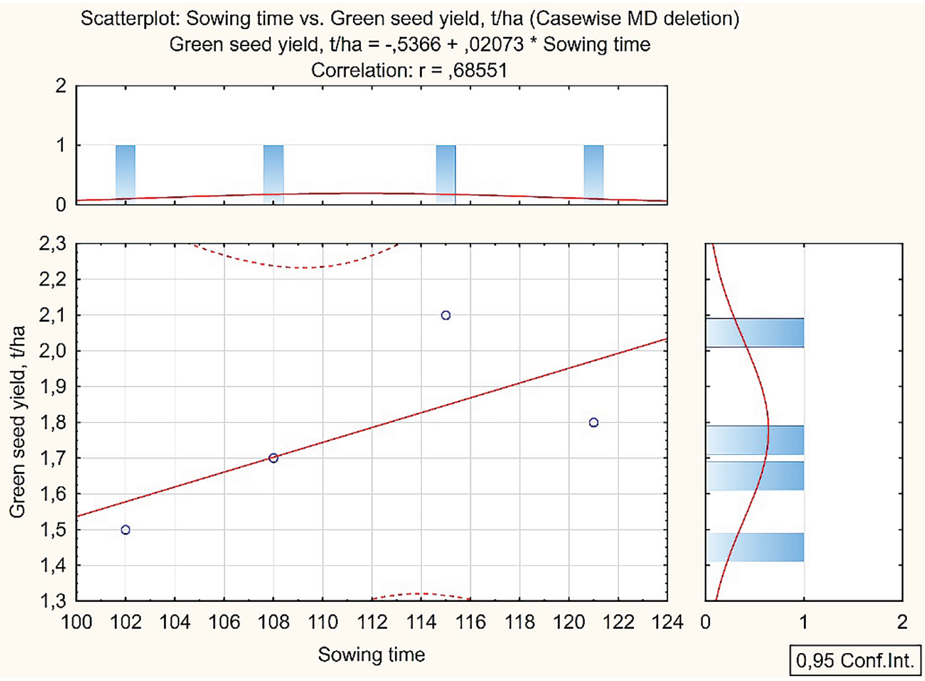

Figure 4. *Relationship between green pods of lablab bean yield and the duration of the growing season (average for 2016-2018)*
Source: *developed by the authors based on the conducted research*

The growth and development of the lablab bean primarily depend on environmental factors, including soil composition, day length, temperature patterns, and the availability of moisture. Temperature is a crucial factor for biological processes and, therefore, for plant growth and development. A specific amount of heat is required for the transition from one growth stage to another, for example, from sowing to emergence. The amount and distribution of precipitation are the second critical condition for successfully growing the lablab bean.

The research showed that for successful cultivation of lablab bean to achieve a marketable yield (1.5-2.1 t/ha) of green pods in the Right-Bank Forest-Steppe region of Ukraine, specific agrometeorological conditions are necessary: a total of active temperatures above 10°C should be between 1,177.3°C and 1,387.1°C during the sowing-to-harvest period, combined with precipitation levels ranging from 268.9 to 341.2 mm. The graphs (Figs. 5 and 6) clearly illustrate the direct relationship between lablab bean yield and the total active temperatures above 10°C, as well as the amount of precipitation. Correlation coefficients of 0.72 and 0.74 respectively confirm the statistical significance of this link. Using the calculated regression equations, it is possible to predict lablab bean yield based on the total air temperatures above 10°C and the amount of precipitation during the growing season. The results of this study indicate that an increase in the total air temperatures above 10°C during the sowing-to-harvest period leads to an increase in the green pod yield of 20.2 kg/ha. At the same time, an increase in precipitation of 10 mm results in a yield increase of 59.1 kg/ha.

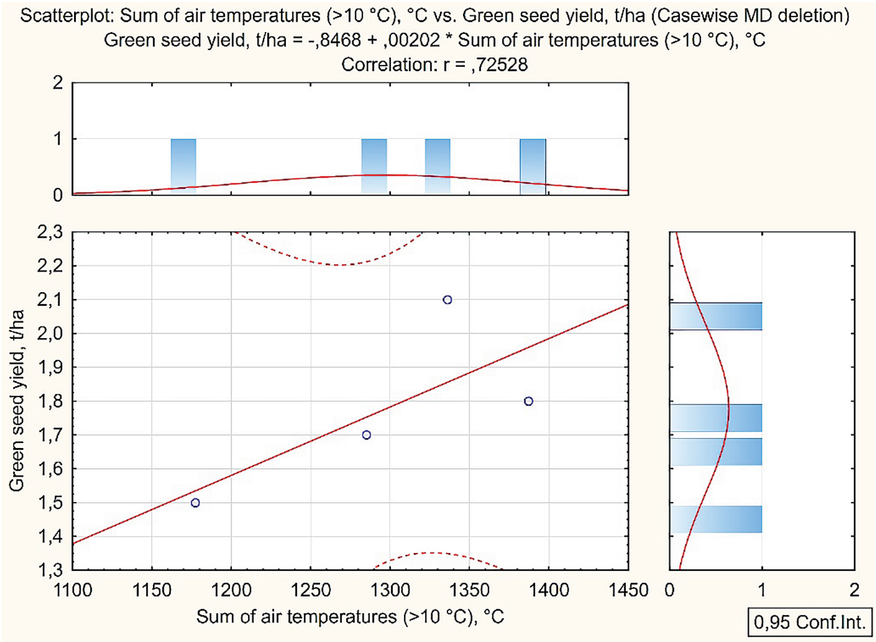

***Figure 5**. Relationship between green pods of lablab bean yield and the sum of temperatures above 10°C during the period from sowing to harvest (average for 2016-2018)*
***Source:** developed by the authors based on the conducted research*

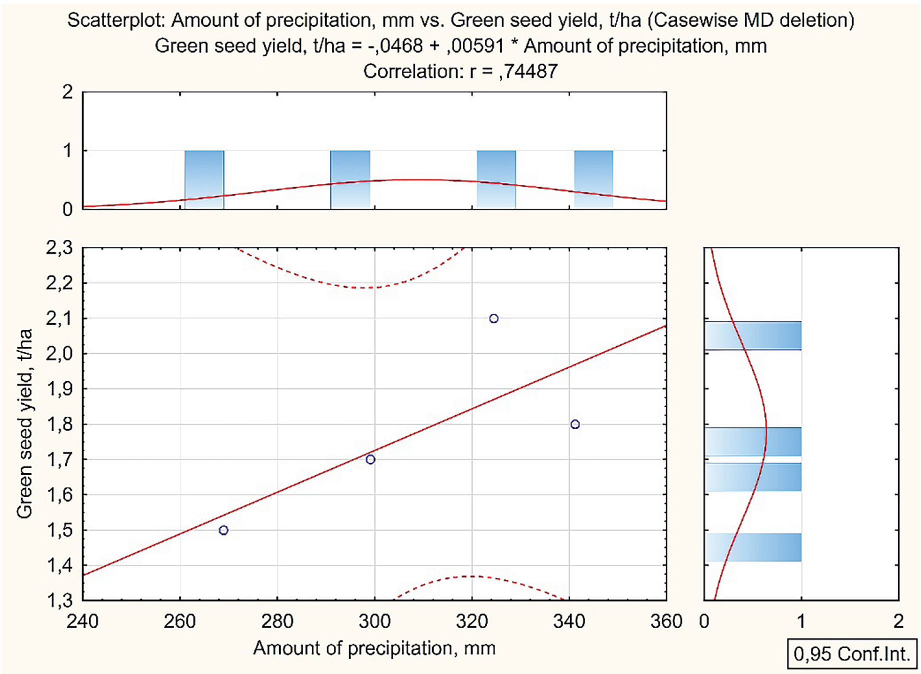

***Figure 6**. Relationship between green pods of lablab bean yield and the level of precipitation during the period from sowing to harvest (average for 2016-2018)*
***Source:** developed by the authors based on the conducted research*

According to Table 1, F = 10.76 and F crit = 9.55, meaning F > F crit. Therefore, the effect of the studied factor on the resulting characteristic can be considered statistically significant, which is also confirmed by the significance level (p-value = 4.78E-05), which is less than 0.05. At the same time, the proportion of influence of sowing dates on the yield of green pods was 50.2%.

Table 1*. Results of variance analysis*

Source of variation	SS	df	MS	F_{05}	p-value	F crit
Between groups	1.6875	3	0.5625	10.76215	4,78E-05	2.90112
Within groups	1.672528	32	0.052267			
Total	3.360028	35				

Source: *developed by the authors based on the conducted research*

To assess the consistency of the studied sample, the coefficient of variation was used, which estimates the relative deviation of the observed values from the arithmetic mean. As shown by the analysis of the coefficients of variation for lablab bean green pods yield, sowing from the third tenday period of April (control) to the first ten-day period of June resulted in moderate variability, as the coefficient of variation in these cases ranged from 11.11% to 17.64% (Table 2). To determine the adaptive capabilities of the lablab bean, the authors considered two indicators: general adaptability, which characterised the ability of plants to achieve stable yields across a wide range of growing conditions, and specific adaptability, which was determined by resistance to specific stress factors (cold, drought, pests, etc.). According to the analysis of the general adaptive capacity of the lablab bean plants, the highest values for this indicator were observed when sown in the first tenday period of May (GAC = 0.325). The lowest values for this indicator were found in plants sown in the first ten-day period of June (GAC = -0.275). Regarding specific adaptability capacity, plants sown from the first ten-day period of May to the first ten-day period of June showed equally good adaptation to the specific growing conditions (SAC = 0.06)

Table 2*. Parameters of the adaptive capacity and stability of the lablab bean at different sowing dates (2016-2018)*

Indicator	Sowing date			
	Third ten-day period of April (control)	The first ten-day period of May	The third ten-day period of May	The first ten-day period of June
Green pod yield (Mean), t/ha	1.8 ± 0.061 [a]	2.1 ± 0.084 [ab]	1.7 ± 0.079 [b]	1.5 ± 0.078 [c]
Coefficient of variation (V), %	11.11	12.60	15.56	17.64
General adaptive capacity (GAC)	0.025	0.325	-0.075	-0.275
Specific adaptability capacity (SAC)	0.03	0.06	0.06	0.06
Relative stability (Sgi), %	1.45	2.67	3.30	3.74
Plasticity (bi)	1.68	1.79	2.32	-1.79
Homeostasis (Hom)	0.16	0.17	0.11	0.09
Breeding value of the genotype (BVG_i)	1.33	1.09	0.69	0.49

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

The concept of relative genotype stability is crucial for making comparative analyses easier across experiments involving different crops, genetic types, environments, and traits being studied. The relative stability of a genotype is similar to the coefficient of variation when examined across various environments. Therefore, under different growing conditions, all the studied treatments showed a high degree of stability in green pod yield (Sgi ranging from 1.45% to 3.75%), as the deviation in this indicator did not exceed 25%. The reaction of a genotype to improvements in environmental conditions can be assessed using the regression coefficient. If the value of this coefficient is greater than one (bi > 1), it indicates a high sensitivity of the species or variety to changes in growing conditions. Under optimal growing conditions, such a variety is capable of producing a significantly higher yield. Conversely, if the coefficient is less than one (bi < 1), it is less sensitive to changes in conditions and, consequently, responds less to improvements in cultivation techniques. In cases where the regression coefficient equals one (bi = 1), changes in the variety's yield are fully correlated with changes in growing conditions.

Further analysis of the data showed that the lowest level of sensitivity to improved growing conditions was demonstrated by the lablab bean sown in the first ten-day period of June. Therefore, for every 1 t/ha increase in average yield, the yield of this treatment only increased by 1.79 t/ha. Out of all the sowing dates studied, the third ten-day period of May proved to be the most sensitive to changes in yield levels under the test conditions (with a 1 t/ha increase in average yield, it increased by 2.32). The next most sensitive were the treatments sown in the first ten-day period of May (bi = 1.76) and the third ten-day period of April (control) (bi = 1.68). Regarding homeostasis, which describes the ability of plants to develop normally under unfavourable environmental conditions, the treatments sown in the first ten-day period of May (Hom = 0.17) and the third ten-day period of April (control) (Hom = 0.16) stood out. The lowest homeostatic value (Hom = 0.09) was observed for the treatment sown in the first ten-day period of June.

It is generally accepted that species (or varieties) that only produce high yields under optimal conditions pose a risk to production, as they may not be able to maintain such yield levels with inadequate care or unfavourable weather. Therefore, to assess the overall characteristics of the lablab bean, considering both their potential yield and their ability to maintain it under different conditions, the breeding value of the genotype was used. High breeding values of the genotype were characteristic of the sowing dates in the third ten-day period of April (control) and the first ten-day period of May, with values of 1.33 and 1.09, respectively. This indicates that these sowing times provided an optimal combination of high yield and stability, which is particularly important in the context of unfavourable growing conditions. The yield of lablab bean green pods showed a strong positive correlation (r = 0.71-0.99) with general adaptability, plasticity, homeostasis, and breeding value of the genotype. In contrast, yield showed a strong negative correlation with the coefficient of variation (r = -0.75) and a moderate negative correlation with relative stability (r = -0.50). The analysis suggests that the yield of lablab bean green pods is closely linked to its adaptive characteristics (Fig. 7).

Mean	Mean							
V	-0.75	V						
GAC	0.99	-0.75	GAC					
SAC	-0.07	0.71	-0.07	SAC				
Sgi	-0.50	0.95	-0.50	0.90	Sgi			
bi	0.67	-0.68	0.67	-0.24	-0.53	bi		
Hom	0.91	-0.95	0.91	-0.47	-0.81	0.63	Hom	
BVGi	0.71	-0.99	0.71	-0.75	-0.97	0.61	0.93	BVGi

Legend

Pearson correlation coefficients between the studied indicators: green pod yield (Mean), coefficient of variation (V), general adaptability capacity (GAC), specific adaptability capacity (SAC), relative stability (Sgi), plasticity (bi), homeostasis (Hom), breeding value of the genotype (BVGi).

Strength of correlation links:		Direction of correlation:	
	1 – perfect;	1 ⩾ r > 0	Positive correlation;
	0.66-0.99 – strong;	-1 ⩽ r < 0	Negative correlation.
	0.33-0.66 – moderate;		
	< 0.33 – weak.		

Figure 7*. Correlation dependence between the parameters of adaptive capacity and stability of the lablab bean at different sowing times (2016-2018)*

Source: *developed by the authors based on the conducted research*

The yield of lablab bean green pods showed a strong positive correlation (r = 0.67-0.99) with general adaptability capacity, plasticity, homeostasis, and breeding value of the genotype. At the same time, yield had a strong negative correlation with the coefficient of variation (r = -0.75) and a moderate negative correlation with relative stability (r = -0.50). No statistically significant relationship was observed between yield and specific adaptability capacity (r = -0.07).

DISCUSSION

Overall, the experimental research produced results similar to those obtained in other countries. Studies in India involving 30 genetic types found that the coefficients of variation for the observable characteristics (phenotype) were generally higher than those for the genetic makeup (genotype). This suggests that the influence of the genotype was reduced by environmental factors (Ganapathi & Akshay, 2020). The results of the cluster analysis showed that Cluster 3, which included 12 samples, had the highest yields of green seeds (82.1 kg) and green pods (152.5 kg) (Jahnavi *et al.*, 2023). R. Preetham *et al.* (2020) identified the genetic type IC-427436 among 45 lablab bean genotypes in India, noting its pod weight of 11.0 g and 6.3 seeds per pod, and it demonstrated a significantly higher pod yield of 13.6 t/ha compared to other genotypes. Based on average performance indicators, the genotypes PYR 15-01, Nagavalli local 1, and Nallur local proved to be the best in terms of yield and its components, while the genotype HA 3 was characterised by early maturity and provided an optimal green pod yield of 327 g per plant (Geetha & Divya, 2021).

The formation of agricultural crop yields largely depends on a combination of farming techniques and soil-climate conditions (Litvinova *et al.*, 2023; Syromyatnikov *et al.*, 2023). The authors' research has shown that sowing dates had a significant impact on plant growth and development, determining the optimal phenological stages for achieving maximum productivity. When growing plants in regions where they are newly introduced, the sowing date is a primary factor that needs careful consideration.

Determining the optimal sowing date is based on the characteristics of the variety and the meteorological conditions of the region (Baum *et al.*, 2020; Bobos *et al.*, 2020, 2022). Temperature patterns and soil moisture are the most critical non-living factors influencing seed germination. If these do not match the optimal conditions, it can lead to delayed seedling emergence, disrupted plant development and, consequently, affect the size and quality of the harvest (Suo *et al.,* 2022). In particular, the authors found that for sowing in the third ten-day period of April, the average daily air temperature during the sowing-to-emergence period ranged from 12.2°C to 18.8°C, with an average of 15.5°C. These temperature conditions led to a delay in seedling emergence of 18 days. Conversely, an increase in the average daily temperature to 19.1°C (ranging from 17.9°C to 20.5°C) in the sowing treatment carried out in the first ten-day period of June accelerated germination, thereby reducing the interval between sowing and emergence to 8 days. This is because germination slows down sharply when temperatures fall below the optimum, as low temperatures hinder metabolism and enzyme activity, affecting the entire germination process (Cafaro *et al.*, 2022).

P. Kimani *et al.* (2022) reported that *Phaseolus vulgaris* L. plants had the highest yields under seasonal temperatures ranging from 11.7°C to 36.7°C, which corresponded to an average temperature of 24.2°C throughout the crop growing season. Furthermore, a maximum temperature of 34°C during the pod formation stage positively influenced the development of pods and seeds, as shown by increased yields in plants exposed to these higher temperatures during this specific growth phase. Research by S. Zeipiņa *et al.* (2022) aimed to optimise vegetable soybean production in the Northern Europe region. Through careful experiments, it was determined that a growing season of 123 to 127 days, a minimum accumulated air temperature above 10°C of 650°C, and a hydrothermal coefficient (HTC) above one produced the most favourable yield results. Presented research also demonstrated that lablab bean plants respond differently to temperature, affecting both the rate of germination and the final yield. For example, the maximum lablab bean yield was obtained when sown in the first ten-day period of May, which coincided with an accumulated air temperature above 10°C of 864°C during the period from emergence to the start of marketable pod maturity, while the minimum yield was noted when sown in the first ten-day period of June – 740°C.

Research by H. Vinay *et al.* (2022) demonstrated that minimum temperature, duration of sunshine, and precipitation amount had a positive correlation with green seed yield. A similar trend was observed in current studies, with a positive correlation between green seed yield and the total accumulated temperature ($r = 0.72$) and precipitation amount ($r = 0.74$) during the plant growth and development period. The influence of genotype and sowing date proved to be statistically significant factors affecting the lablab bean green pod yield, as well as the content of crude fibre, crude protein, and total dry matter (Venkatesan *et al.*, 2024). Genotypes with early and mediumearly maturity periods, specifically Phule gauri (145.3 days), AKWAL1816 (146.7 days), and DOL-VARK-18-04 (147.3 days), were found to be the most promising for cultivation (Pachkhande *et al.*, 2022). Simultaneously, the authors of this study determined that the yield of the lablab bean is a result of the interaction between genotype, environmental conditions, and cultivation techniques, and statistical analysis showed that every additional 10 days of the growing season increased yield by 207.3 kg/ha.

Intercropping of agricultural crops is a fundamental and traditional practice among local farmers in Hararghe (Ethiopia), primarily due to the lack of available land. Research findings indicated that growing sorghum together with *Dolichos lablab* at different sowing times affects the grain yield of the sorghum. It is recommended that 4 weeks after sowing sorghum is the optimal time for sowing *Dolichos lablab* in intercropping (Dinkale *et al.,* 2022). Aphid populations are influenced by numerous factors, including environmental conditions, the characteristics of the host plants, and natural predators. Among these factors, weather conditions play a crucial role in shaping aphid populations by affecting their reproduction, development, dispersal, and survival (Sun *et al.*, 2022). A chronological consistency was observed between temperature fluctuations and the initial establishment of aphid colonies, with a peak occurring in mid-June. This aligns with data from M. Almogdad *et al.* (2024) regarding the correlation between rising temperatures and increased aphid activity at this growth stage. Research by C. Mwani *et al.* (2021) found that aphid numbers were low at the seedling stage but gradually increased as the plants developed. Therefore, sowing lablab beans at the optimal times, determined by the specific weather conditions of the year, helped to control and reduce pest damage.

In conclusion, it is clear that selecting the best sowing dates is a key factor that determines the growth and development of lablab bean plants, as well as the yield levels achieved. It was established that the sowing date influenced the balance of temperature and soil moisture, which is critically important for the crop's yield formation. It is recognised that these indicators can vary across different geographical areas depending on the climate and the specific weather conditions of a given year. Presented research suggests that the impact of farming techniques and the region's weather patterns had a decisive influence on the marketable yield of lablab bean green pods.

CONCLUSIONS

The green pod yield in the study ranged from 1.5 t/ha (first ten-day period of June) to 2.1 t/ha (first ten-day period of May), with an average of 1.8 t/ha. The resulting values for the coefficient of variation in yield (11.1%-17.6%) indicate that the studied sample had a moderate level of variation in this trait. Lablab bean plants sown at the investigated times showed high stability ($Sgi < 25$) in terms of yield. The assessment of the environmental flexibility of the lablab bean revealed that sowing from the third ten-day period of April (control) to the third ten-day period of May would increase green pod yield due to improved growing conditions. Sowing in the third ten-day period of May provided the highest level of flexibility, characterised by a high positive regression coefficient ($bi = 2.32$). The weakest response to improved growing conditions, with the lowest green pod yield, was found with sowing in the first ten-day period of June, which had a regression coefficient of $bi = -1.79$. Among the studied sowing dates for the lablab bean, high levels of consistency across different conditions ($Hom = 0.16$-0.17) and breeding value of the genotype ($BVGi = 1.09$-1.33) were obtained with sowing in the third ten-day period of April (control) and the first ten-day period of May. Future research will focus on improving the genetic potential of the lablab bean to enhance yield, nutritional value, and resilience to climate change, which will expand the understanding of the crop's benefits for producing valuable food products.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Вплив термінів сівби на екологічну стабільність, пластичність та адаптивність доліхоса (*Dolichos lablab* L)

Ірина Бобось
Кандидат сільськогосподарських наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0001-5193-7192
Олександр Комар
Кандидат сільськогосподарських наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0001-7511-4190
Іван Федосій
Кандидат сільськогосподарських наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0002-5044-9960
Наталя Ілюк
Кандидат сільськогосподарських наук
Відкритий міжнародний університет розвитку людини «Україна»
03115, вул. Львівська, 23, м. Київ, Україна
https://orcid.org/0000-0002-3296-4790
Олена Сєдова
Асистент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0003-4869-1560

Анотація. Розуміння результатів впливу ґрунтово-кліматичних умов на сільськогосподарські рослини є основою для розробки та впровадження інноваційних технологій та стратегій, які мінімізують негативний вплив на фермерські господарства та сільське господарство в цілому. Мета досліджень – вивчення впливу різних термінів сівби доліхоса для розширення потенційних можливостей вирощування цієї культури в умовах Правобережного Лісостепу України. Для вивчення цієї проблеми використано наступні методи: польовий – для вивчення взаємодії об'єкта дослідження з біотичними та абіотичними факторами та статистичний – для аналізу результатів досліджень з метою визначення параметрів адаптивності доліхоса. Встановлено, що максимальна врожайність зеленого горошку доліхоса (2,1 т/га) досягалася за сівби в І декаді травня, що на 0,3 т/га (16,7 %) перевищувало показник контрольного варіанту (ІІІ декада квітня – 1,8 т/га). Мінімальна врожайність (1,5 т/га) спостерігалася за сівби в І декаді червня. Дослідження також виявило залежність врожайності від тривалості вегетаційного періоду (r = 0,68), суми активних температур (>10 °C) (r = 0,72) та суми опадів (r = 0,74). Встановлено сильну позитивну кореляцію між врожайністю доліхоса та загальною адаптивною здатністю (r = 0,99), пластичністю (r = 0,67), гомеостатичністю (r = 0,91) та селекційною цінністю (r = 0,71). З іншого боку, виявлено негативну кореляцію між врожайністю та коефіцієнтом варіації (r = -0,75) та відносною стабільністю (r = -0,50). Відносна стабільність врожайності (Sgi) варіювалася від 1,45 % до 3,74 %. Коефіцієнт варіації врожайності коливався від 11,11 % до 17,64 % залежно від терміну сівби. В агрокліматичних умовах проведення досліджень високою пластичністю володіли варіанти за сівби доліхоса від ІІІ декади квітня (контроль) до ІІІ декади травня, а низьке значення bi було лише за сівби в І декаді червня, отже, доліхос мав низьку екологічну пластичність. Найвища селекційна цінність генотипу (GBVi = 1,09-1,33) спостерігалася для варіантів за сівби в ІІІ декаді квітня (контроль) та І декаді травня, тоді як найнижча (GBVi = -0,275) – в І декаді червня

Ключові слова: кліматичні фактори; генотип; урожайність; продовольча безпека; бобові

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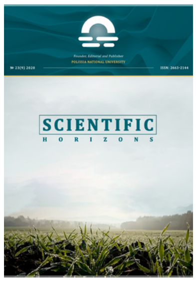

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Use of poultry in the production of high-quality baby food products: Literature review

Moldir Kurmanakhynova*
Doctoral Student
Almaty Technological University
050012, 100 Tole bi Str., Almaty, Republic of Kazakhstan
https://orcid.org/0009-0003-6544-1472

Gulshat Zhaksylykova
PhD in Technical Sciences, Associate Professor
Almaty Technological University
050012, 100 Tole bi Str., Almaty, Republic of Kazakhstan
https://orcid.org/0000-0003-0563-4304

Talgat Kulazhanov
Doctor of Technical Sciences, Professor
Almaty Technological University
050012, 100 Tole bi Str., Almaty, Republic of Kazakhstan
https://orcid.org/0000-0001-8984-0011

Lyazzat Baybolova
Doctor of Technical Sciences, Professor
Almaty Technological University
050012, 100 Tole bi Str., Almaty, Republic of Kazakhstan
https://orcid.org/0000-0002-8118-1581

Sholpan Abzhanova
PhD in Technical Sciences, Associate Professor
Almaty Technological University
050012, 100 Tole bi Str., Almaty, Republic of Kazakhstan
https://orcid.org/0000-0003-3209-6855

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Abstract. Poultry meat and eggs are important components of baby food due to the high biological value of protein, rich content of essential amino acids, minerals and vitamins necessary for the normal development of the child's body. This review aimed to systematically assess the nutritional and technological potential of poultry meat and eggs for use in the production of high-quality baby food. A content analysis of 51 peer-reviewed scientific sources published between 2012 and 2024 was conducted to

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**Corresponding author*

synthesise data on the amino acid composition, digestibility, and processing characteristics of chicken and turkey meat, as well as poultry eggs. The analysis showed that turkey meat contained up to 31.65% protein and only 4.55% fat, indicating its value as a lean protein source. Chicken breast muscle provided 9,872.7 ± 465.09 mg of essential amino acids per 100 g, while turkey breast offered 115.3 mg/100 g. Eggs demonstrated a high proportion of essential amino acids (over 43% of the total amino acid content) and were identified as a key dietary source of choline important for early cognitive development. The review also evaluated traditional and modern processing methods, including pasteurisation, sterilisation, lyophilisation, hydrothermal treatment, and non-thermal technologies such as pulsed electric field, radio frequency heating and ultrasound. It was found that modern methods such as PEF and lyophilisation preserved up to 97% of vitamins and reduced microbial loads by 5-6 log without significantly altering nutritional value. The findings underscored the importance of selecting appropriate processing technologies to preserve both the safety and nutritional quality of poultry-based baby foods

Keywords: biological value; processing technologies; amino acid composition; food safety; complementary foods

INTRODUCTION

Rational baby food is one of the key components of a child's healthy development. According to O.O. Gorach and Y.V. Istomina (2024), the growing number of food allergies, metabolic disorders and the need for optimal nutritional balance necessitate careful quality control of products for children. The authors emphasised that current trends in baby food should prioritise products with high bioavailability of nutrients and minimum content of potential allergens. Poultry and eggs are attracting considerable attention from researchers as a source of high-quality protein, which is important for the growth and development of a child's body. In particular, N. Kondratiuk *et al.* (2022) note that poultry meat is substantial in the nutritional balance of young people's diets, as it contains complete protein, a range of essential amino acids, trace elements, and is highly digestible.

However, traditional methods of heat treatment can significantly reduce the content of thermolabile vitamins and trace elements in poultry meat and eggs (Szeląg-Sikora *et al.*, 2024). N. Pasdar *et al.* (2024) emphasise that modern non-thermal technologies, such as pulsed electric field, high pressure and ultrasonic processing, can minimise the loss of beneficial nutrients in baby food. The authors stated that such processing methods can increase the bioavailability of protein and reduce the risk of undesirable chemical compounds that occur during traditional heat treatment. Similarly, S. Baizhanova *et al.* (2023) addressed the introduction of innovative technologies in the production of functional foods that contribute to improving their composition and safety. In particular, the authors analysed the prospects of bioactive additives and modification of the texture of meat to increase its digestibility by young children.

The issue of the safety of poultry products also attracts the attention of researchers. M. Abenova *et al.* (2021) analysed the safety indicators of poultry meat produced in farms and small farms and identified possible risks of microbiological contamination. The authors recommend improving quality control methods and introducing effective food safety inspection systems to reduce the risk of contamination with pathogenic microorganisms. At the same time, S.A. Kozhabayeva and N.T. Sartanova (2021) highlights the development of turkey meat production in Kazakhstan as a promising source of food proteins. The authors demonstrated that turkey meat contains more essential amino acids compared to chicken and has a lower cholesterol level, which makes it suitable for baby food.

In terms of exporting poultry products, A. Ibyzhanova *et al.* (2022) explored the opportunities of the international market and the issue of product compliance with international standards. The authors noted that one of the key factors for successful exports is the introduction of modern technologies for maintaining the quality and safety of poultry meat, which is especially important for baby food. Additionally, A.Z. Temirbekova *et al.* (2024) analysed the role of probiotics and biological products in improving the quality of poultry products, which can have a positive impact on the final product for baby food. The authors argued that the use of probiotic cultures in poultry feeding contributes to the nutritional value of meat and its microbiological safety. The importance of food proteins, particularly poultry and eggs, in children's diets is emphasised in the recommendations of the World Health Organization (2023), which has developed guidelines for complementary foods for children aged 6-23 months. These guidelines emphasise the need to ensure that children's diets contain sufficient levels of protein and essential micronutrients. The global increase in the consumption of commercially available formula milk, which is changing the food systems for infants and young children, was noted by P. Baker *et al.* (2021).

Despite numerous studies on the nutritional value of poultry meat and eggs, there is no systematic assessment of the impact of different processing methods on the preservation of essential elements in infant food production. This study examined the amino acid composition and nutritional value of poultry products, as well as the impact of modern and traditional processing methods on the preservation of essential nutrients necessary for infant development.

A thorough content analysis of 51 peer-reviewed sources published from 2012 to 2024 was conducted. The emphasis was on empirical studies and expert assessments of the chemical composition, safety standards and processing technologies of poultry products used in infant food. The main focus was on chicken and turkey meat due to its prevalence, better digestibility, and favorable protein to fat ratio. The study did not take into account unconfirmed, outdated or unverified information, instead focusing on interdisciplinary perspectives from nutrition science, food technology and public health. The information was systematised using thematic content analysis, categorising the literature by nutritional value, microbiological safety, and processing. This method allowed us to formulate a science-based understanding of ideal processing technologies to improve the nutritional value and safety of poultry baby food.

NUTRITIONAL VALUE OF POULTRY MEAT AND EGGS IN BABY FOOD

Poultry meat and eggs are central in children's nutrition due to their nutritional value, which is determined by the presence of a protein of high biological value, essential amino acids, trace elements and vitamins necessary for the normal growth and development of children. According to scientific research, poultry meat, in particular chicken, is a source of protein with a high biological value due to its good ratio of essential amino acids (Kucheruk & Zasekin, 2020) (Table 1). The composition of amino acids in poultry meat meets the needs of the child's body, ensuring the optimal functioning of various systems and organs, including the muscular and nervous systems (Abylgazinova *et al.,* 2023).

***Table 1**. Amino acid composition of breast and thigh muscles of chickens (mg per 100 g of product)*

Amino acid	Chest muscles	Thigh muscles
Essential amino acids	9,872.7 ± 465.09	8,338.60 ± 50.60
Valine	959.00 ± 11.30	795.20 ± 8.20
Isoleucine	1,012.20 ± 19.60	741.30 ± 8.50
Leucine	1,573.10 ± 29.00	902.00 ± 18.00
Lysine	1,744.00 ± 35.50	1,374.10 ± 4.10
Methionine	524.10 ± 8.20	457.10 ± 8.10
Threonine	899.90 ± 17.50	809.20 ± 7.50
Tryptophan	321.10 ± 12.80	215.10 ± 4.30
Phenylalanine	813.00 ± 14.20	906.40 ± 17.10
Arginine	1,420.50 ± 23.70	1,600.40 ± 13.70
Histidine	605.80 ± 14.70	537.80 ± 8.50
Essential amino acids	11,261.60 ± 193.9	9,461.70 ± 25.70
Alanine	1,380.60 ± 25.10	1,424.10 ± 5.60
Aspartic acid	2,013.30 ± 36.60	1,635.40 ± 15.00
Glycine	1,474.50 ± 19.00	1,314.70 ± 14.00
Glutamic acid	3,500.40 ± 122.50	2,710.50 ± 24.00
Proline	1,053.90 ± 21.70	924.10 ± 6.00
Serine	913.30 ± 11.50	734.40 ± 5.50
Tyrosine	695.70 ± 19.10	528.30 ± 6.10
Cystine	180.10 ± 8.40	134.40 ± 2.00
Oxyproline	49.80 ± 2.30	55.80 ± 1.20
The sum of all amino acids	2,134.30 ± 160.7	17,800.30 ± 63.8

***Source:** compiled by the authors based on M. Kucheruk and D. Zasekin (2020)*

Following the table, chicken meat contains important essential amino acids such as leucine, lysine, methionine and threonine, which are essential for the normal development of children. Leucine and lysine promote muscle growth and recovery, methionine is important for normalising metabolic processes, and threonine maintains healthy skin and tissues. An important feature is also the high content of glutamic and aspartic acids, which are important for maintaining the functions of the central nervous system and ensuring energy metabolism in the body (Abylgazinova *et al.,* 2023). Due to the optimal balance of these amino acids, chicken meat is a valuable component of baby food that ensures the proper development and maintenance of all body systems, including the muscular and nervous systems.

The amino acid composition of turkey meat, in particular breast and thigh muscles, demonstrates a high level of essential amino acids, which makes this product suitable for inclusion in the diet of infant food (Table 2). Turkey meat is characterised by a high content of lysine (20.83 mg/100 g in breast muscles and 16.35 mg/100 g in thigh muscles), leucine (18.65 mg/100 g and 14.91 mg/100 g, respectively), as well as amino acids important for the growth and development of a child, such as valine, threonine and methionine (Czech *et al.,* 2024). The absence of significant fat content, especially in the pectoral muscles, makes turkey an easily digestible and low-calorie source of protein, which normalises children's nutrition. The high level of essential amino acids, such as histidine and isoleucine, confirms the biological value of turkey meat for children who need high-quality and balanced protein sources for normal physical development.

Table 2. *Amino acid composition of turkey breast and thigh muscles (mg per 100 g of product)*

Amino acid	Chest muscles	Thigh muscles
Histidine (His)	13.26	6.21
Isoleucine (Ile)	10.44	7.94
Leucine (Leu)	18.65	14.91
Lysine (Lys)	20.83	16.35
Methionine (Met)	6.57	5.07
Cysteine (Cys)	2.55	2.35
Phenylalanine (Phe)	9.61	7.90
Threonine (Thr)	13.21	10.77
Valine (Val)	11.29	8.74
Tryptophan (Trp)	8.86	8.49
The sum of essential amino acids	115.3	88.71
Aspartic acid (Asp)	24.31	19.11
Serine (Ser)	8.77	7.52
Glutamic acid (Glu)	39.58	34.47
Proline (Pro)	11.65	15.07
Glycine (Gly)	8.65	9.53
Alanine (Ala)	12.16	11.10
Tyrosine (Tyr)	10.47	7.10
Arginine (Arg)	14.94	12.28
The sum of essential amino acids	130.5	116.2
Sum amino acids	245.8	204.9

Source: *compiled by the authors based on A. Czech et al. (2024)*

The protein concentration in chicken meat can reach 22%, which makes it one of the main components of the protein part of children's diets. The nutritional properties of chicken are determined not only by its composition but also by its low-fat content (compared to other types of meat, such as beef), which makes chicken meat easy for children to digest (Table 3). In addition, the fat content of chicken depends on the part of the chicken: for example, chicken breast meat contains significantly less fat than thighs, which should also be taken into account when formulating a diet for children (Barbut & Leishman, 2022). Turkey meat is also a valuable source of protein, with a concentration of up to 31.65%, which is biologically complete, as its composition meets the body's need for all amino acids.

Table 3. *Chemical composition of chicken and turkey meat*

Indicators	Chicken	Turkey
Water, %	71.14 ± 0.11	74.24 ± 2.15
Mineral substances, %	1.98 ± 0.02	1.31 ± 0.15
Protein, %	20.11 ± 0.12	31.65 ± 1.63
Lipids, %	7.60 ± 0.1	4.55 ± 0.21
Calorific value, kJ	620	701.03 ± 29.62

Source: *compiled by the authors based on M. Kucheruk and D. Zasekin (2020), R. Feduniak and R. Peleno (2024)*

Poultry produces 70-95 g of body protein from 100 g of animal protein. Turkey meat is lower in fat than chicken, especially in the thigh muscles, making it an even more dietary option. Due to its high protein and low-fat content, turkey meat is recommended for baby food as it contributes to the normal growth and development of the body by providing essential amino acids and minerals (Gautron *et al.,* 2022). Eggs, in turn, are another essential source of protein and important nutrients in baby food. They contain proteins of high biological value, as they contain all essential amino acids in the appropriate proportion for a child's body (Table 4). Egg protein is highly digestible, making it an important component for the development of tissues and organs in children.

Table 4. *Amino acid composition of chicken and turkey eggs (mg per 100 g of product)*

Amino acid	Chicken egg	Turkey egg
Glutamine (Glu)	1.285 ± 0.086	1.335 ± 0.057
Asparagine (Asp)	1.110 ± 0.072	1.127 ± 0.051
Leucine (Leu)	0.916 ± 0.058	0.995 ± 0.041
Serine (Ser)	0.697 ± 0.042	0.734 ± 0.030
Alanine (Ala)	0.662 ± 0.043	0.606 ± 0.032
Valine (Val)	0.631 ± 0.040	0.624 ± 0.030
Methionine (Met)	0.624 ± 0.042	0.653 ± 0.043
Phenylalanine (Phe)	0.592 ± 0.036	0.599 ± 0.033
Lysine (Lys)	0.570 ± 0.038	0.626 ± 0.029
Arginine (Arg)	0.545 ± 0.036	0.504 ± 0.023
Isoleucine (Ile)	0.514 ± 0.029	0.575 ± 0.026
Threonine (Thr)	0.473 ± 0.032	0.593 ± 0.024
Proline (Pro)	0.420 ± 0.061	0.418 ± 0.075
Tyrosine (Tyr)	0.380 ± 0.023	0.473 ± 0.025
Glycine (Gly)	0.350 ± 0.022	0.395 ± 0.016
Histidine (His)	0.224 ± 0.015	0.241 ± 0.015
Essential Amino Acids (EAA)	4.32 ± 0.26	4.66 ± 0.21
Total Amino Acid Content (TAA)	9.99 ± 0.61	10.50 ± 0.45
EAA/TAA (%)	43.23 ± 0.42	44.44 ± 0.44

Source: *compiled by the authors based on C. Sun et al. (2019)*

Recent research addressed choline, an important nutrient found in eggs. Choline is essential for brain development, in particular for the formation of nerve cell membranes, and for the normal functioning of the liver. Studies show that choline can help improve cognitive function, which is important for child development, particularly in early childhood (2-6 years), when brain structures are actively forming (Gautron *et al.,* 2022). However, excessive heat treatment of eggs can lead to the loss of some nutrients. In particular, high temperatures can reduce the biological value of protein and decrease the choline content.

Thus, chicken and turkey meat, as well as their eggs, are important components of children's diets due to the high biological value of protein, and the presence of essential amino acids and trace elements. They not only support normal growth and development but also contribute to the health of the nervous system, cognitive function and overall strengthening of the immune system.

THE IMPACT OF INDUSTRIAL PROCESSING METHODS ON PRODUCT QUALITY AND SAFETY

Pasteurisation and sterilisation are the key methods of heat treatment of meat products used in the production of baby food. Pasteurisation involves heating the product to a temperature of 60-85°C to kill pathogens while retaining essential nutrients such as proteins, fats and vitamins. It minimises the loss of thermolabile substances, such as B vitamins, making it the optimal method for baby food (Gorach & Istomina, 2024). Sterilisation is characterised by a higher temperature treatment (110-135°C), which ensures the destruction of all microorganisms, including spore forms of bacteria. However, such intensive heat treatment can cause changes in the structure of proteins and a decrease in the level of certain trace elements, such as vitamin C and folic acid. To minimise the negative impact, gentle sterilisation modes are used, such as ultra-high temperature (UHT) treatment, which involves short-term heating to 135°C for several seconds. Modern industrial technologies compensate for possible losses of nutrients by using enriched formulations. In addition, the combination of sterilisation and vacuum packaging extends the shelf life of products without the use of preservatives, which is critical for baby food safety (Gorach & Istomina, 2024).

Freeze-drying is a modern method of processing meat products that ensures maximum preservation of nutritional value. The process involves freezing the product at ultra-low temperatures (-40°C and below), followed by removing moisture under vacuum. This avoids the thermal destruction of nutrients and preserves the natural structure of proteins. The advantage of lyophilisation is the preservation of up to 97% of vitamins and minerals, which makes it ideal for the production of dry infant formula. For instance, compared to conventional drying, this process allows for the retention of more iron, zinc and magnesium, which are critical for the development of the baby. In addition to preserving nutritional value, freeze-dried products have a long shelf life without the need for preservatives (Iakubchak *et al.*, 2024). It is also easy to use, as the products quickly regain their texture when liquid is added, making it easy to adapt them to different age groups of children. Hydrothermal processing of meat includes cooking, braising and steaming, which can significantly improve its digestibility (Borsolyuk & Verbytskyi, 2023). The basic principle behind this method is the use of hot water or steam to break down connective tissue and reduce anti-nutritional factors such as purines and glycosaminoglycans.

In the industrial production of baby food, vacuum cooking at low temperatures (sous vide) is widely used to preserve the protein structure as much as possible and prevent the loss of water-soluble vitamins. This method ensures uniform heat treatment without the formation of carcinogenic compounds, which can be observed in traditional frying or baking. Hydrothermal treatment also helps to increase the bioavailability of minerals such as calcium and phosphorus, which are vital for the growth of children's bone systems. Combining this method with a pre-enzymatic treatment (e.g. using natural enzymes) can further increase the digestibility of proteins and micronutrients. The use of non-thermal processing methods in baby food made from poultry meat is becoming increasingly important due to their ability to preserve product quality, nutritional value and safety. Among the most promising technologies are pulsed electric field (PEF), radio frequency heating (RF) and ultrasonic processing (US). These methods can significantly reduce microbiological risks and preserve bioactive compounds, which is especially important for baby food, as they minimise the formation of undesirable thermal by-products and contaminants (Pasdar *et al.,* 2024).

The PEF is one of the most effective non-thermal technologies used for the disinfection of liquid and semi-solid products, including purees and emulsions based on poultry meat. PEF is based on the generation of high-voltage pulses that cause electroporation of the cell membranes of pathogenic microorganisms, leading to their death. Compared to traditional thermal pasteurisation, PEF ensures better preservation of food proteins, vitamins and bioactive components, which is critical for ensuring optimal growth and development of infants. Studies demonstrated that the use of PEF at 35-40 kV/cm with a pulse duration of 2-4 μs effectively reduces the level of Salmonella enterica and Listeria monocytogenes in products by 5-6 log (Pasdar *et al.,* 2024). RF heating is another promising technology based on heating a product using electromagnetic radiation in the 1-300 MHz range. Compared to traditional heating, which is conducted by thermal conduction, RF creates an even temperature distribution throughout the product, which prevents local overheating and preserves the sensory characteristics of the product. In baby food made from poultry meat, RF technology can be used for rapid pasteurisation or sterilisation without significant changes in the structure of proteins and fats. At optimal parameters (40-50 MHz, 55-60°C, 5 min), RF provides a 5-log reduction in pathogenic microorganisms while maintaining the taste and microstructure of the product (Pasdar *et al.,* 2024).

US is another method that is being actively investigated for use in the production of baby food. High-frequency waves (20-100 kHz) contribute to the destruction of microbial cell membranes and improve mass transfer processes in products. Studies demonstrated that sonication with an intensity of 10-20 W/cm² significantly improves the rheological characteristics of meat emulsions and reduces the level of microbial contamination by 3-4 log. In addition, the combined use of ultrasound and antimicrobial agents, such as organic acids or essential oils, can significantly increase the efficiency of disinfection of baby food products (Pasdar *et al.,* 2024). In general, non-thermal processing technologies are a promising alternative to traditional pasteurisation and sterilisation methods in the production of baby food from poultry meat. They can achieve a high level of microbial safety while maintaining the quality, taste and nutritional value of the product. Further research in this area should address the optimisation of process parameters and the development of combined approaches to improve processing efficiency.

USE OF POULTRY PRODUCTS IN THE PRODUCTION OF BABY FORMULA AND SPECIALITY PRODUCTS

Poultry-based products, such as purees, soups and minced meat, are widely used in the diets of infants and young children. They are a source of high-value protein, iron and B vitamins, which are essential for normal growth and development (Zand *et al.,* 2012). However, studies have shown that these products may contain traces of heavy metals such as cadmium and lead, which require constant monitoring (Mielech *et al.,* 2021). Some commercially available baby meat products contain added thickeners, salt and other additives that may affect their nutritional value (Gasparre *et al.,* 2022). Therefore, consumers should carefully study the composition of products and give preference to certified organic products.

The process of producing finished meat products includes several key stages: raw material selection, heat treatment, homogenisation and packaging. An important aspect is to maintain sterility and control the temperature regime to avoid the development of pathogens (Uazhanova *et al.*, 2024). High-quality products do not contain preservatives, artificial colours or flavours, and their composition is adapted to the needs of children's bodies (Shemet & Hulai, 2023). Ready-to-eat meat products for children are usually available in the form of pasty purees, which makes them easier to eat for infants, or as canned soups and minced meat for use at a later age. A balanced combination of meat with vegetables, cereals and healthy fats is given special attention to ensure a complete diet. In addition, modern processing methods, such as high-temperature pasteurisation and sonication, can improve the microbiological safety of meat products without significant loss of nutrients (Maslin & Venter, 2017).

Eggs are an important source of protein, vitamins A, D, B12, folic acid and choline, which are essential for the cognitive development of children (Yalçin & Yalçin, 2013). Studies confirm that the choline content in eggs contributes to normal brain development and memory in early childhood. In addition, eggs contain biotin, which supports the health of the child's skin, hair and nervous system. Eggs are widely used in the production of infant milk formulas, cereals, biscuits and other complementary foods due to their high nutritional value. Despite their health benefits, eggs contain some of the most common food allergens, including ovomucoid, which remains heat-resistant even after processing. This makes eggs unsuitable for children with hypersensitivity to animal proteins (Maslin & Venter, 2017). Allergic reactions can include rashes, gastrointestinal distress, or even anaphylactic shock, which underlines the need to control their use of specialised baby food. Some studies show that products containing egg components may have elevated fluoride levels if they are made from raw materials obtained from industrial farms with high levels of water mineralisation (Opydo-Szymaczek & Opydo, 2011). Excessive fluoride intake in childhood can cause fluorosis, a disease that affects tooth enamel and bone tissue. Therefore, the quality control of egg products in baby food should be particularly strict, with a mandatory analysis of their mineral composition.

In baby foods, eggs are often used in powdered or pasteurised liquid yolk form, which reduces the risk of salmonella and other bacteria (Katiforis *et al.,* 2021). Pasteurisation, drying or freezing processes help to keep eggs safe, but they can change the structure of the protein, which affects its digestibility. For instance, during heat treatment, some B vitamins, especially riboflavin (B2) and folic acid (B9), can be partially destroyed, which requires additional vitaminisation of baby food. In baby foods, eggs are often used in powdered or pasteurised liquid yolk form, which reduces the risk of salmonella and other bacteria (Katiforis *et al.,* 2021). Pasteurisation, drying or freezing processes help to keep eggs safe, but they can change the structure of the protein, which affects its digestibility. For instance, during heat treatment, some B vitamins, especially riboflavin (B2) and folic acid (B9), can be partially destroyed, which requires additional vitaminisation of baby food. To replace egg components, vegetable emulsifiers (sunflower or soya lecithin) and alternative sources of fats and phospholipids, such as algae oil or fish oil, are used in the production of baby food. In cases of allergy to both types of protein, meat and egg, the child is prescribed specialised therapeutic mixtures based on amino acids. Thus, modern baby food production technologies adapt the composition of products to meet the individual needs of babies, providing them with safe and nutritious food.

MODERN PROCESSING METHODS AND THE SAFETY OF POULTRY AND EGG-BASED PRODUCTS IN INFANT NUTRITION

The results of this study demonstrate that the use of non-thermal methods of processing poultry meat and eggs helps to preserve the nutritional value of products, which is important for ensuring optimal baby food. In particular, the study demonstrated that a pulsed electric field and high pressure minimise the loss of proteins and amino acids, which is consistent with the findings of N. Pasdar *et al.* (2024). At the same time, this contradicts the findings of F. Javed *et al.* (2021), who identified that certain processing methods can cause the formation of undesirable compounds, in particular furan, in baby food products. An important aspect of the analysis is the safety of the final product. O.D. Garuba *et al.* (2024) contribute to the analysis of the health risks arising from heavy metal contamination, which can be critical for the safety of baby food. The findings, which address the nutritional value of poultry and eggs, highlight the importance of food safety and quality, where heavy metal research can serve as an important complement to ensuring safe food for children. This correlates with the study by A. Zergui *et al.* (2023), who noted that eggs and honey can be used to indicate environmental pollution, which potentially affects poultry products. The current study focuses on the nutritional value of eggs, in particular their importance as a source of protein for children. This highlights the importance of controlling heavy metal contamination in eggs, as such toxins can affect children's health and distort their nutritional value.

C. Bozkir *et al.* (2025) determined that most baby food products in the UK do not meet WHO model standards for nutritional composition. This fact underlines the importance of developing new food processing technologies that will improve their quality and compliance with international standards. The study also notes the importance of introducing modern methods of processing meat and eggs, such as pasteurisation, sterilisation and lyophilisation, which help to preserve their nutritional value and ensure product safety, which is important for baby food. S. Li *et al.* (2019) demonstrated that consumer confidence in the safety of baby food significantly affects product choice. Similarly, the results emphasise the importance of transparency in the production process and the need for information support on product processing methods.

The findings of this study also confirm the importance of a balanced diet for children, highlighting that poultry meat, particularly chicken and turkey, is a dietary option due to its low-fat content and high amino acid composition, which contributes to the development and health of children. This is consistent with the study by A.L. Garcia *et al.* (2020), who determined a significant increase in the share of snacks and sweet products in the UK baby food segment, which is consistent with observations on the importance of a balanced diet for children. The results obtained on the safety and quality of poultry and eggs, in particular, indicate the importance of implementing effective processing methods, such as pasteurisation, sterilisation and freeze-drying, which minimise the risk of contamination with harmful substances, particularly heavy metals. These findings confirm the conclusions of P.A. Wester (2017), which emphasise the importance of the Hazard Analysis and Preventive Control (HARPC) system in ensuring the safety of baby food. The author identified potential risks associated with heavy metal contamination, such as cadmium and lead, in poultry-based products. This indicates the need for further improvement of quality standards and their strict observance. M. Herrera *et al.* (2019) investigated the content of aflatoxins and deoxynivalenol in cereal products for infants, finding certain levels of contamination. This study also analysed the content of contaminants and found that modern processing methods, such as pasteurisation and sonication, can minimise the risk of contamination. This confirms that the problem of food contamination is an urgent one that requires further research and monitoring.

The results obtained on the nutritional value of poultry meat and eggs are confirmed in many modern studies, although they reveal some differences. For instance, J.J. Haszard *et al.* (2024) highlight the excessive sugar content of commercial infant foods, which contrasts with the findings of low fat and optimal amino acid composition of poultry meat. This highlights that poultry may be a more suitable option for infant diets than foods that are high in sugar. K.F. da Rocha *et al.* (2021) investigated the impact of ultra-processed foods on children's health, finding high levels of sugar, salt and additives. The results highlight the importance of using natural products, such as poultry and eggs, which can be an alternative to ultra-processed foods. However, in contrast to a study by K.F. da Rocha *et al.,* these results show that modern processing methods, such as freeze-drying and vacuum cooking, can preserve the nutritional value of foods without the use of harmful additives. The results on the nutritional value of poultry meat and eggs are confirmed in many modern studies, although they show some differences. For instance, the study by A. Hässig-Wegmann *et al.* (2024) analysed the attitudes of parents towards commercial infant foods in Germany and determined that parents prefer natural products because of their safety and health benefits. This correlates with the results that emphasise the importance of poultry and eggs as natural sources of protein with high biological value. However, in contrast to A. Hässig-Wegmann *et al.,* the data show that modern industrial processing methods, such as pasteurisation and sonication, can preserve the nutritional value of foods, making them safe and beneficial for children.

ENSURING THE NUTRITIONAL VALUE AND SAFETY OF BABY FOOD THROUGH PROCESSING METHODS AND PROTEIN SOURCES

The study emphasises the importance of safe processing methods, such as pasteurisation and lyophilisation, to maintain product quality and safety. This correlates with research on the need to control the microbiota in the production of foods for children, in particular, D. Stanley and Y. Bajagai (2022) focused on feed safety and gut microbiota development in poultry. This study highlighted how changes in the diet can affect the biochemical composition of meat and its safety for consumption. This is an important aspect, as it is impossible to study the nutritional value of foods without taking into account microbiological factors that can affect the nutritional properties and safety of poultry meat consumed by humans, including children (Zhurenko *et al.*, 2024). The studies by M. Çakmak *et al.* (2024) and Nurliyani *et al.* (2023) analysed the amino acid composition of eggs of different poultry species. The current results, which also emphasise the importance of eggs as a source of protein with high biological value for baby food, correlate with the findings of these authors. The important aspects highlighted in this study are the presence of all the essential amino acids in eggs, which are optimally suited for the development of children.

J. Ullberg *et al.* (2021) emphasise the importance of food safety for children, particularly given the potential for allergic reactions to proteins in poultry and eggs. The current results, regarding the optimal amino acid composition and processing methods, also highlight the importance of ensuring food safety while maintaining nutritional value. Thus, the study results are consistent with the authors' analysis, highlighting the need to consider both nutritional value and safety of foods for children, especially in the context of allergies and sensitivities to certain proteins. E. Arslan *et al.* (2022) analysed the quality of food for children in the context of fast food and traditional meals. This study compares fast food menus for children with traditional dishes, pointing to the need for a balanced diet. The results highlight the need for optimal protein and fat composition of foods for children, such as poultry and eggs. This correlates with the approach of E. Arslan *et al.,* emphasising the importance of healthy foods for children. At the same time, attention to processing methods to preserve nutritional value is an additional important aspect of achieving healthy baby food.

K.J. Moding *et al.* (2024) emphasise the importance of meat in children's diets, in particular, due to the high content of iron and zinc, which are important micronutrients for children's development. This is consistent with the results of the present study, which focuses on the importance of poultry meat as a source of protein and important amino acids for children's development. In addition, A.B. Falowo (2021) also confirms that meat is an important source of minerals such as iron and zinc, which is consistent with the findings on the nutritional value of poultry meat for infant feeding. The results on the importance of protein in children's diets are consistent with the study by H. Kim *et al.* (2020), which provides statistics on protein consumption trends among children and adolescents in the United States, confirming the importance of ensuring the right balance between different protein sources, including poultry, for optimal development. The study established that poultry meat is the optimal choice for baby food, as it is an important source of high-quality protein and amino acids necessary for growth and development. This is confirmed by A. Baviera-Puig *et al.* (2021) in an analysis of the consumption of chicken and turkey meat among consumers in Spain, considering various aspects of dietary lifestyle. The authors demonstrated that the demand for poultry meat, in particular chicken and turkey, remains high due to their benefits as low-fat, high-protein dietary products. At the same time, the food lifestyle study cited by the authors confirms the importance of educating parents about the choice of meat products for children, which also echoes the recommendations for preserving nutritional value during food processing.

S. Mehranfar *et al.* (2020) investigated the relationship between protein intake and anthropometric parameters in children, emphasising the importance of protein diets for the physical development of children, particularly those aged six years. This study reinforces the findings that highlight the importance of the amino acid composition of poultry meat as a source of protein for children. In particular, the findings on the importance of protein for the development of muscles and the nervous system in children are consistent with the results of S. Mehranfar *et al.*, confirming the positive impact of high-protein diets on children's physical growth and health. Thus, the findings are consistent with many current studies, while also revealing some differences that may be explained by specific factors such as processing methods, sources of raw materials or regional characteristics. This highlights the need for further research to better understand the impact of different factors on the quality and safety of baby food.

CONCLUSIONS

The study showed that poultry meat and eggs have high biological value, which makes them important components in the production of baby food. Chicken breast muscle contains 9,872.7 ± 465.09 mg of essential amino acids per 100 g, while turkey breast contains 115.3 mg/100 g, which confirms their effectiveness as excellent protein sources for infants and young children. Turkey meat has higher protein concentration (31.65 ± 1.63%) and lower fat content (4.55 ± 0.21%) compared to chicken (20.11 ± 0.12% and 7.60 ± 0.1%, respectively), confirming its nutritional advantages.

The total amino acid concentration of eggs is 10.50 ± 0.45 mg/100 g in turkey and 9.99 ± 0.61 mg/100 g in chicken, indicating significant nutritional value, with important amino acids accounting for nearly 43% of the total amino acids. Choline content, essential for neurodevelopment, is maintained in pasteurised and freeze-dried forms, but is reduced by excessive heat processing, highlighting the need for technical optimisation. In evaluating processing methods, freeze drying was found to preserve up to 97% of vitamins and minerals, while pulsed electric field treatment at 35-40 kV/cm reduced microbial load by 5-6 log without significant degradation of protein structure. Radiofrequency heating at 40-50 MHz and 55-60°C for 5 min resulted in a significant reduction of pathogens (by 5 log) while maintaining flavor and nutritional quality. Ultrasonic treatment at a power of 10-20 W/cm^2 reduced microbiological contamination by 3-4 log and improved the rheology of the product, making it suitable for use in infant food formulations.

Based on the results obtained, non-thermal methods should be prioritised in the preparation of poultry-based baby food because of their ability to preserve amino acid composition, vitamin content and microbiological safety. The presence of allergens in eggs and the risk of contamination with heavy metals such as cadmium and lead require strict control of raw materials and continuous monitoring throughout production. The study offers evidence-based recommendations to optimize the use of poultry and egg products in infant nutrition production with a focus on preserving nutrients and ensuring safety through modern technological methods. Subsequent research should be aimed at evaluating the preservation of nutrients when using complex processing technologies and assessing their compliance with international standards for infant nutrition.

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CONFLICT OF INTEREST

None.

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Використання м'яса птиці у виробництві високоякісних продуктів дитячого харчування: Огляд літератури

Молдір Курманахинова
Докторант
Алматинський технологічний університет
050012, вул. Толе бі, 100, м. Алмати, Республіка Казахстан
https://orcid.org/0009-0003-6544-1472
Гульшат Жаксиликова
Кандидат технічних наук, доцент
Алматинський технологічний університет
050012, вул. Толе бі, 100, м. Алмати, Республіка Казахстан
https://orcid.org/0000-0003-0563-4304
Талгат Кулажанов
Доктор технічних наук, професор
Алматинський технологічний університет
050012, вул. Толе бі, 100, м. Алмати, Республіка Казахстан
https://orcid.org/0000-0001-8984-0011
Ляззат Байболова
Доктор технічних наук, професор
Алматинський технологічний університет
050012, вул. Толе бі, 100, м. Алмати, Республіка Казахстан
https://orcid.org/0000-0002-8118-1581
Шолпан Абжанова
Кандидат технічних наук, доцент
Алматинський технологічний університет
050012, вул. Толе бі, 100, м. Алмати, Республіка Казахстан
https://orcid.org/0000-0003-3209-6855

Анотація. М'ясо птиці та яйця є важливими компонентами дитячого харчування завдяки високій біологічній цінності білка, багатому вмісту незамінних амінокислот, мінеральних речовин і вітамінів, необхідних для нормального розвитку дитячого організму. Метою цього огляду була системна оцінка харчового та технологічного потенціалу м'яса птиці та яєць для використання у виробництві високоякісного дитячого харчування. Для узагальнення даних щодо амінокислотного складу, засвоюваності та технологічних характеристик м'яса курки та індички, а також яєць птиці було проведено контент-аналіз 51 рецензованого наукового джерела, опублікованого в період з 2012 по 2024 роки. Аналіз показав, що м'ясо індички містить до 31,65 % білка і лише 4,55 % жиру, що свідчить про його цінність як джерела нежирного білка. М'язи курячої грудки містять 9 872,7 ± 465,09 мг незамінних амінокислот на 100 г, тоді як грудка індички – 115,3 мг/100 г. Яйця продемонстрували високий вміст незамінних амінокислот (понад 43 % від загального вмісту амінокислот) і були визначені як основне дієтичне джерело холіну, важливого для раннього когнітивного розвитку. В огляді також оцінювалися традиційні та сучасні методи обробки, включаючи пастеризацію, стерилізацію, ліофілізацію, гідротермічну обробку, а також нетермічні технології, такі як імпульсне електричне поле, радіочастотне нагрівання та ультразвук. Було виявлено, що сучасні методи, такі як ПЕП і ліофілізація, зберігають до 97 % вітамінів і зменшують мікробне навантаження в 5-6 разів без істотної зміни поживної цінності. Отримані результати підкреслили важливість вибору відповідних технологій переробки для збереження безпечності та поживної якості дитячого харчування на основі м'яса птиці

Ключові слова: біологічна цінність; технології переробки; амінокислотний склад; безпечність харчових продуктів; додаткові продукти харчування

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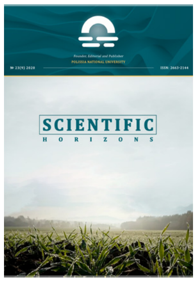

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Weather derivatives and maize yield risk in the South African agricultural market

Hendrik Weiermans

Bachelor of Commerce Honours, Postgraduate Researcher

North-West University

PO Box 1174, Vanderbijlpark Campus, Vanderbijlpark, Potchefstroom, South Africa

https://orcid.org/0009-0006-8342-2592

Daniel Mokatsanyane*

Master of Commerce, Lecturer and Researcher

North-West University

PO Box 1174, Vanderbijlpark Campus, Vanderbijlpark, Potchefstroom, South Africa

https://orcid.org/0000-0003-4074-3258

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Abstract. Climate variability significantly impacts agricultural productivity, rendering risk management tools essential for stabilisation of yields and financial returns. The study aimed to evaluate the effectiveness of weather derivatives as a risk management tool to mitigate maize yield volatility in South Africa. A quantitative research approach was employed, utilising Ordinary Least Squares (OLS) regression models to analyse the relationship between rainfall patterns and maize yields from 2000 to 2024. The study assessed historical rainfall data and maize yields in three key maize-producing regions: Bothaville, Harrismith, and Hoopstad. The study determined that rainfall variability influences maize production, although the impact differs by location. The effectiveness of weather derivatives, specifically rainfall options, was examined as a hedging strategy for farmers against unpredictable weather patterns. The study outlined two primary strategies – long-call and long-put options, which can provide financial protection against excess or insufficient rainfall. Findings indicated that while weather derivatives could mitigate financial risks associated with adverse weather conditions, challenges such as basis risk and limited market availability in South Africa remain. Additionally, results suggested that integrating rainfall options could complement traditional risk management methods such as insurance, offering farmers a more flexible approach to managing climate-related uncertainties. The study results are relevant for policymakers, financial institutions, and agricultural producers seeking alternative risk management solutions. The implementation of weather derivatives can improve resilience in the agricultural sector, ensuring more predictable financial outcomes for maize farmers facing climate uncertainty

Keywords: climate change; risk management; hedging strategies; food security; agricultural finance; commodity markets

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**Corresponding author*

INTRODUCTION

Agriculture is a crucial pillar of economic growth and food security in developing nations, including South Africa. The sector not only contributes to employment and GDP but also provides income for millions, particularly small-scale farmers. However, agricultural production is highly susceptible to climatic variability, which poses significant risks to yields and farmer incomes. Extreme weather events such as droughts and erratic rainfall patterns have intensified, increasing uncertainty in agricultural output. As maize is a staple food crop and one of the most extensively cultivated commodities in South Africa, its production is directly influenced by weather conditions. Given the unpredictability of climate patterns, there is a pressing need for effective risk management tools to mitigate production losses. One such financial instrument is weather derivatives, which can protect farmers from adverse weather conditions that impact crop yields. Despite their potential benefits, the adoption and effectiveness of weather derivatives in South Africa remain underexplored. The study aims to fill this gap by evaluating how weather derivatives can be used to manage maize yield risks in the South African agricultural market.

A. Caldwell and D. Esterhuizen (2024) investigated the effects of the El Niño phenomenon on Southern African agriculture, highlighting the severe drought conditions that disrupted food production. Their study emphasised the necessity of adaptive strategies such as financial instruments to mitigate weather-related risks. Several studies also explored the use of weather derivatives in agricultural markets. J.D. Necker (2023) analysed how weather derivatives could protect from climate-induced yield fluctuations, highlighting that these methods provide financial stability to farmers during extreme weather events. J. Ngango *et al.* (2022) assessed the role of weather-indexed insurance in sub-Saharan Africa and found that such instruments help to reduce income volatility for smallholder farmers, thereby promoting agricultural investment. Additionally, M.R. Benso (2023) compared weather derivatives to traditional insurance mechanisms and argued that derivatives offer a more flexible and efficient risk management approach, as they do not require on-site damage assessments.

Furthermore, G. Kutrolli (2021) explored different weather-related financial instruments, including temperature and rainfall derivatives, emphasising their potential applications in commodity markets. The study suggested that integration of weather derivatives into existing agricultural financial frameworks could enhance farmers' resilience to climatic shocks. S. Ramachandran *et al.* (2024) analysed the adoption challenges of weather derivatives in developing economies, noting that limited financial literacy and market accessibility hinder their widespread use. On the other spectrum, K.C. Machete *et al.* (2024) argued that increasing awareness and providing policy support could encourage greater adoption among South African farmers. Despite these insights, gaps remain in understanding the practical implementation of weather derivatives in South Africa's maize market. The limited ability of farmers to accurately forecast weather conditions and commodity yields poses a significant challenge in planning production and financial strategies. Additionally, there is insufficient information and tools available for developing effective hedging strategies against weather-induced production risks.

Therefore, the study aimed to analyse the effectiveness of weather derivatives as a risk management method to mitigate maize yield volatility in the South African agricultural market.

MATERIALS AND METHODS

In this section, the relationship between rainfall and maize yield was highlighted by statistical tests. Further analysis quantified the effects of rainfall and maize yield and determined how it affected the price of maize. Weather insurance was evaluated to determine whether it was suitable for farmers to effectively hedge against adverse weather events. Weather derivatives were examined by proposing two different strategies for rainfall options: long call, and long put, and tested their effectiveness as a hedging method for farmers. This study used a quantitative design where secondary data were used. Secondary data refers to the use of data/information gathered or created by other institutions or researchers. OLS models were used to determine the correlation between rainfall and maize yields, proposing hedging strategies for farmers based on hypothetical scenarios.

The first step in the empirical portion of this study involved gathering data from multiple sources, including Grain SA, the South African Weather Service, and the Johannesburg Stock Exchange (JSE). The historical data collection was subject to encompass rainfall, input costs, spot prices for maize, and yields for white maize farmed in the North-Western Free State from 2000 to 2024. The South African Weather Service (SAWS, 2024) provided historical rainfall records, Grain SA provided historical yields, and the JSE provided historical spot prices for maize (JSE, 2024). Grain SA also supplied historical input costs (Grain SA, 2024). The secondary data gathered were processed annually, to ensure stability in the models. OLS models were used to determine the relationship between rainfall and maize yield while considering other variables, that provided a complete picture of factors affecting maize yield. Three Ordinary Least Squares (OLS) models were estimated for three different regions in the North-Western Free State. These OLS models were used to indicate the relationship between the yields and costs involved that guide farmers in making informed decisions to hedge their crops. The equation below was the OLS model for Bothaville.

$$Y = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 3X3 + \beta 4X4 + \beta 5X5 + \epsilon, \quad (1)$$

where Y – dependent variable, in this model it was Bothaville Yield; X – independent variables; 0 – intercept (the value of Y when all X's = 0); $\beta 1$ – slope for Bothaville rainfall; $\beta 2$ – slope for Spot prices; $\beta 3$ – slope for Total Capital cost; $\beta 4$ – slope for Total cost per hectare; $\beta 5$ – slope for Cost per ton.
The equation below was the OLS model for Harrismith.

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$$\mathrm{Y} = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 3X3 + \beta 4X4 + \beta 5X5 + \epsilon, \quad (2)$$

where Y – dependent variable, in this model it was Harrismith Yield; X – independent variable; 0 – intercept (the value of Y when all X's = 0); $\beta 1$ – slope for Harrismith rainfall; $\beta 2$ – slope for Spot prices; $\beta 3$ – slope for Total Capital cost; $\beta 4$ – slope for Total cost per hectare; $\beta 5$ – slope for Cost per ton.

The equation below was the OLS model for Hoopstad.

$$\mathrm{Y} = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 3X3 + \beta 4X4 + \beta 5X5 + \epsilon, \quad (3)$$

where Y – dependent variable, in this model it was Hoopstad Yield; X – independent variable; 0 – intercept (the value of Y when all X's = 0); $\beta 1$ – slope for Hoopstad rainfall; $\beta 2$ – slope for Spot prices; $\beta 3$ – slope for Total Capital cost; $\beta 4$ – slope for Total cost per hectare; $\beta 5$ – slope for Cost per ton.

RESULTS AND DISCUSSION

This section illustrates and describes the descriptive statistics of the data used throughout the study. Descriptive statistics determined the used collected data. To provide an overview of the data used, the following descriptive statistics are analysed and discussed with the mean, median, maximum, minimum and standard deviations of all variables (Bothaville rainfall, Harrismith rainfall, Hoopstad rainfall, Bothaville yield, Harrismith yield, Hoopstad yield, Total cost, Total capital cost, Cost per ton and spot prices). Table 1 shows the descriptive statistics of all variables for the period 2000 to 2024.

***Table 1**. Descriptive statistics*

	Bothaville rainfall	Harrismith rainfall	Hoopstad rainfall	Bothaville yield ton/ha	Harrismith yield ton/ha	Hoopstad yield ton/ha	Total cost pe/ha	Total capital cost	Cost/ton	Spotprices
Mean	36.4354	44.1847	25.9847	4.5550	4.4721	4.9658	6,721.7988	770.1029	16261.2971	2213.7515
Median	33.8833	45.5750	24.7500	4.7700	4.6350	5.0850	6,710.7350	831.6400	1,204.7080	2,003.4418
Maximum	70.6000	78.1667	47.5000	6.3000	7.2300	6.9800	12,000.2100	1,075.4000	2,467.0208	4,446.6083
Minimum	0.0000	9.1200	3.7000	2.0800	2.7700	2.7300	2,206.8500	481.4500	582.2823	693.6215
Std. Dev.	19.1392	15.6521	12.1013	1.0857	1.2299	1.1125	3,003.6583	204.5236	508.1064	1,042.5540
Skewness	0.2087	-0.0561	-0.0794	-0.4425	0.3759	-0.2239	0.0493	-0.1406	0.5203	0.7476
Kurtosis	2.1255	3.0470	2.1247	2.4681	2.3881	2.2893	1.8096	1.5553	2.4364	2.7696
Jarque-Bera	0.9389	0.0148	0.7914	1.0663	0.9397	0.7056	1.4267	2.1661	1.4005	2.2888
Probability	0.6254	0.9926	0.6732	0.5868	0.6251	0.7027	0.4900	0.3386	0.4965	0.3184
Observations	24	24	24	24	24	24	24	24	24	24

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

Table 1 indicated that Bothaville has a mean of 36.44 mm of rain during the period 2000 until 2024, with a minimum (min) rainfall of 0 and a maximum (max) of 70.60 mm, and Bothaville has a high standard deviation (std dev) of 19.14. The standard deviation indicated a significant volatility in the weather patterns in Bothaville. Harrismith has a higher mean than Bothaville with 44.18 mm, a minimum of 9.12 mm, and a maximum of 78.17 mm. Harrismith's rainfall during the period 2000 to 2024 was less volatile than Bothaville, with a std dev of 15.65. Hoopstad received a mean rainfall value of 25.98 mm during the period 2009-2024 with a minimum of 3.7 mm and a maximum of 47.50 mm. The std dev for Hoopstad is 12.10 indicating less volatility in weather over the years. Possible reasons for volatility may be climate change due to the season of drought in all free states. Harrismith received the most rainfall, and Hoopstad the least rainfall on average.

Data represent the yield in Bothaville, Harrismith, and Hoopstad in tons per hectare (tt/haha). Bothaville has an average of 4.56 t/ha with a min value of 2.08 t/ha and a max value of 6.30 t/ha with a standard deviation of 1.09 indicating a moderate level of volatility. Harrismith has a lower mean yield compared to Bothaville with a mean of 4.47 t/ha and a min of 2.77 t/ha and a max of 7.23 t/ha, although the yield range is higher than Bothaville, the std dev of Harrismith is higher than 1.23, indicating higher volatility in yields over the period of 2000 until 2024. Hoopstad has the highest mean yield of 4.97 t/ha with a minimum value of 2.73 t/ha and a maximum value of 6.98 t/ha. The std dev of Hoopstad is 1.11, which indicates lower volatility compared to Harrismith and higher volatility compared to Bothaville.

In this Section, the total cost per hectare (ZAR/ha), total capital cost (ZAR), and the cost per ton (ZAR/t) are presented. The mean of the total cost per hectare is 6,721.80 ZAR/ha with a min value of 2,206.85 ZAR/ha and max value of 12,000.21 ZAR/ha and has a high volatility shown by the std dev of 3003.66. The total capital cost has a mean of 770.10 ZAR with a min of 481.45 ZAR and a max of 1,075.40 ZAR. The std dev of the total capital cost is 204.52, which indicates the medium levels of volatility experienced during the period 2000 to 2024. The cost per ton has a mean value of 1,261.30 ZAR with a min of 582.28 ZAR and a max of 2,467.02 ZAR, with a std dev of 508.11, which indicates high volatility over the period. The high volatility in cost per ton is attributable to the COVID-19 pandemic, which affected the entire economy and disrupted the supply and demand for agricultural commodities. The mean of the spot price has a value of 2,213.75 ZAR with a min of 693.62 ZAR and a max of 4,446.61 ZAR, with a std dev of 1,042.55, indicating that there was high volatility on the stock exchange for 2000 until 2024.

Most variables have skewness values close to zero, indicating a relatively symmetrical distribution. However, the price per ton and the price at the point of sale show positive skewness, suggesting a longer tail on the right side, and all variables with negative skewness indicate that it has a longer tail on the left side. Kurtosis values close to 3 indicate a normal distribution. Most variables have kurtosis values ranging around 2-3, suggesting a distribution close to normal. The Jarque Bera test for all variables indicates that the probabilities for all variables are higher than 0.05, indicating that the data do not deviate significantly from a normal distribution.

This section analysed the relationship between rainfall and maize yield. Rainfall is measured in millimetres (mm) and yields in tons per hectare. The correlation between rainfall and maize yields will be investigated for the three areas: Bothaville, Harrismith, and Hoopstad. Figure 1 illustrates how rainfall and maize yields changed from 2000 to 2024. Figure 1 illustrates that the rainfall has experienced great rainfall during the periods of 2003/04, 2005/06, and 2006/07, with the highest amount of rainfall over this period being for Harrismith, however, Harrismith experienced a downward trend in terms of rainfall in millimetres, which implies that over the sample period of 2000 to 2024 each year the amount of rainfall recorded is diminishing. Bothaville had a significant increase in rainfall from the 2008/09 season to 2011/12 and again in 2018/19 until 2022/23. Hoopstad had increased rainfall over seasons 2007/08 to 2011/12, then again in 2012/13 to 2014/15, again from 2015/16 until 2016/17, and in 2022/23 until 2023/24. Hoopstad receives on average less rainfall than Harrismith and Bothaville. The yields of all areas remain much more stable than the rainfall; this can also be determined by excessive rainfall during certain stages of the season, it does not result in higher yields. This implies that white maize will only need a certain amount of rainfall to a certain point where the excess rain will not cause the yield to increase, and a lot of excess rain can cause yield losses. This study is different from another study where J.D. Necker (2023) used three locations, namely: Bultfontein, Wesselsbron, and Hoopstad, whereas this study focused on Bothaville, Harrismith, and Hoopstad. Thus, in terms of location, only Hoopstad was used in both studies, the sample period is also different as this study used 2000 until 2024 whereas J.D. Necker (2023) used 2000 until 2020.

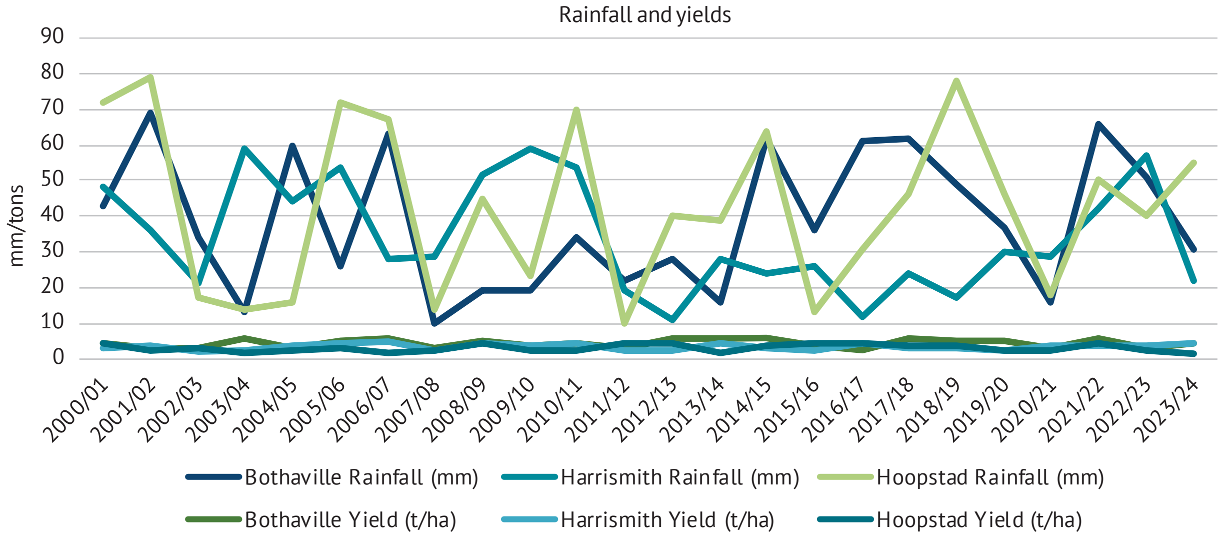

Figure 1. *Rainfall and maize productions*

Source: *compiled by authors*

Figure 2 shows a positive correlation between rainfall (mm) and yields (t/ha) for Bothaville. Figure 2 illustrates that rain will positively affect the yield in Bothaville; as rainfall increases, the yield will also increase, but only to an extent because extreme rainfall can destroy the harvest.

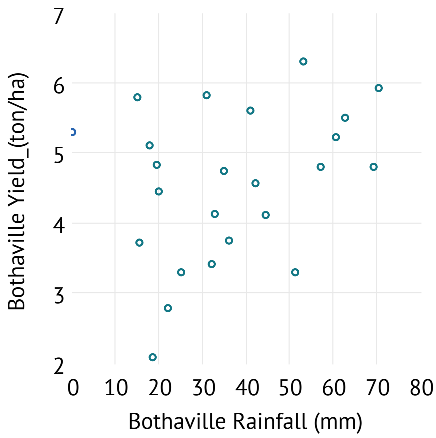

***Figure 2**. Bothaville correlation*
***Source:** compiled by authors*

Figure 3 shows a negative correlation between rainfall (mm) and yields (t/ha) for Harrismith. Figure 3 illustrates that rain will negatively affect yield in Harrismith; as rainfall increases, yield will decrease.

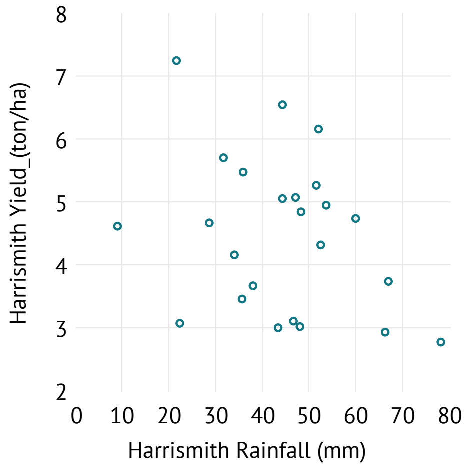

***Figure 3**. Harrismith correlation*
***Source:** compiled by authors*

Figure 4 demonstrated a positive correlation between rainfall (mm) and yields (t/ha) for Hoopstad. Figure 4 illustrates that rain will positively affect the yield in Hoopstad as rainfall increases, the yield will also increase, but only to an extent as extreme rainfall can destroy the harvest.

The previous study by J.D. Necker (2023) also graphically illustrated the correlation between rainfall and maize yields, and the results are similar in that this study also illustrated the positive correlation between rainfall and maize yields. In Table 2 the (OLS) model was implemented where the yield per ton per hectare is a dependent variable to determine how independent variables affect the yield. Interception (C) is statistically significant, which means that if all other variables are zero, the yield per hectare is 4.27 tons. Rainfall in Bothaville has a positive and small influence on yields, therefore rainfall in this model has insignificant impact on yields. This finding related to a study by T.A. Marton *et al.* (2020) which also found that rainfall has an impact on crop yield.

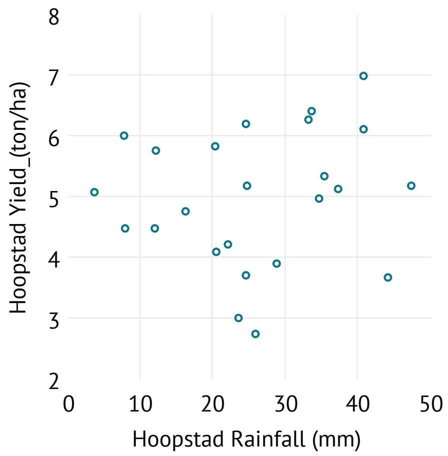

***Figure 4**. Hoopstad correlation*
***Source:** compiled by authors*

Although in Figure 2 there is a positive relationship between rainfall and yield, additional variables are needed to ensure significant effects. Spot prices have a negative impact on yields but are not significant. Total capital costs have a positive, but statistically insignificant, impact on yields. This indicates that changes in capital cost do not significantly affect yield. The total cost of each hectare has a positive and statistically significant impact on yields. This shows that higher costs per hectare are associated with higher yields. The cost per ton has a negative and statistically significant effect on the yield. This indicates that higher per-tonne costs are associated with lower yields. The squared R of this 0.4069 model indicates that this model explains 40.69% of the yield variations. Adjusted R squared of 0.2422 shows that, after adjustment, the model explained only 24.22% of the yield variation. The probability (F-statistic) of 0.0716 indicates that the overall model is statistically significant at 10%, indicating that the variables together explain the variability of the yield significantly. However, some variables, such as the total cost per hectare and the cost per ton, are statistically important, and the overall model is not suitable to effectively determine yields and additional variables, or different models are needed.

Table 2. *Bothaville OLS model*

(a)		(b)	Bothaville		
(c)	Variables	(d)	Coefficient	(e)	Probability
(f)	C	(g)	4.270846	(h)	0.000089
(i)	BOTHAVILLE_RAINFALL_MM_	(j)	0.004826	(k)	0.695158
(l)	SPOTPRICES	(m)	-0.000375	(n)	0.295484
(o)	TOTAL_CAPITAL_COST	(p)	0.000556	(q)	0.778585
(r)	TOTAL_COST__PE_HA_	(s)	0.000453	(t)	0.022964
(u)	COST__TON_	(v)	-0.002010	(w)	0.014025
(x)		(y)		(z)	
(aa)	R-squared	(bb)	0.406903		
(cc)	Adjusted R-squared	(dd)	0.242154		
(ee)	Prob(F-stat)	(ff)	0.071653		

Source: *compiled by the authors*

In Table 3 of the OLS model, the dependent variable is the Harrismith yield ton per hectare, that determined how the independent variables affect the yield. The intercept is statistically significant when all other independent variables are zero and have a value of 3.70 tons per hectare. Harrismith rainfall has a negative value and is also not significant and thus does not substantially impact the yield in the model. This finding contradicts the results of T.A. Marton *et al* (2020) which found that rainfall has little impact on yield. Spot prices have a negative, but not statistically significant, effect on yield. This indicates that changes in spot prices do not significantly affect yield. The total capital cost has a positive and statistically significant effect on the yield. This suggests that higher capital costs are associated with higher yields. The total cost per hectare has a positive but not statistically significant effect on yield. This indicates that higher costs per hectare do not significantly affect yield. The cost per ton has a negative and statistically significant effect on yield. This suggests that higher costs per ton are associated with lower yields. This model has an R-squared of 0.5188 which indicates that 51.88% of the variation in yield is explained by this model. After adjustments in variables, the adjusted R-squared has a coefficient of 0.3851 which indicates that 38.51% of the variation in yield is explained by this model. The Prob(F-stat) is 0.0146 which indicates that the model is statistically significant at a 5% level and that the model together explains the variation in the yield.

Table 3. *Harrismith OLS model*

(a)		(hh)	Harrismith		
(ii)	Variables	(jj)	Coefficient	(kk)	Probability
(ll)	C	(mm)	3.69920694	(nn)	0.0318
(oo)	HARRISMITH_RAINFALL_MM	(pp)	-0.02248777	(qq)	0.2842
(rr)	SPOTPRICES	(ss)	-0.00031579	(tt)	0.3803
(uu)	TOTAL_CAPITAL_COST	(vv)	0.00571212	(ww)	0.0067
(xx)	TOTAL_COST__PE_HA_	(yy)	0.0001005	(zz)	0.6283
(aaa)	COST__TON_	(bbb)	-0.0020684	(ccc)	0.0104
(ddd)		(eee)		(fff)	
(ggg)	R-squared	(hhh)	0.518811		
(iii)	Adjusted R-squared	(jjj)	0.385148		
(kkk)	Prob(F-stat)	(lll)	0.014595		

Source: *compiled by the authors*

In this Table 4 of the OLS model, the dependent variable is the Hoopstad yield ton per hectare, to determine how the independent variables affect the yield. The intercept is statistically significant at all levels with a coefficient of 3.95 tons per hectare when all other variables are zero. Hoopstad rainfall has a negative but insignificant effect on yield, which implies that the variation in rainfall does not significantly affect yield in this model. This finding contradicts the results of T.A. Marton *et al* (2020) which found that rainfall has little impact on yield. Spot prices have a negative, but statistically significant, impact on yields. This indicates that changes in spot prices do not have a significant impact on yields. The total capital cost has a positive and insignificant effect on the yield; therefore, variations in total capital cost do not impact the yield. Total cost per hectare has a positive and statistically significant effect on yield. This indicates that higher costs per hectare are associated with higher yields. The cost per ton has a negative and statistically significant effect on yield. This suggests that higher costs per ton are associated with lower yields. This model has an R-squared of 0.7995 which indicates that 79.95% of the variation in yield is explained by this model. The adjusted R-square of 0.7438 indicates that 74.38% of the variation in yield is explained by this model after adjusting the variables. This is a notable pattern, which the adjusted R-squared and R-squared are indicating. The Prob (F-stat) is 0.00001; thus, the model is statistically significant at all levels, and it does significantly determine the variation in yield.

***Table 4**. Hoopstad OLS model*

(mmm)		(nnn)	Hoopstad		
(ooo)	Variables	(ppp)	Coefficient	(qqq)	Probability
(rrr)	C	(sss)	3.94543737	(ttt)	0.0000
(uuu)	HOOPSTAD_RAINFALL_MM	(vvv)	-0.0014734	(www)	0.9104
(xxx)	SPOTPRICES	(yyy)	-6.383E-05	(zzz)	0.7603
(aaaa)	TOTAL_CAPITAL_COST	(bbbb)	0.00116963	(cccc)	0.3923
(dddd)	TOTAL_COST__PE_HA	(eeee)	0.00054684	(ffff)	0.0001
(gggg)	COST___TON_	(hhhh)	-0.002677	(iiii)	0.0000
(jjjj)		(kkkk)		(llll)	
(mmmm)	R-squared	(nnnn)	0.799497		
(oooo)	Adjusted R-squared	(pppp)	0.743802		
(qqqq)	Prob(F-stat)	(rrrr)	0.000010		

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

The study highlighted the importance of agriculture in South Africa by analysing food security, stability, and contribution to the GDP. The various risks associated with agriculture were highlighted, while the yield risk, specifically in the maize commodity, was defined as primary. Illustration of how yield risk varied in climate change. Weather derivatives are determined by their use as protection against weather conditions, rather than weather insurance as the only mitigation of these risks. The differences between weather insurance and weather derivatives were analysed in detail to highlight the importance of weather derivatives as a risk management method to mitigate yield risk. Rainfall options will be outlined to determine if it is financially feasible for South African farmers, as well as the ability to manage yield risk.

The agricultural sector was deemed to be complex, and a market filled with volatility (Mbatha, 2020). The agricultural industry has changed in many ways, drought and declining rainfall impacted the agricultural sector significantly causing farming profitability to drop; keeping up with the latest technology in a constantly changing sector, has costly implications for crop farmers, as they need to employ new farming techniques and improved products for them to continue producing and compete in the competitive agricultural sector (Blaker, 2021). The agriculture sector in South Africa is responsible for producing a variety of products: wine, fruits, vegetables, grains, oils, cereals, and many others. Production of all different crop types is exposed to different factors that influence production and the environment (Necker, 2023). Agriculture is particularly important in contributing to economic growth in various countries and economies around the world (World Bank, 2024). Agriculture globally contributes 4% to GDP, while in developing countries it can be more than 25% (World Bank, 2024).

According to J.D. Necker (2023), it is necessary prioritise a well-defined and healthy agricultural sector to contribute to GDP, promise food security and create employment opportunities in the agricultural sector of South Africa. During the COVID-19 pandemic, the South African economy suffered severely; however, out of all sectors, the agricultural sector contributed the most to the economy in terms of GDP growth in the last quarter of 2021 (Stats SA, 2022). This demonstrated that agriculture is crucial for a strong economy and is a key driver of economic growth, although there are many risks in the agricultural sector. Agriculture, forestry and fishing grew by 13.5% in Q1 of 2024 and contributed 0.3% to GDP growth, while the whole economy with all sectors considered indicates that in Q1 of 2024, the GDP declined by 0.1%, this highlights the significant role that agriculture plays in the economy, due to being the highest growing sector in South Africa according to statistics from Stats SA in the first quarter of 2024 (Stats SA, 2024).

Production risks are common in the agricultural sector; farmers must produce crops to comply with regulations to ensure that the commodity is safe and healthy to consume. However, it does not stop pests as they can also destroy a harvest, for instance, many birds eat the crops, and insects kill the crops (ERS, 2024). Financial risks in agriculture include the need for more funds/capital to continue their operations and are forced to borrow money, thus to repay their debt. To repay their debt, farmers need to ensure sufficient profit with the crop yields. The study by A. Polevoy *et al.* (2021) highlighted the significant impact of climate change on maize productivity in the Western Forest-Steppe of Ukraine, emphasising the increasing variability in temperature, precipitation, and extreme weather events. Their findings align with the present research, reinforcing the necessity of adapting agricultural practices to mitigate climate-related risks in maize cultivation.

The rapid growth in food demand relative to global warming transfers numerous pressures on farmers to adapt to farming practices that will result in less crop loss due to climate change, specifically drought and extreme heat conditions (Hall & Leng, 2019). A significant constraint to crop yield is drought as an adverse weather condition, since drought influences crop satisfaction to grow efficiently to provide optimal harvest, drought also has a negative effect on farmers, as irrigation is now necessary to provide the optimal water levels that will influence profit levels and the financial space that farmers are in (Hall & Leng, 2019). Variations in weather conditions and temperature changes are called climate changes. Production, together with prices in agriculture, is exposed to more risk due to increased climate change (Elum *et al.*, 2018).

The term “weather sensitivity” refers to the degree to which weather factors, such as temperature, sunshine, rainfall, frost, snowfall, wind, etc., affect sales, production, or expenses. A sector is considered weather-sensitive if weather variations affect its volatility of production. A wide range of people whose livelihoods depend on land and resources are negatively impacted by climate change Agriculture in South Africa faces a greater risk of climate and yield due to the large percentage of agriculture that depends on rainfall/irrigation (Nhamo *et al.*, 2019). The main source of income in South Africa is agriculture formally and informally. A study outlined climate change and how it affects agricultural production; analysed an increase in temperature and a decrease in rainfall and the effect of variability in weather conditions on the production of agricultural commodities. The study concluded that changes in temperature and rainfall have a negative impact on production (Abbas & Mayo, 2021; Moore, 2021). According to S. Abbas and Z.A. Mayo (2021), low levels of rainfall causes in low yields, thus climate change negatively affects the agricultural sector not only in terms of financial challenges but in terms of production yields. Weather insurance or weather derivatives are a solution to the climate change problem, which directly impacts agriculture and is a risk management tool farmers can use to hedge against yield risk/climate change.

Due to financial losses that increase from climate change and climate-related risks, weather derivatives were created and developed in 1999 in the United States to help mitigate losses incurred by adverse weather conditions. The first weather derivatives contract was initiated in 1999. Derivative products, such as options and swaps, can be traded or sold to the seller to act as weather insurance, as highlighted by J. Li *et al.* (2024). Weather derivatives can be bought and sold before maturity to ensure the profit. The seller of a weather derivative contract agrees to pay a certain amount to the buyer in exchange for a premium if a weather event occurs or the buyer suffers a financial loss related to the weather before the end of the contract. If the contract expires and damages are not caused, the seller’s profit is the premium or derivative price at the time of its creation, according to CDI (2021). The weather indices determine the derivative contract; the index of the weather derivatives acts as the underlying asset because, unlike other derivative contracts, weather derivatives do not have a spot market.

Weather insurance is more commonly used as a risk management method as it can be used to account for adverse weather events by covering a low probability of occurrence but can result in substantial losses, as explained by J. Tack and J. Yu (2021). Weather derivatives, in contrast to insurance, are suitable for high-probability occurrences that may result from weather conditions or climate change. The researchers emphasise that weather derivatives offer protection against high-probability events such as droughts and extreme heat or the opposite, with excessive rain or extreme cold. What distinguishes weather derivatives from weather insurance is the lower costs involved. Because individual yield changes are usually not related to the relevant weather variables, the use of weather derivatives still involves a large amount of risk for producers, as the risk remains with producers.

Weather derivatives also have a risk that might occur due to inaccuracies in measuring the weather. A well-known risk associated with weather derivatives is the basis risk. G. Kutrolli (2021) described basis risk as a case where the derivative price does not show the same movements as that of the underlying instrument, meaning there is no perfect correlation. Basis risk would be experienced in weather derivative contracts when there are different weather conditions or climate change at various weather measurement plants within the borders of the country. While basis risk cannot be eliminated due to inherent inaccuracies in measurement, farmers must acknowledge and accept this risk when using weather derivatives to hedge against maize yield. According to J. Li *et al.* (2003), the significant relationship between production variables and weather factors is an important motivation for participating in weather derivative contracts.

There are numerous ways in which rainfall options can be made. The most popular options that benefit farmers consist of “locking” at a certain amount of rainfall: the long call option, the long-put option, and a combination of the long call and put options, as described by G. Kutrolli (2021). A long-call option can be used to protect against adverse rainfall. For example, farmers may buy 5-month call options in case of excessive rainfall and flooding. If the average rainfall in the area is, for example, 425 mm over a certain period, farmers will protect themselves from excess rainfall. Farmers can use a long-put option if there is a need for a certain amount of rainfall. For instance, if they need rain between March and May, the farmer can buy a 3-month put option and be protected if less rain falls during that specific period. When the farmer needs rain during a specific period from January to June, a combination of put and call options can be employed. Farmers are then protected against excessive or insufficient rain during this period. With a rainfall index, the rainfall choice would have a strike rate determined by historical rainfall data for the location. J.D. Necker (2023) stated that the strike point would be established by the amount of rain, measured in millimetres, during a given period. For instance, a 6-month call option covering the period from January to June will have a 350 mm strike rate if the area's average rainfall during that time is 350 mm. The actual amount of rain that falls over that period will decide the option's payout, which is predetermined per millimetre. Therefore, weather derivatives will be beneficial in mitigating exposures to weather fluctuations.

Agriculture is central in South Africa due to promotion of economic growth in terms of GDP, alleviating poverty through employment, and ensuring food security nationwide, as noted by J.D. Necker (2024). South African agriculture sector, more specifically commercial agriculture, is the driving force in the industry with the highest growth rate, according to Stats SA (2024). Maize is not only a staple food but also the largest contributor to GDP in the farming industry. Climate risk is the main reason for the extreme level of demand for products that protect against weather conditions negatively affecting farmers. Thus, as J. Li *et al.* (2024) noted, weather derivatives are a solution against climate risks or adverse weather conditions. Similarly to any other risk management method, the most important objective of weather derivative implementations is to mitigate the volatility of income and expenses brought on by non-catastrophic weather uncertainty, as J.D. Necker (2023) states. Rainfall options will be applicable for farmers to use to protect them against yield risk, enabling adaptation and and survival in a rapidly changing environment, providing essential protection against climate change.

The study determined that rainfall and maize yield have a positive relationship in general, and the three OLS models that were done indicate that the model does explain the variables in yield. However, as Santam (2024) notes, there are several ways of insurance drought and extreme rainfall. This can be done in various ways, such as weather insurance and weather derivatives. In South Africa, Santam offers insurance against droughts, with the exception that it cannot be irrigated or damaged from plague and pests, hail, wind, or even frost. Weather insurance is commonly used to mitigate yield risk against adverse weather events with a low probability of occurring. However, as G. Kutrolli (2021) highlighted, the drawback of weather insurance is that in South Africa, there are no crop insurance offers to protect farmers against rain specifically for maize. Rainfall options are used to hedge farmers for the difference in yield lost due to excess shortage or rainfall, whereas weather insurance covers the entire harvest.

White maize is a highly liquid agricultural commodity that is traded, which causes prices to vary. G. Kutrolli (2021) stated that weather derivatives offer two main types of hedging strategies for farmers to use: futures contracts and rainfall options. Rainfall options are more relevant than futures as, with options, farmers have the right but not the obligation to act, whereas, with futures, they need to hold the contract and adhere to the conditions. Using rainfall options, farmers will benefit more compared to futures contracts due to the fact that with options, they are only subject to a loss in the premium paid. In summary, as G. Kutrolli (2021) stated, rainfall options offer greater flexibility, fewer risks, and potentially lower costs, making them more attractive for farmers who want to hedge against certain weather-related risks without the requirement of fulfilling a contract under unfavourable conditions.

The farmer can use a long call option depicted in Figure 5 to be protected against adverse rainfall, for example, farmers can buy 6-month call options at R2350, which may be a threat of excessive rainfall and flooding. If the average rainfall in the area is, for example, 425 mm over a certain period, farmers will be protected from excess rainfall. The buyer of the option has the right but not the obligation to exercise. Therefore, if the rainfall is higher than when the option was bought, the farmers will profit. And when the farmer decides to exercise the right, a significant profit will be made. When the rainfall is less, the farmer or buyer of the option will only lose the paid premium.

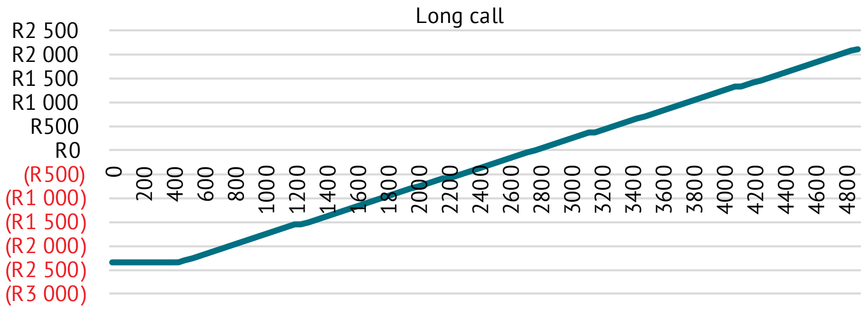

***Figure 5**. Long-call option example*

***Source:** compiled by authors*

Farmers can use a long-put option depicted in Figure 6 to be protected from rainwater shortage; for instance, if they need rain between March and May, the farmer can buy a 3-month put option and then be protected if the farmer receives less rain during the specific period.

A long-put option will provide farmers with the benefit of being able to receive less rainfall than when the option was purchased. If the rainfall levels were exceeded, only the premium will be lost otherwise with less rainfall, in the case of a drought, significant profits/benefits will be provided.

***Figure 6**. Long put option example*

***Source:** compiled by authors*

The key difference between this study and J.D. Necker (2023) is that it explores hedging strategies less thoroughly, does not price rainfall options, and instead focuses on hypothetical scenarios. The main objective of the study was to determine whether weather derivatives are effective as a risk management method to mitigate against volatility of maize yields in the South African agricultural market. Weather derivatives cover low-risk and high-probability events, whereas insurance covers high-risk and low-probability events. The rain option as the weather derivative gives farmers the option to make a profit with the unpredictability of rainfall. With the input cost increasing due to inflation and out-of-control as well as weather events, rainfall options are a tool that offers a hedge against yield risk at a lower cost. With a long-call option or long-put option, farmers can now hedge yield risk in times of drought or less-than-needed rainfall and times when there is excess rainfall damaging the harvest. Thus, rainfall options are a great strategy farmers can use to hedge against yield risk; however, in South Africa, rainfall options are not yet traded on the exchange. Therefore, South Africa's agricultural market, will not be able to use rainfall options as it is yet, but in the near future, it will be possible if weather derivatives become more popular and available.

CONCLUSIONS

The study analysed the effectiveness of weather derivatives as a risk management method for mitigating maize yield risk in South African agricultural markets. The study conducted a literature review on agricultural importance, climate change and weather derivatives as a more beneficial alternative to weather insurance together with the methodology section to illustrate the relationships between rainfall and maize yield. The methodology section used OLS models to estimate the effects of input costs and rainfall on maize yields for the respective location samples for the period of 2000 to 2024. The study highlighted that higher costs per hectare are associated with higher yields, and that rainfall does impact yield, but it is not always statistically significant. The problem that farmers face is the impossibility of accurate measurement of the rainfall, as weather stations capture the data for that location, but it is not accurate for farmers close to the area to assume they have the same since rainfall varies significantly. Therefore, farmers may need to measure their rainfall to effectively be able to estimate their yields and rainfall with highly accurate data.

The study demonstrated that it can be financially feasible for farmers to use weather derivatives as a risk management tool to mitigate the risk of maize yield. For future research opportunities, a larger location sample can be used to gather more data to determine if the results are similar to a larger study area covered. Pricing rainfall options accurately is needed to be able to provide farmers with effective strategies, and the period can be increased to incorporate more economic and geopolitical events which will affect the price. Further study should expand geographical coverage beyond the studied regions to assess broader applicability, incorporate additional variables such as temperature and soil moisture for improved model accuracy, and explore the pricing and market feasibility of rainfall derivatives in South Africa. Comparative analysis with traditional insurance models could determine the most effective risk management approach. Extending the study period to capture long-term economic and climate trends, along with simulation-based risk assessments, would provide deeper insights into maize yield volatility and hedging strategies.

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CONFLICT OF INTEREST

None.

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Погодні деривативи та ризик врожайності кукурудзи на сільськогосподарському ринку Південної Африки

Хендрік Ваєрманс
Бакалавр комерції з відзнакою, післядипломний науковий співробітник
Північно-Західний університет
Поштова скринька 1174, кампус Вандербейлпарк, м. Вандербейлпарк, Південна Африка
https://orcid.org/0009-0006-8342-2592
Даніель Мокацаняне
Магістр комерції, викладач та дослідник
Північно-Західний університет
Поштова скринька 1174, кампус Вандербейлпарк, м. Вандербейлпарк, Південна Африка
https://orcid.org/0000-0003-4074-3258

Анотація. Кліматична мінливість суттєво впливає на продуктивність сільського господарства, що зумовлює необхідність у застосуванні інструментів управління ризиками для стабілізації врожаїв та фінансових результатів. Метою цього дослідження було оцінити ефективність погодних деривативів як інструменту управління ризиками для зменшення волатильності врожайності кукурудзи в Південній Африці. Було застосовано кількісний підхід до дослідження із використанням моделей регресії найменших квадратів (OLS) для аналізу взаємозв'язку між кількістю опадів та врожайністю кукурудзи у 2000-2024 роках. Аналіз охопив історичні дані про опади та врожайність у трьох ключових регіонах вирощування кукурудзи: Ботавілл, Гаррісміт та Хупстад. Встановлено, що варіативність опадів впливає на виробництво кукурудзи, хоча інтенсивність впливу варіюється залежно від локації. Було розглянуто ефективність погодних деривативів, зокрема опціонів на дощі, як стратегії хеджування для фермерів, які стикаються з непередбачуваними погодними умовами. У дослідженні описано дві основні стратегії — опціони типу «лонг-кол» та «лонг-пут», які забезпечують фінансовий захист у разі надлишкових або недостатніх опадів. Результати засвідчили, що погодні деривативи можуть зменшити фінансові ризики, пов'язані з несприятливими погодними умовами, однак залишаються виклики, зокрема ризик невідповідності базових показників (basis risk) та обмежена доступність таких інструментів на ринку Південної Африки. Крім того, встановлено, що інтеграція опціонів на дощі може ефективно доповнити традиційні інструменти управління ризиками, зокрема аграрне страхування, надаючи фермерам більш гнучкий підхід до реагування на кліматичні ризики. Отримані результати становлять практичну цінність для органів державної влади, фінансових установ та сільськогосподарських виробників, які шукають альтернативні шляхи пом'якшення ризиків. Запровадження погодних деривативів здатне посилити стійкість аграрного сектору, забезпечуючи більш передбачувані фінансові результати для виробників кукурудзи в умовах кліматичної невизначеності

Ключові слова: зміна клімату; управління ризиками; стратегії хеджування; продовольча безпека; аграрне фінансування; товарні ринки

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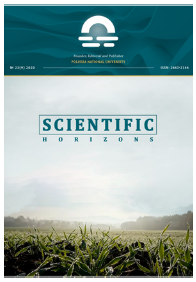

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Dairy industry as a driver of economic growth

Chinara Adamkulova*
Doctor of Econimic Sciences, Professor
Kyrgyz National University named after Jusup Balasagyn
720033, 547 Frunze Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0003-2172-7831

Kishimzhan Zhakshylykova
PhD in Pedagogical Sciences, Associate Professor
Arabaev Kyrgyz State University
720026, 51A Razzakov Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0005-8075-6565

Rustambek Asanov
PhD in Econimic Sciences, Associate Professor
Arabaev Kyrgyz State University
720026, 51A Razzakov Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0005-0166-9229

Nelli Akylbekova
Doctor of Economic Sciences, Professor
Kyrgyz National University named after Jusup Balasagyn
720033, 547 Frunze Str., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0002-8829-0094

Nuri Mambetkazieva
Doctoral Student
Kyrgyz National University named after Jusup Balasagyn
720033, 547 Frunze Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0000-6722-3936

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Abstract. The aim of the study was to examine the current state of the dairy industry in Kyrgyzstan, assess its economic impact, and identify the main challenges and opportunities for further development. The dynamics of milk production in the country in 2016-2024 were analysed, regional peculiarities of development were assessed, trends in import and export operations and their impact on the economic growth of Kyrgyzstan were identified. The factors of increasing the competitiveness of domestic dairy products are studied, and forecast estimates are made for the

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*Corresponding author

volumes of its imports and exports for the period 2025-2028. It was established that the total volume of milk production in the Kyrgyz Republic increased by 16.6%, reaching 1823 thousand tonnes in 2024, which indicates a positive trend in the development of the industry. Regional differences in production rates were found, with the highest volumes in Issyk-Kul and Jalal-Abad regions and lower volumes in the cities of Bishkek and Osh, which could be due to structural issues or changes in consumer preferences. Dairy production increased overall, especially in the ice cream, butter, cheese, and yoghurt segments. However, production of cream was volatile due to fluctuations in demand and raw material supplies. According to the SWOT analysis, Kyrgyzstan's dairy industry has its advantages: environmental friendliness, high demand and processing infrastructure, but faces low levels of technology, fragmented production and quality issues. Opportunities include export development, investment and growing demand for organic products, while threats include import competition, high costs and unstable regulation. Development requires government support, modernisation and improved product quality. The forecast for the period 2025-2028 showed positive trends for the dairy industry in the Kyrgyz Republic. The volume of imports is expected to decrease by 4% annually, indicating a strengthening of domestic production and a decrease in dependence on imported products. The obtained results contribute to the formation of scientifically based recommendations for improving the efficiency of dairy production, reducing risks and strengthening its competitive advantages

Keywords: export; domestic production; competitiveness; forecast; diversification of the product range

INTRODUCTION

The dairy industry is an important component of the agro-industrial complex, providing a wide range of food products, creating jobs and developing rural areas. It contributes to food security, economic stability and the competitiveness of the national economy. The development of the dairy sector in different countries has its own peculiarities, which are determined by the level of technological development, access to finance, government regulation and the state of the domestic and foreign markets.

Scientific research shows a significant economic impact of the dairy sector. In particular, L.J. Banda *et al.* (2021) note that the stable development of the industry has a positive impact on rural employment and increases farmers' incomes. In addition, it stimulates the development of related sectors, such as food processing, transportation, and sales, which improves the economy as a whole. Research from European countries also confirms that the stable development of the dairy sector has a favourable impact on the level of economic activity and social stability of regions (Matkovski *et al.*, 2022). A significant impact on the study of economic aspects of dairy development was made by Z. Gołaś (2020) and V. Fiorillo and B.M. Amico (2024), who analysed the effect of state support on the competitiveness of dairy products. They found that subsidies and financing programmes significantly increase the level of production efficiency and allow farmers to reduce the cost of feed and veterinary care.

At the same time, M.F. Azooz *et al.* (2020) point out the importance of technological modernisation to improve the efficiency of dairy production. According to the authors, the introduction of the latest technologies, such as process automation, the use of digital technologies to monitor animal welfare and production processes, as well as innovations in feed and veterinary medicine, can significantly improve productivity and reduce costs. A. Otunchieva *et al.* (2021) draw attention to the problem of uneven development of the dairy sector in different countries. In particular, the researchers note that countries with a high level of agricultural infrastructure development demonstrate significantly higher productivity and profitability compared to countries with insufficient investment in dairy production. This view is confirmed by N.L. Kim *et al.* (2021), who believe that the lack of modern technology and weak logistics infrastructure are the main barriers to dairy exports. The authors also emphasise that the limited availability of cooling systems and the lack of modern processing facilities lead to high milk losses during storage and transportation.

In addition, a number of researchers emphasise the existence of serious challenges in the industry. In particular, M. Hladiy and O. Prosovych (2022) analyse the impact of price volatility for milk and feed, which creates financial difficulties for producers. High price fluctuations can lead to instability in farmers' incomes and limit their ability to invest in the production process (Gutsul *et al.*, 2023). G. Koutouzidou *et al.* (2022) find that there is a problem of access to investment, which limits the ability to modernise production and adopt environmentally friendly technologies. Lack of financing also reduces the ability of enterprises to adapt to changes in market conditions and meet international product quality standards. According to a study by P. Shah *et al.* (2023), one of the key challenges to attracting investment in the dairy sector is high lending rates and the lack of government support programmes, which makes it difficult to access financial resources.

Other authors, in particular N. Clay *et al.* (2020) and M. Krstić and A. Gawel (2023), draw attention to the threat of increased competition from plant-based alternatives to dairy products, which affects the structure of market demand. In many countries, there is an increase in the popularity of plant-based milk, such as soya, almond or oat milk, which reduces the consumption of traditional dairy products (Dudarev, 2024). Studies show that the main drivers of the growth in demand for plant-based alternatives are changing consumer preferences related to healthy eating, environmental considerations and ethical issues regarding animal agriculture. According to estimates by A. Nurullaev *et al*. (2025), dairy producers need to adapt their strategies, in particular to expand their product range to include functional dairy products containing additional beneficial ingredients such as probiotics, vitamins and protein supplements.

It is worth noting that Kyrgyzstan is an example of a country where the dairy industry plays a key role in agriculture and the economy as a whole. According to D. Sakkaraeva and M. Kumashev (2024), dairy production in Kyrgyzstan is showing gradual growth, but at the same time faces a number of challenges, including low livestock productivity, limited financial resources for farm modernisation, and underdeveloped marketing infrastructure. The study by V. Kozhogulova *et al*. (2023) shows that Kyrgyzstan's dairy industry has the potential to expand exports, in particular to the Eurasian Economic Union, but needs to improve quality standards and product certification. At the same time, L. Euna and S. Mah (2024) and A. Kuipers *et al*. (2024) note that the development of the dairy sector in Central Asian countries is limited by the lack of modern technologies and weak logistics infrastructure, which are the main barriers to dairy exports.

Despite a substantial volume of research, the integration of the dairy industry into global value chains, assessment of the environmental and economic impact of the industry, and the role of government support in improving its competitiveness remain insufficiently studied. The aim of the study was to analyse the current state of the dairy industry in Kyrgyzstan, determine its economic contribution and assess the main challenges and opportunities for further development.

MATERIALS AND METHODS

The methodology for studying the development of the dairy industry in the Kyrgyz Republic was based on an integrated approach that included the collection and analysis of data for 2016-2024. Official statistical sources and publications of the National Statistical Committee of the Kyrgyz Republic (2025; n.d.), Statista (2025), the International Trade Administration (2024) and the evaluation data of the International Fund for Agricultural Development (2024), which allowed to identify key trends and structure of the country's dairy market. The dynamics of milk production in 2016-2024 was analysed. This approach made it possible to identify the main trends in the industry and assess the growth or decline in production, as well as the sustainability of the dairy industry in the Kyrgyz Republic.

To analyse the long-term changes in the country's dairy production, the method of building a linear trend was applied using the R software in the stats package and the Excel "Linear Trend" tool. This allows building a model that reflects general trends in the industry dynamics. Calculations were made on the basis of official statistical data, and the model was evaluated using the coefficient of determination (R^2), which ensured the reliability of the results. This approach made it possible not only to assess the current state of the industry, but also to make forecasts for the further development of dairy production, taking into account economic and climatic stability. Particular attention was paid to regional differences in milk production, as dairy production in the Kyrgyz Republic has a distinct territorial specificity. This approach made it possible not only to compare the dynamics of dairy production in different oblasts, but also to identify strong and weak regions. A cause-and-effect analysis was carried out, which helped identify key barriers to the industry's growth and formulate recommendations for their elimination. For a more in-depth analysis, the methods of a systematic approach to assessing exports and imports of milk and dairy products were applied, which made it possible not only to study the current market situation but also to determine the prospects for the development of the dairy industry in the country. This contributed to a comprehensive understanding of the challenges facing the industry and opportunities for its further growth.

A SWOT analysis was conducted to systematically study the characteristics of the dairy industry and its prospects. This method allowed identifying the industry's strengths and weaknesses, as well as potential opportunities and threats that could affect its development. Based on the results of the SWOT analysis, the key factors that can provide competitive advantages to the dairy sector in Kyrgyzstan were formulated, and problems that need to be addressed urgently to improve production efficiency and ensure sustainable growth of the industry were identified.

RESULTS

The results demonstrate the stable growth of the dairy industry in Kyrgyzstan. Thus, in 2016, the value of milk production was 1,524.6 million tonnes, while in 2024 it increased to 1,823 million tonnes, indicating a total increase of 299 million tonnes or 15.5% over the entire analysed period. The average annual growth rate was approximately 1.9%, which indicates the progressive development of the dairy industry (Janob, 2024). The growth rate exceeded 100% throughout the entire period, which underlines the positive dynamics. The highest growth rate was recorded in 2016 (102.9%), and the lowest in 2021 (101.9%). Starting in 2021, there was a gradual recovery in growth rates, which was reflected in an increase in this indicator to 102.8% in 2024. This data demonstrates the resilience of the sector and its ability to adapt to economic changes (Fig. 1). The trend in milk production in the Kyrgyz Republic is described by a linear function of the form y = 36.289x + 1,486.3. The linear relationship indicates a steady increase in milk production in the country. Such dynamics may be associated with improved processing technologies, an increase in the number of farms and growing demand for dairy products. At the same time, the coefficient of determination $R^2 = 0.9905$ indicates that the linear model accurately reflects the dynamics of the data, and this trend can be used for forecasting. Thus, this model is reliable for describing and forecasting milk production volumes under stable economic and climatic conditions.

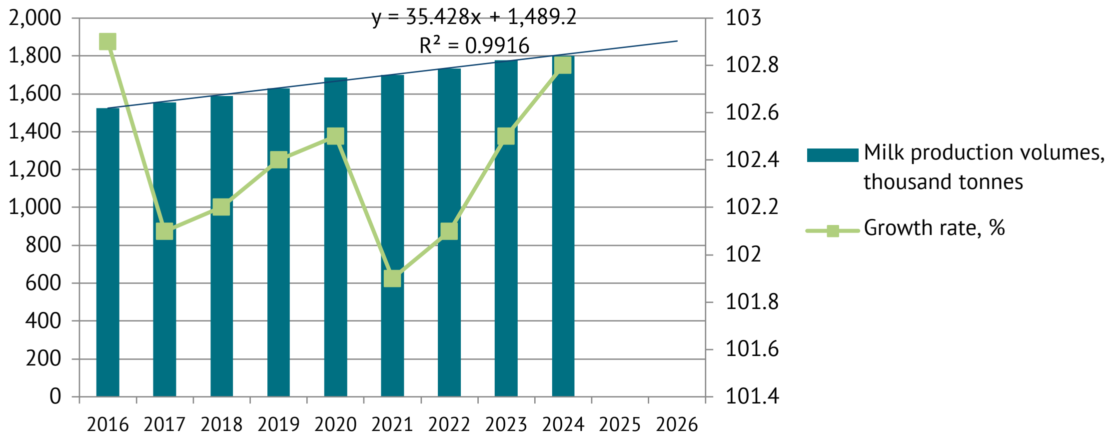

***Figure 1**. Milk production volumes and growth rate in 2016-2024*

***Source:** developed by the authors on the basis of Kyrgyzstan: A Comprehensive Overview of the Dairy Industry (2025), Kyrgyzstan Increases Milk Production by 2.6% in 2024 (2025), National Statistical Committee of the Kyrgyz Republic (n.d.), Statista (2025)*

An analysis of milk production volumes by region of the Kyrgyz Republic shows a mixed development of the industry depending on local conditions and economic factors (Fig. 2). In the Batken region, milk production showed moderate growth. However, the growth rate is lower than in most other regions; this may be due to limited infrastructure development, which hinders access to modern dairy farming technologies. In addition, the population of the region is relatively small, which may affect the level of local demand for dairy products and limit the prospects for expanding production.

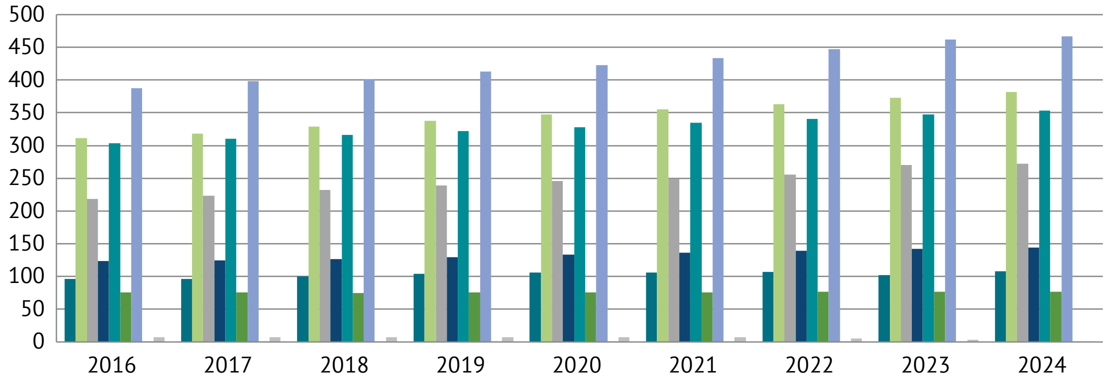

***Figure 2**. Milk production by regions of the Kyrgyz Republic, thousand tonnes*

***Source:** developed by the authors on the basis of Kyrgyzstan: A Comprehensive Overview of the Dairy Industry (2025), Kyrgyzstan Increases Milk Production by 2.6% in 2024 (2025), Statista (2025)*

The Jalal-Abad region has one of the highest milk production growth rates, which is due to the active development of the agricultural sector, including the introduction of new technologies in livestock farming, which increases productivity. The region also enjoys a convenient geographical location, which facilitates efficient sales of products both domestically and internationally. In the Issyk-Kul region, the stable growth in milk production is due to favourable natural conditions for livestock farming. Due to the availability of pastures and the tradition of livestock breeding, dairy production here has high potential. In addition, the developed tourism industry creates additional demand for dairy products, which stimulates the development of the industry. Milk production is also gradually increasing in the Naryn region. The region has traditionally specialised in livestock farming, but the introduction of new technologies is slower here due to its distance from major economic centres and limited opportunities to invest in farm modernisation, which explains the relatively slow pace of development in the industry.

The Osh region has seen a moderate increase in milk production, which may be due to the high population density. A significant part of agricultural land is used for growing grain and other crops, which limits the opportunities for expanding dairy production. In Talas region, milk production has remained virtually unchanged in recent years, as a result of structural constraints in local livestock production, low investment in the development of the dairy industry and a relatively small consumer market, which does not encourage producers to increase production. The Chui region has experienced a significant increase in milk production, which is explained by favourable agricultural conditions, well-developed infrastructure and proximity to major markets, including the capital city. Significant investments in production have also contributed to the modernisation of the industry and increased its efficiency.

The city of Osh has seen a significant decline in milk production, which is typical for urbanised areas. The decrease of the agricultural land area due to urban expansion and rising land prices make dairy farming within the city economically unviable. Consequently, milk production is gradually declining, and its main supply is provided by other regions of the country (Production of meat…, 2025). Thus, the data obtained confirm the existence of significant regional differences in milk production volumes, which are caused by various factors, such as the level of investment, natural conditions and agricultural development policies in each region. In particular, regions with higher levels of investment and favourable climatic conditions, such as Jalal-Abad, Issyk-Kul and Chui regions, have shown significant growth in milk production. In Jalal-Abad, the high rate of development is driven by the active introduction of new technologies in livestock farming and favourable natural conditions that allow for efficient marketing of products both on the domestic and foreign markets. The Issyk-Kul region, due to its natural pastures and livestock breeding traditions, ensures stable growth in milk production and also benefits from a developed tourism industry that stimulates demand for dairy products. The Chui region has enjoyed high growth rates due to investments in modernisation and infrastructure development, which has increased the efficiency of dairy production and provided easier access to markets due to its proximity to the capital. In summary, these regions have enjoyed high growth rates due to a combination of favourable natural conditions and high levels of investment, which have significantly increased dairy productivity.

An analysis of dairy production volumes in the Kyrgyz Republic for 2016-2024 showed significant changes in various product categories, reflecting both the industry's achievements and challenges. In particular, butter production increased from 3,130.6 tonnes in 2016 to 32,500 tonnes in 2024 (Butter production increased, 2025). As for the production of cream, there was an increase of 376.3% between 2016 and 2022, when the volume reached 5,101.1 tonnes. However, in 2024, there was a significant decline in cream production to 660 tonnes, indicating the instability of this market segment. This decline in cream production can be explained by several factors. The main reasons include a decrease in domestic demand due to economic difficulties, such as rising prices and reduced purchasing power, and limited supply of raw materials due to climatic conditions and disruptions in the supply chain, which contributed to the production decline. In addition, the decline in the cream market may be due to lower demand for this product and the unprofitability of its production. Therefore, the overall instability in the dairy market is the result of both economic factors and structural problems in the industry (International Trade Administration, 2024; Kyrgyzstan Increases Milk…, 2025).

At the same time, it should be noted that cheese production increased from 4,109.7 tonnes in 2016 to 15,255 tonnes in 2024 (+137.12%). Yoghurt production almost doubled between 2016 and 2024, growing by 195.4%. The highest production was achieved in 2021, when the volume was 2,499.6 tonnes, but in 2023 it dropped to 1,376.3 tonnes, indicating market saturation or a change in consumer preferences. In contrast, the ice cream segment showed significant growth, from 3,790.1 tonnes in 2016 to 11,941.3 tonnes in 2024, an increase of 315%. This is the highest growth rate among all categories, which indicates high demand for these products in both domestic and foreign markets (Kyrgyzstan: A Comprehensive…, 2025).

The dynamics of dairy imports in Kyrgyzstan showed an increase from 2016 to 2022, when imports increased from 9.4 thousand tonnes to 24.3 thousand tonnes. The growth was particularly sharp in 2021-2022. However, in 2023, imports began to decline, and in 2024 fell to 14.5 thousand tonnes, indicating a change in market conditions or increased domestic production. Dairy exports also tended to grow, reaching a peak in 2022 (54.3 thousand tonnes). However, in 2023, there was a sharp decline of almost half to 32.2 thousand tonnes. In 2024, the situation partially stabilised, and exports increased to 33.4 thousand tonnes, which may indicate that the market is adapting to new economic and trade conditions (Growth of dairy…, 2025; Kyrgyzstan's Export of…, 2025; Stanbic Bank Group, 2025). The general trend shows that until 2022, there was an active increase in both imports and exports of dairy products. However, in 2023, both indicators declined significantly, which may be due to external economic factors, government regulation policies, or changes in demand. In 2024, the market is showing signs of stabilisation, with further prospects for domestic production and exports (Kyrgyzstan reduced imports…, 2025; Osmonalieva, 2025).

According to the Ministry of Agriculture of Kyrgyzstan, in 2024, the largest exports of dairy products were milk powder (7,634 tonnes), ice cream (4,448 tonnes), and butter (1,796.9 tonnes). Most of all, Kyrgyzstan imported cheese (1,160.6 tonnes), ice cream (1,933.7 tonnes) and milk powder (534.5 tonnes) (Kyrgyzstan has exported…, 2024). The large difference between exports and imports indicates the strengthening of the Kyrgyz Republic's position in foreign dairy markets (Fig. 3).

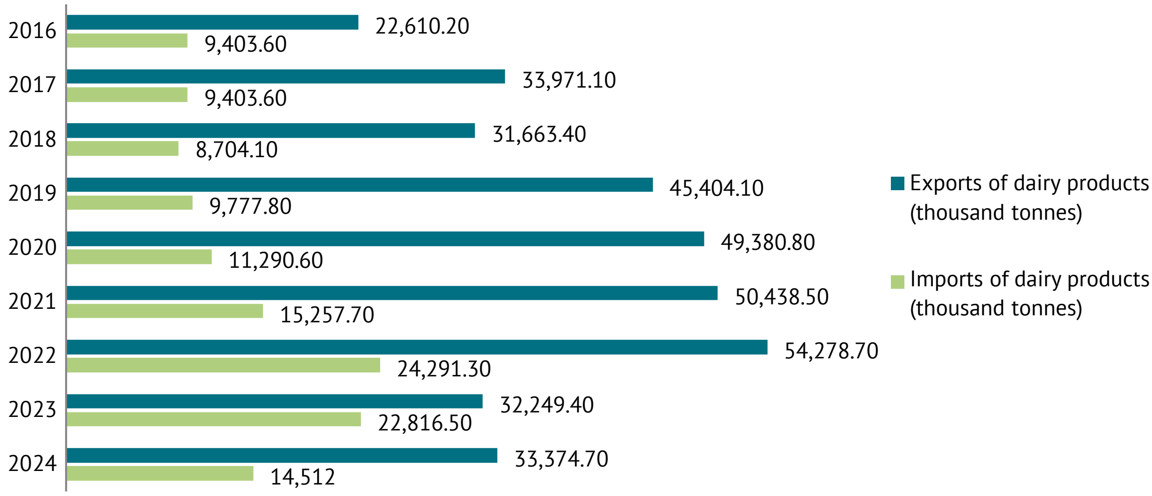

Figure 3*. Exports and imports of milk and dairy products by the Kyrgyz Republic, thousand tonnes*
Source: *developed by the authors on the basis of Kyrgyzstan's Export of Milk and Cream to Uzbekistan Increased Eightfold in Seven Months of 2024 (2024), Stanbic Bank Group (2025), Growth of dairy exports from Kyrgyzstan to EAEU countries (2025), B. Osmonalieva (2025)*

In the forecast period 2025-2028, the volume of imports shows a gradual downward trend. While in 2025 imports are expected to reach USD 12,779.3 thousand, by 2028 they will decrease to USD 11,223.2 thousand. The average annual decline is about 4%, which may be due to the strengthening of domestic production and reduced dependence on imported products. This is a positive signal that indicates the development of the domestic dairy industry and an increase in the share of local products in the domestic market. In contrast to import, export is projected to grow steadily. The volume of exports is expected to increase from 46,910 thousand USD in 2025 to 55,113.8 thousand USD in 2028 (Fig. 4).

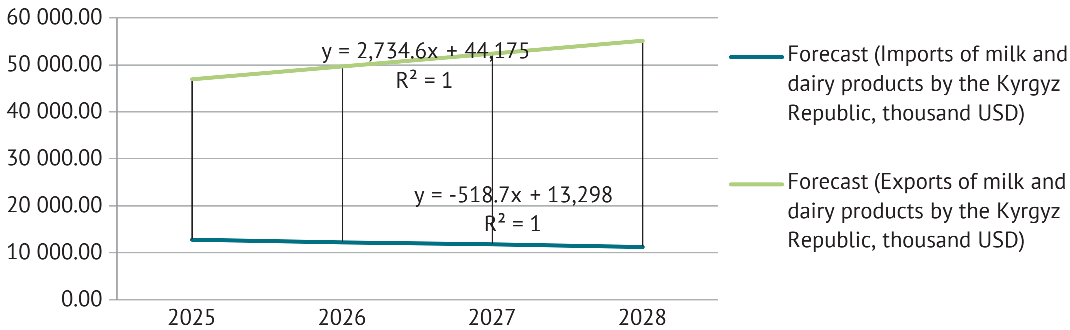

Figure 4*. Forecast estimates of imports and exports of milk and dairy products by the Kyrgyz Republic, thousand USD*
Source: *developed by the authors*

The average annual growth rate of exports is about 14.4%, which indicates the high competitiveness of Kyrgyz dairy products on international markets. The export growth is likely to be driven by increased productivity, improved product quality, and expanded access to new exports markets. The gap between exports and imports will increase in the coming years: in 2025, export will exceed import by 4 times, and in 2028 – by almost 5 times. This imbalance indicates positive changes in the industry, where exports are becoming the main driver of economic growth. Thus, Kyrgyzstan's dairy industry has great potential, but in order to realise this potential, significant challenges need to be overcome, particularly in the areas of technology, financing and production organisation. In the area of technology, the main problem is the low level of automation and the insufficient use of modern milk processing equipment. Many farms continue to use outdated livestock husbandry methods, which negatively affects productivity. The absence of effective quality control systems also creates risks in terms of product compliance with international standards.

Financial difficulties are associated with limited access to credit and investment. High interest rates on loans make it difficult to modernise production, and the lack of government support programmes does not contribute to the development of the dairy industry (CEIC, 2025). In addition, volatile milk prices and exchange rate instability make business less predictable for farmers and processors. Underdeveloped co-operation between farmers and processors leads to instability in the supply of raw materials. Lack of proper logistics complicates the transportation and storage of dairy products, leading to high losses. In addition, low staff qualifications and a shortage of veterinary and dairy specialists limit the potential for improving farm efficiency. At the same time, existing development opportunities in the domestic and foreign markets, as well as infrastructure modernisation, can help to increase the competitiveness and efficiency of the industry. The SWOT-analysis of the dairy industry in Kyrgyzstan shows that this sector has several important aspects that require attention for further development (Fig. 5). For example, the country's strengths include the fact that Kyrgyzstan has favourable conditions for the development of dairy farming due to the large area of highland pastures known as zhailau, which provide cattle with high-quality natural fodder. Due to the clean environment of the mountainous regions, dairy products produced in the country do not contain any harmful impurities, which makes them competitive. The temperate climate means that cattle can graze outdoors for most of the year, reducing feed and housing costs.

Strengths Favourable natural conditions for pasture farming. Traditions and experience in cattle breeding. Pure dairy products without harmful impurities. High domestic demand for dairy products. Developed infrastructure of dairy plants. Local cattle breeds with high milk production.	**Weaknesses** Low level of technology Disorganisation and fragmentation of production Restrictions on access to finance Problems with quality
Opportunities Development of organic dairy production Investments in infrastructure and technology Growing demand for dairy products: Export development	**Threats** Competition with imported products Climate change and environmental factors High production costs Uncertainty in law and the political situation

***Figure 5**. SWOT analysis of the dairy industry in Kyrgyzstan*

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

Kyrgyzstan's long tradition of livestock farming ensures that farmers are highly competent in caring for cattle. The country breeds that are well adapted to local environmental conditions, including Alaatai and Kazakh Whitehead, which are highly productive in the dairy sector. Strong domestic demand for dairy products drives the industry, as milk and its derivatives are an important part of the national diet. Dairy production plays a key role in the country's agriculture. Many rural households derive their main income from livestock farming, which provides employment and stability to regional economies. Kyrgyzstan also has a well-developed processing infrastructure, which allows it not only to supply the domestic market but also to export to neighbouring countries, including Kazakhstan, Uzbekistan and China.

However, there are several weaknesses that hinder the development of the industry. In particular, the low level of technology in Kyrgyzstan's dairy production significantly hinders the development of the industry. The main problem is the use of outdated or manual milking methods, as most small farmers do not have access to modern milking machines. This leads to low productivity and possible problems with milk quality, including bacterial contamination. Another problem is the structure of milk supply, as most dairies purchase raw materials from small households. This makes it difficult to control the quality and safety standards of dairy products, which makes it difficult to enter export markets. The lack of adequate cooling infrastructure at the stage of milk collection also affects its quality, as without rapid cooling, milk spoils quickly, limiting its suitability for industrial processing. In addition, the imperfect certification system and the lack of modern laboratories to test product quality are significant obstacles. Many dairy enterprises do not meet international standards, which limits their ability to export to the

EU and other countries with strict quality requirements. Insufficient implementation of automated quality control systems at dairies also leads to losses and reduced competitiveness of Kyrgyz dairy products on the international market.

Many farms do not have access to modern equipment for storing, transporting and processing milk, which leads to a decrease in production efficiency. In addition, dairy production in the country remains fragmented and unorganised, in particular due to a lack of coordination between producers, which also makes it difficult to enter new markets and improve product quality. There are also problems with access to finance due to several factors. Firstly, high interest rates on loans make them unaffordable for farmers and dairy enterprises. Secondly, the lack of effective government support programmes and subsidies limits the opportunities for investment. In addition, insufficient financial literacy and limited access to information on financing opportunities are also obstacles to the development of the sector.

To improve the situation, government support programmes should be developed, including subsidising interest rates on loans, providing grants for production modernisation and the introduction of modern technologies. It is also important to improve the financial literacy of farmers and entrepreneurs so that they can effectively use available financial instruments. The dairy industry also faces threats that may affect its further development. One of the main threats is competition from imported dairy products, which may limit opportunities for local producers. High production costs, in particular for feed and other inputs, are a major challenge for farmers. In addition, climate change, which may lead to a reduction in pasture areas, as well as instability in the political and legislative environment, may complicate the business and cause uncertainty about the future of the industry. Despite these challenges, the dairy industry has significant growth potential due to a number of opportunities. In particular, the demand for organic products is growing in international markets, which opens up prospects for exports of organic milk and dairy products (Oliynyk *et al.*, 2021). Investments in infrastructure, such as modernisation of processing facilities and milk storage systems, could significantly improve production efficiency and competitiveness of local farmers. In addition, the growing demand for dairy products in the domestic market and the development of exports create additional opportunities for expanding production volumes.

Thus, the dynamics of indicators of the dairy industry in the Kyrgyz Republic indicates a positive development trend, which indicates the growing competitiveness of dairy products in international markets. This confirms that the country's dairy products have the potential for further successful development and can become one of the key drivers of economic growth. Given the importance of this industry, strategic initiatives, including strengthening ties with external partners, export development, and investment in innovative technologies, should be implemented to ensure its sustainable development and maintain competitive advantages in the market. Increased imports of dairy products underscore the need to support local producers through preferential programmes, subsidies and other incentives that would help reduce dependence on foreign suppliers and at the same time stimulate the development of domestic production. One of the most important aspects is to create conditions for improving the quality of dairy products, which will help them to be competitive on the international market. This can be achieved by modernising production technologies, introducing the latest milking systems, and aligning quality standards and certification of dairy products with international norms.

In addition, the dairy industry is closely linked to other sectors of the economy, including agriculture, food and processing. Therefore, the development of this industry not only contributes to the improvement of economic performance, but also stimulates the growth of related sectors, creating an efficient economic model that contributes to the improvement of the country's overall economic situation. The introduction of innovations in the industry, development of marketing strategies and integration of modern processing technologies can significantly increase the added value of products, contributing to the growth of exports and reducing dependence on imports (International Fund for Agricultural Development, 2024; Kyrgyzstan: A Comprehensive…, 2025).

Given these factors, an important step for the further development of the dairy industry is its integration into the national economic development strategy, which includes measures to support small and medium-sized businesses in rural areas, stimulate investment in modern production facilities, improve infrastructure, and provide access to finance and the latest technologies. In addition, the importance of training and professional development of dairy workers should be taken into account, which will increase overall productivity and quality. In the long term, the dairy industry in Kyrgyzstan has the potential to become not only an important component of the agricultural sector, but also a significant factor of economic growth at the national level, which can happen provided that there is effective resource management, a clear strategic focus on innovation, active support for local producers and the development of competitive products. Only with a comprehensive approach and the introduction of systemic changes will the dairy industry be able to fully realise its potential and become an important component of the country's economic development.

DISCUSSION

The findings of the study on the dairy sector of the Kyrgyz Republic for the period 2016-2024 indicate positive trends but also reveal several challenges that require attention for further development. Firstly, the steady growth in milk production volumes, which increased from 1,524.6 thousand tonnes in 2016 to 1,823 thousand tonnes in 2024, demonstrates the stable development of the sector. The average annual growth rate of 1.9% suggests that the dairy industry is capable of adapting to changes in demand and economic conditions. However, despite the overall positive trend, there are significant regional disparities in growth rates, indicating uneven sectoral development across different parts of the country. In particular, regions such as Jalal-Abad and Issyk-Kul have shown substantial growth in milk production, linked to improved agricultural practices and investment. Meanwhile, Batken and Talas regions exhibit slower growth, suggesting constraints in resource access or insufficient demand for dairy products. This situation highlights the need for targeted measures to support less developed regions to ensure more balanced sectoral growth.

Secondly, the analysis of dairy product production reveals significant fluctuations in output across different categories. While some categories, such as ice cream, butter, and cheese, show impressive growth, others, like cream and yoghurt, experienced a decline in 2024, indicating market saturation or shifts in consumer preferences. This requires producers to be flexible and adapt to new conditions. Dairy trade reflects the strong position of the Kyrgyz Republic in foreign markets, as exports consistently exceed imports, underscoring the competitiveness of the country's dairy products. However, the rise in imports signals the need to enhance domestic production to meet growing demand for dairy goods (Florya *et al.*, 2023).

The study's findings demonstrate positive dynamics in the development of the Kyrgyz Republic's dairy sector, particularly in the growth of milk production volumes and export potential, indicating the industry's capacity for further expansion and its importance for economic growth. Notably, the increase in dairy product exports in international markets and reduced import dependency highlight the growing competitiveness of Kyrgyz dairy products. These results align with the conclusions of J.V. Andrei *et al.* (2022), who note that high-quality dairy products can become a key component of foreign trade. They also emphasise that a well-developed dairy sector boosts exports and generates additional foreign currency earnings, positively impacting the economy by strengthening the national currency and fostering growth in other economic sectors.

The study found that milk production in Kyrgyzstan has grown steadily, with a 15.5% increase between 2016 and 2024. This confirms a positive trend in dairy sector development, resulting from technological improvements, an increase in the number of farms, and rising demand for dairy products. Similar trends have been observed in studies by other authors, such as A. Wahid and S. Srivastava (2023), who note that in Central Asian countries, milk production growth is largely linked to infrastructure improvements and adaptation to changing climatic conditions. However, unlike authors who stress the need for government support in modernising the sector, the findings show steady growth without significant reliance on state subsidies, suggesting greater sectoral independence in Kyrgyzstan. Nevertheless, the results diverge from the conclusions of researchers studying other agricultural sectors in Kyrgyzstan, particularly A. Nurullaev *et al.* (2025), who argue that the dairy industry still faces major structural issues, including low investment levels and outdated technologies in some regions. Additionally, significant infrastructure modernisation is needed, which limits production growth potential.

It should also be noted that W. Czubak *et al.* (2021) argue that the decline in dairy production is not only due to economic difficulties but also structural shifts in the dairy market, where cream is being displaced by more popular products such as cheese and yoghurt. The scholars highlight that changing consumer preferences and unstable demand can significantly impact production. This aspect is also reflected in the study, where the drop in cream production in 2024 is linked to low demand and economic challenges in the domestic market. Forecasting based on the study's data suggests that technological modernisation could increase milk production volumes and improve quality, ensuring stability in the domestic market while strengthening the competitiveness of Kyrgyz dairy products internationally. This approach aligns with the arguments of A. Zimmermann and G. Rapsomanikis (2023), who state that innovation in dairy farming helps reduce costs and enhance sector efficiency – a key factor for sustainable development and economic resilience. Automation of farm processes, advances in animal genetics, and improved feed technologies can reduce energy, feed, water, and labour costs, thereby lowering production expenses (Alimardanova *et al.*, 2021). The study's findings can be compared to the conclusions of L. Čechura *et al.* (2021) regarding the importance of investment in dairy sector infrastructure. The scholars also emphasise the need for government support to attract private investment, particularly in improving production capacity, processing technologies, and logistics chains. The absence of such support may lead to inefficient resource allocation and reduced sector competitiveness in international markets (İsmayilov *et al.*, 2022).

Kyrgyzstan has favourable natural conditions for pasture-based livestock farming, with access to eco-friendly green fodder, which could become a key competitive advantage. This finding aligns with the research of E. Muunda *et al.* (2023) on sustainable dairy sector development, particularly in feed base improvement. E. Muunda *et al.* consider this issue critical, as feed quality and diversity affect not only milk yield but also animal health. Providing cattle with balanced, high-quality feed enhances productivity, reduces treatment costs, and improves overall herd health. Such measures are essential for stable and sustainable dairy sector development amid changing economic conditions (Bórawski *et al.*, 2020, Zhu & Oude Lansink, 2022).

According to the study, weaknesses in Kyrgyzstan's dairy sector include disorganisation and production fragmentation due to non-compliance with international quality standards and inadequate infrastructure. Similar challenges have been noted by E.C. Okolo *et al.* (2025) and N. Ökten-Kemaloglu and E. Çoruk (2024), who link them to insufficient coordination and cooperation, hindering productivity growth and sectoral development. The authors stress that the lack of collaboration between producers and processors often leads to unstable raw material supplies, limiting the ability of processing plants to meet production demands and maintain high quality. Comparable trends are observed in European countries, where, as noted by W. Poczta *et al.* (2020), and A. Parzonko and P. Bórawski (2020), urbanisation and demographic changes contribute to dairy farm fragmentation. Researchers highlight that declining rural labour and urban migration create additional challenges for cooperation and efficient sector functioning. As a result, dairy farmers face supply constraints and labour shortages, potentially reducing output and product quality.

The study also identifies risks related to declining feed quality and animal health, possibly linked to shrinking pastureland due to climate change. This aligns with the conclusions of I. Cortés-Fernández *et al.* (2023), who stress the importance of adapting the dairy sector to new climatic conditions through innovative feed production and water management methods. As noted by I. Cortés-Fernández *et al.*, government support should extend beyond financial aid to creating favourable conditions for small and medium enterprises, a key factor in successful sectoral transformation. This conclusion aligns with the study's findings on the need for cooperation between government bodies and producers.

Thus, Kyrgyzstan's dairy sector, as a key driver of economic growth, shows positive trends. However, realising its full potential requires overcoming several major challenges. Key priorities include investment in modern technology and production automation to boost efficiency and reduce costs. Infrastructure modernisation – particularly in transport, storage, and milk processing – along with support for local producers through funding programmes and market access, will be crucial for sectoral development. Additionally, adapting to shifting consumer preferences, such as rising demand for organic and natural dairy products, could enhance competitiveness in domestic and international markets. Accounting for regional factors, including raw material availability and climatic conditions, is also vital for sustainable dairy industry growth. Only a comprehensive approach to addressing these issues will fully unlock the potential of Kyrgyzstan's dairy sector.

CONCLUSIONS

Obtained results indicate a stable growth of the dairy industry in Kyrgyzstan. Milk production volumes increased by 15.5% from 2016 to 2024, indicating the progressive development of the industry. The average annual growth rate was 1.9%, which confirms a steady increase in production. The positive dynamics of milk volume growth is sustainable, as the growth rate exceeded 100% throughout the period. The highest growth rate was recorded in 2016, and the lowest in 2021. However, after that, growth rates recovered, which demonstrates the industry's ability to adapt to changes. The growth trend in milk production in Kyrgyzstan is described by a linear function, which indicates a steady increase in production. The high coefficient of determination ($R^2 = 0.9905$) confirms the accuracy of this model in describing the dynamics of milk production and its potential for predicting further changes. Such stable dynamics may be due to improved milk processing technologies, an increase in the number of farms and growing demand for dairy products. An important characteristic is the regional disparity in milk production. The highest growth rates were recorded in Issyk-Kul and Jalal-Abad regions, indicating favourable conditions for dairy farming in these regions. At the same time, there is a decline in production in the cities of Bishkek and Osh, which indicates structural problems or changes in consumer preferences.

It has been established that the production of dairy products in the Kyrgyz Republic in 2016-2024 shows a general upward trend in volumes in most categories, especially in the ice cream segment (+315%), which indicates high demand. At the same time, there is instability in the production of butter, cheese and yoghurt, which may be due to fluctuations in the supply of raw materials, changes in consumer preferences and economic factors. A SWOT analysis of the Kyrgyz dairy industry has shown that its strengths include favourable natural conditions for livestock breeding, environmentally friendly products, long-standing livestock traditions, high domestic demand and the availability of processing infrastructure. At the same time, weaknesses include low levels of technology, fragmented production, milk quality issues, lack of modern infrastructure and limited access to finance. Opportunities include growing demand for organic products, investments in modernisation and export development, while threats include competition from imports, high production costs, climate change and an unstable regulatory environment. Government support programmes are needed to develop the dairy sector, including credit subsidies, grants for modernisation, improving financial literacy of farmers and improving quality control of dairy products. Further research should focus on analysing the efficiency of existing logistics channels and distribution routes for dairy products, including exploring opportunities to reduce transportation costs and improve access of dairy products to various markets, both domestic and foreign. A limitation of the study is that data on milk and dairy production may be incomplete or insufficiently detailed, especially with regard to regional differences.

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CONFLICT OF INTEREST

None.

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Молочна галузь як драйвер економічного зростання

Чинара Адамкулова
Доктор економічних наук, професор
Киргизький національний університет імені Жусупа Баласагина
720033, вул. Фрунзе, 547, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0003-2172-7831
Кишимжан Жакшиликова
Кандидат педагогічних наук, доцент
Киргизький державний університет імені І. Арабаєва
720026, вул. Раззакова, 51А, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0005-8075-6565
Рустамбек Асанов
Кандидат економічних наук, доцент
Киргизький державний університет імені І. Арабаєва
720026, вул. Раззакова, 51А, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0005-0166-9229
Неллі Акилбекова
Доктор економічних наук, професор
Киргизький національний університет імені Жусупа Баласагина
720033, вул. Фрунзе, 547, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0002-8829-0094
Нурі Мамбетказієва
Докторант
Киргизький національний університет імені Жусупа Баласагина
720033, вул. Фрунзе, 547, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0000-6722-3936

Анотація. Метою дослідження було вивчення поточного стану молочної галузі Киргизстану, оцінка її впливу на економіку країни, визначення основних викликів та можливостей для подальшого розвитку. Проаналізовано динаміку виробництва молока в країні в 2016-2024 рр., оцінено регіональні особливості розвитку, виявлено тенденції в імпортно-експортних операціях та їх вплив на економічне зростання Киргизстану. Досліджено фактори підвищення конкурентоспроможності вітчизняної молочної продукції та зроблено прогнозні оцінки обсягів її імпорту та експорту на період 2025-2028 рр. Встановлено, що загальний обсяг виробництва молока в Киргизькій Республіці збільшився на 16,6 %, досягнувши 1823 тис. тонн у 2024 році, що свідчить про позитивну тенденцію розвитку галузі. Були виявлені регіональні відмінності в темпах виробництва, з найвищими обсягами в Іссик-Кульській та Джалал-Абадській областях та нижчими обсягами в містах Бішкек та Ош, що може бути пов'язано зі структурними проблемами або змінами в уподобаннях споживачів. Виробництво молочних продуктів загалом зросло, особливо в сегментах морозива, масла, сиру та йогуртів. Однак виробництво вершків було нестабільним через коливання попиту та поставок сировини. Згідно з SWOT-аналізом, молочна промисловість Киргизстану має свої переваги: екологічність, високий попит і переробну інфраструктуру, але стикається з низьким рівнем технологій, фрагментарним виробництвом і проблемами якості. Можливості включають розвиток експорту, інвестиції та зростаючий попит на органічні продукти, тоді як загрози включають конкуренцію з боку імпорту, високі витрати та нестабільне регулювання. Розвиток вимагає державної підтримки, модернізації та підвищення якості продукції. Прогноз на період 2025-2028 рр. показав позитивні тенденції для молочної галузі в Киргизькій Республіці. Очікується, що обсяг імпорту зменшуватиметься на 4 % щорічно, що свідчить про зміцнення внутрішнього виробництва та зменшення залежності від імпортної продукції. Отримані результати сприяють формуванню науково обґрунтованих рекомендацій щодо підвищення ефективності молочного виробництва, зниження ризиків та посилення його конкурентних переваг

Ключові слова: імпорт; експорт; внутрішнє виробництво; конкурентоспроможність; прогноз; диверсифікація асортименту

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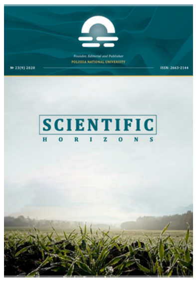

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Comparative analysis of the cherry industry in Kyrgyzstan and Chile and market development strategies in China

Miaolong Zhou
Doctoral Student
Kyrgyz National University named after Jusup Balasagyn
720033, 547 Frunze Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0001-8707-1500

Dzhapar Alybaev*
Doctor of Economic Sciences, Professor
Kyrgyz National University named after Jusup Balasagyn
720033, 547 Frunze Str., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0003-0931-9846

Guanying Xu
Doctoral Student
Kyrgyz National University named after Jusup Balasagyn
720033, 547 Frunze Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0008-6627-1782

Haohe Yuan
Doctoral Student
Kyrgyz National University named after Jusup Balasagyn
720033, 547 Frunze Str., Bishkek, Kyrgyz Republic

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Abstract. The purpose of the study was to conduct a comparative analysis of cherry production and exports in Kyrgyzstan and Chile, assess their competitiveness in the global market, and identify key barriers and opportunities for expanding exports to China. The analysis was based on statistics on cherry production and exports, an estimate of logistics costs, customs procedures, and government support, as well as a calculation of the share of exports and the growth rate of supplies to the Chinese market. The results showed substantial differences between Kyrgyzstan and Chile in the development of the cherry industry. In 2024, cherry production in Chile reached 641 thousand tonnes, while in Kyrgyzstan, this figure is only 4.12 thousand tonnes, which reflects a substantial difference in the scale of production and the level of technological development. Chile provided 92.36% of Chinese cherry imports using efficient trade mechanisms, optimised logistics, and government incentives, while

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**Corresponding author*

Kyrgyzstan's exports remain unstable and limited. High logistics costs in Kyrgyzstan (USD 900 per tonne) compared to Chile (USD 500 per tonne) reduced the competitiveness of products. The lack of modern transport corridors, storage facilities, and proper refrigeration equipment substantially complicate stable exports to China, leading to high losses of products during transportation. The analysis also showed that strict sanitary requirements, certification, and phytosanitary control created additional barriers for Kyrgyz products to enter the international market, which requires strategic changes in public policy and attracting investment in the modernisation of the industry. The study demonstrated that the competitiveness of cherry exporters is determined by the level of logistics infrastructure, the efficiency of trade mechanisms, and compliance with international requirements, which indicates the need to optimise logistics, create refrigerated warehouses, and simplify customs clearance to increase exports from Kyrgyzstan

Keywords: competitiveness; logistics; sanitary requirements; trade barriers; customs clearance; quality control

INTRODUCTION

In the current context of globalisation, agricultural markets are showing increasing integration, which creates both new opportunities and challenges for producing countries. Cherry is one of the most popular fruit and berry crops on the world market, in particular, in China, which remains the largest consumer of this product. In 2024, the total volume of cherry imports to China reached 641 thousand tonnes, of which 92.36% accounted for Chile, which retains its leading position in this segment. Therewith, the potential of other producing countries, particularly Kyrgyzstan, remains unrealised: the share of Kyrgyz cherries in the Chinese market was only 0.4%, which indicates substantial barriers to its export (Shu, 2024). The Food and Agriculture Organisation (n.d.) emphasises the importance of diversifying suppliers of agricultural products to reduce food risks and support small farms. The development of International Cherry trade through technological modernisation, logistics improvement, and quality improvement has become a priority task of the industry. According to the Food and Agriculture Organisation, global crop production continued to grow in 2024, which indicates a stable demand for fruit and berry products. Cherry production also increased, especially in exporting countries, in particular, Chile, the United States, Canada, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkey, which confirms the high level of its consumption on the international market.

International cherry market research confirms that successful exports largely depend on efficient logistics, access to foreign markets, and adaptation of agricultural technologies. Improved customs clearance and the development of transport infrastructure contributed to the growth of Chile's share in China, which was analysed in detail by X. Shu (2024), who stressed the crucial role of optimising logistics processes in international trade. Thereby, the competitiveness of developing countries in the field of cherry exports was examined by J. Ninaquispe *et al.* (2024), emphasising that success in the global market is determined not only by production volumes but also by the ability of countries to build effective export strategies. The impact of agroclimatic changes on yield and the need for technological modernisation have become the main focus of the paper of D. Bali *et al.* (2022), who noted the importance of adapting cultivation to climate change. An equally substantial aspect is the potential of Central Asia in the cultivation of fruit crops, which was considered in the study by B. Vinceti *et al.* (2022), which stressed the role of traditional gardens in preserving biodiversity and the possibilities of integrating the region into the global market.

The scientific papers also emphasise the importance of organising production, developing export strategies, and using technological innovations in the field of cherry cultivation. Authors B. Gonçalves *et al.* (2021) investigated the agronomic features of sweet cherry cultivation, emphasising the importance of introducing modern breeding methods to improve fruit quality and increase yield. The effectiveness of such approaches is particularly critical for countries seeking to gain a foothold in the international market, which is confirmed by T. Qureshi (2022), analysing the potential for exporting horticultural products from Central Asia to China. The author draws attention to the need to increase competitiveness by improving cultivation methods and improving the conditions for post-harvest processing. N. Kemaloğlu and E. Çoruk (2024) examine the organisational aspects of agricultural trade in Kyrgyzstan, pointing out the fragmentation of production and poor coordination between producers, which makes it difficult to enter foreign markets.

Another important factor in the development of the cherry sector is skilful resource management and optimisation of growing processes. Researchers T. Montenegro-Romero *et al.* (2022) investigated the dynamics of fruit production in Chile, paying attention to the need for effective land and water management. A similar approach is also relevant for global production, which is confirmed by S. Baicu *et al.* (2023), analysing trends in global cherry production growth. The study highlights the role of technological progress in improving industry efficiency. In turn, C. Stone *et al.* (2023) draws focus to the production challenges of growing cherries in protected systems, underscoring that the use of modern agricultural technologies can substantially improve the quality of products and reduce the risks associated with changing growing conditions.

Despite its substantial natural potential, Kyrgyzstan's cherry industry remained underdeveloped due to weak production organisation, limited storage capacity, lack of investment in technology modernisation, and insufficient integration into global logistics networks (Sakkaraeva & Kumashev, 2024). The lack of specialised transport corridors and modern storage systems limited export opportunities, while the competitiveness of the industry was studied fragmentally, mainly in the context of the domestic market and certain aspects of product marketing. The study aimed to assess the production and marketing characteristics of the cherry market in Kyrgyzstan and Chile, identify key restrictions for its development, and justify measures to expand exports to China. The following tasks were solved to achieve this goal: to analyse the factors that influenced the formation of the export potential of the cherry industry in Kyrgyzstan and Chile, to determine the role of infrastructure, logistics, and trade barriers in the access of Kyrgyz products to the Chinese market, as well as to assess the possibilities of adapting successful practices of Chile to strengthen Kyrgyzstan's position in international trade.

MATERIALS AND METHODS

The study analysed data on the production, export, and competitiveness of cherries in Kyrgyzstan and Chile, and trends in the consumption of these products in China. In addition to these countries, the experience of the United States, Canada, Turkey, Uzbekistan, and Tajikistan as important players in the cherry market was considered to compare and evaluate global trends. The analysis of import demand in China considered the influence of other suppliers, including Australia, Argentina, Serbia, Moldova, Iran, Italy, South Korea, and Pakistan, which also export cherries to the Asian region and have different levels of integration into international trade.

Official Food and Agriculture Organisation (n.d.), as well as open databases on cherry exports. Data from customs statistics of the General Administration of Customs of China (n.d.), reports of the China Chamber of Commerce for Import and Export of Foodstuffs, Native Produce and Animal By-products (n.d.), and market research that analysed changes in demand for imported Cherries to assess market trends in China. The study used various methods to analyse the development of the cherry sector in Kyrgyzstan and Chile, in particular, economic and statistical analysis, which was used to assess the dynamics of cherry production, exports, and market share in the two countries, enabling the identification of the main trends and changes in the market structure. The market share was calculated, determined by the formula to determine the competitiveness of the products of the studied countries in the Chinese market (1):

$$\mathrm{Mi} = \left(\frac{\mathrm{Xi}}{\mathrm{Xw}}\right) \times 100\%, \tag{1}$$

where M_i – market share of a particular country; X_i – volume of cherry exports from the country i; X_w – total volume of cherry imports to China.

In addition, to assess changes in the export structure, the calculation of export growth rates was used, which allowed tracing the dynamics of changes in supplies in different years. The growth rate was calculated using the formula (2):

$$\mathrm{G} = \left(\frac{\mathrm{Xt}-\mathrm{Xt}-1}{\mathrm{Xt}-1}\right) \times 100\%, \tag{2}$$

where G – export growth rate; X_t – export volume in the current year; X_{t-1} – export volume in the previous year.

The comparative analysis allowed comparing production processes, marketing strategies, logistics capabilities, and government support, which revealed critical advantages of Chile, in particular, a developed infrastructure and stable trade relations. Thereby, it is established that Kyrgyzstan faces barriers related to the Coordination of producers, the supply of products and an insufficient level of logistics. Induction allowed identifying the patterns of global cherry trade, in particular, simplified access to the Chinese market, stability of supply volumes, and compliance with the requirements of importers as key success factors. The deduction was used to assess restrictions that reduce Kyrgyzstan's competitiveness, including weak logistics, small production volumes, and insufficient integration into international trade networks. The synthesis of the results obtained enabled the integration of various approaches and formed a comprehensive idea of the prospects for exporting Kyrgyz cherries. Summarising the results allowed developing recommendations for improving logistics, improving product quality, adapting to Chinese requirements, and improving the organisational efficiency of manufacturers. Systematisation of the final data allowed for identifying essential areas of Industry Development and determining strategic measures that can help increase cherry exports from Kyrgyzstan to the international market.

RESULTS

Dynamics of cherry production and exports in Kyrgyzstan and Chile. Cherry production and exports are important segments of the agricultural sector in Kyrgyzstan and Chile, but their development differs substantially in scale, structure, and integration into World Trade. Chile is the world's leading exporter of cherries, especially to the Chinese market, due to effective government policies, substantial investment in production, and a developed infrastructure (Bamber & Fernandez-Stark, 2016). Therewith, Kyrgyzstan, having favourable natural and climatic conditions, occupies a small share in the global cherry sector due to low yields, a weak logistics system, and insufficient state support (Shaiyldaeva *et al.*, 2024).

Chile shows a steady increase in cherry production, which is a consequence of the use of modern agricultural technologies, mechanised harvesting systems, and effective water resources management. In 2022, production volumes amounted to 397 thousand tonnes, in 2023 – 414 thousand tonnes, and in 2024 reached 641 thousand tonnes, which confirms an increase in production areas and a growing focus on exports. High yields in Chile are the result of the use of breeding varieties, drip irrigation systems, and effective management of phytosanitary risks (Tudela *et al.*, 2023). However, Kyrgyzstan does not show such positive dynamics. In 2022, cherry production amounted to 6.4 thousand tonnes, in 2023 – 4.1 thousand tonnes, and in 2024 – 4.12 thousand tonnes, which indicates the absence of substantial development of the sector (Table 1). The main limitations are the small area of plantings, the low level of mechanisation of production and the lack of investment in the modernisation of farms (Shaiyldaeva *et al.*, 2024).

***Table 1**. Comparison of cherry production in Kyrgyzstan and Chile (2022-2024)*

Year	Kyrgyzstan (thousand tonnes)	Chile (thousand tonnes)
2022	6.4	397
2023	4.1	414
2024	4.12	641

***Source:** compiled by the authors based on P. Bamber and K. Fernandez-Stark (2016), A.K. Shaiyldaeva et al. (2024)*

The data indicate a substantial difference in the scale of production between countries. Chile shows a steady increase in production volumes, which in 2024 reached 641 thousand tonnes, while Kyrgyzstan does not show dynamic development, remaining at the level of 4.12 thousand tonnes. This indicates the high efficiency of the Chilean agricultural sector, due to state support and active investment, while in Kyrgyzstan, the lack of infrastructure and low level of funding do not allow for a substantial increase in production capacity. Chile is the world's leading cherry exporter, and its share in the Chinese market continues to grow (Table 2). The main success factors of Chile are optimised logistics processes, strategic agreements with China, and a well-developed product certification system. The growth rate of Chile's total exports and the growth rate of cherry exports to China were determined using formula (2).

***Table 2**. Dynamics of cherry exports from Chile (2022-2024)*

Year	Total exports of Chile (thousand tonnes)	Export growth rate (%)	Export volumes to China (thousand tonnes)	Export growth rate to China (%)
2022	397	-	358	-
2023	414	4.28%	377	5.31%
2024	641	54.83%	592	56.98%

***Source:** compiled by the authors based on General Administration of Customs of China (n.d.), China Chamber of Commerce for Import and Export of Foodstuffs, Native Produce and Animal By-products (n.d.)*

The data shows a substantial increase in Chile's exports to China. In 2024, shipments to China increased by 56.98%, as a result of increased trade cooperation between the two countries, high confidence in Chilean products, and improved logistics processes. Kyrgyzstan, on the other hand, shows unstable exports, which largely depend on logistical constraints and unpredictable changes in demand. In 2022, due to the COVID-19 pandemic, it was completely stopped (Table 3). Data that allow estimating the country's contribution to the total volume of cherry supplies to the Chinese market were calculated using Formula (1).

***Table 3**. Cherry exports from Kyrgyzstan and Chile to China (2022-2024)*

Year	Kyrgyzstan (tonnes)	Chile (thousand tonnes)	Chile's share in China's imports (%)
2022	0	358	90.18%
2023	12.06	377	91.06%
2024	1.65	592	92.36%

***Source:** compiled by the authors based on General Administration of Customs of China (n.d.), China Chamber of Commerce for Import and Export of Foodstuffs, Native Produce and Animal By-products (n.d.)*

As can be seen from the table, Chile continues to strengthen its position in the Chinese market, while Kyrgyzstan loses even small export volumes. This may indicate problems with product certification, non-compliance with sanitary standards, and limited transportation options. The impact of factors such as low yields, high transportation costs, and lack of logistics capacity reduces the competitiveness of Kyrgyz Cherries (Table 4). The data was calculated using Formula (2).

***Table 4**. Dynamics of cherry exports from Kyrgyzstan (2022-2024)*

Year	Total export of Kyrgyzstan (thousand tonnes)	Export growth rate (%)	Export volumes to China (thousand tonnes)	Export growth rate to China (%)
2022	0.64	-	0	-
2023	0.41	-35.94%	0.01206	-
2024	0.412	0.49%	0.00165	-86.32%

***Source:** compiled by the authors based on General Administration of Customs of China (n.d.), China Chamber of Commerce for Import and Export of Foodstuffs, Native Produce and Animal By-products (n.d.)*

These results confirm the need to strengthen government support, investment in logistics, and conclude long-term trade agreements to strengthen Kyrgyzstan's position in the Chinese market. In addition, Chile has a well-developed sea transportation system that minimises product losses during transportation. The Cherry Express programme reduces delivery time from 30 to 22 days, ensuring stable deliveries during peak demand. The use of a cold chain allows maintaining product quality and reducing the risk of spoilage. Kyrgyzstan faces serious logistical difficulties. The limited number of modern transport corridors, the lack of specialised warehouses with cooling systems, and high transportation costs make cherry exports economically unprofitable. Customs barriers related to China's sanitary and phytosanitary requirements substantially complicate the stable entry of Kyrgyz products into the Chinese market.

Chile actively supports cherry producers through subsidies, investment in infrastructure development, and export promotion. These measures allow farmers to introduce modern technologies, expand production areas, and improve product quality. In Kyrgyzstan, the situation is radically different. The lack of state support, low level of investment attraction, and weak integration into world markets lead to a lack of dynamic development of the industry. Solving these problems requires a comprehensive approach, including expanding investment in logistics, signing new trade agreements, and introducing modern agricultural technologies (Bujdosó & Hrotkó, 2017; Yunusov & Demirsoy, 2024). Chile is the main supplier of cherries, which ensures its stable growth in production and exports due to government support, investment in logistics, and modern agricultural technologies. Kyrgyzstan, although it has the potential to grow cherries, faces serious constraints, including insufficient infrastructure development, weak government support, and unstable export flows. It is necessary to invest in the modernisation of production facilities, improve logistics chains, and conclude new trade agreements to increase the competitiveness of Kyrgyzstan, which will increase export volumes and strengthen the country's position in the international market.

Global cherry production and sales: Trends and market leaders. The global cherry market is growing dynamically, covering a wide range of producing countries, including Turkey, the United States, Chile, Uzbekistan, Tajikistan, Canada, Kyrgyzstan, Australia, and Argentina. The main factors for the development of the industry are favourable agroclimatic conditions, access to international markets, modernisation of production technologies and state support (Arısoy *et al.*, 2023; Cramer, 2023). Countries with developed logistics and stable trade relations show more stable export indicators (Table 5).

***Table 5**. Cherry production in different countries of the world (thousand tonnes, 2024)*

Country	Production (thousand tonnes)	Main export markets
Turkey	800	EU, Middle East
USA	435	Canada, EU, China
Chile	641	China, USA, Europe
Uzbekistan	240	Commonwealth of Independent States, China
Tajikistan	35	Commonwealth of Independent States, China
Canada	60	USA, China
Kyrgyzstan	4.12	China, Kazakhstan
Australia	85	China, Southeast Asia, EU
Argentina	30	China, Brazil

***Source:** compiled by the authors based on H. Arısoy et al. (2023), C. Cramer (2023), G.A. Lang (2017)*

Turkey is the largest producer, providing more than 800 thousand tonnes annually, which is explained by the favourable climate and developed agricultural technologies. A substantial share of products is exported to Europe and the Middle East, but dependence on weather conditions and the need to modernise processing facilities remain the main challenges. The United States, one of the largest exporters, produces about 435 thousand tonnes per year, with the main share consumed in the domestic market. American manufacturers ensure stable deliveries to Europe and China, where their products are in high demand due to strict quality standards. Chile is the world's leading exporter of cherries, supplying 641 thousand tonnes annually, of which more than 90% goes to China. A high level of mechanisation, modern logistics systems, and effective state support programmes ensure stable export growth. The seasonal advantage allows Chile to occupy key positions in the Chinese market during the period of cherry shortage in the Northern Hemisphere. Uzbekistan is actively expanding production, focusing on the Commonwealth of Independent States and Chinese markets. With state support programmes, modernisation of irrigation systems and the introduction of high-yielding varieties, the country is strengthening its position in international trade.

Other countries, such as Tajikistan, Canada, and Kyrgyzstan, have substantially lower production volumes. Tajikistan produces 35 thousand tonnes of cherries per year, but weak infrastructure and unstable exports limit the development opportunities of the industry. Canada focuses on exports to the United States and China, but its production (60 thousand tonnes) is constrained by harsh climatic conditions. Kyrgyzstan remains the smallest producer among the analysed countries with an indicator of 4.12 thousand tonnes per year, which is due to weak investment, logistics restrictions, and difficulties in entering international markets. Australia takes advantage of seasonality, which allows it to export cherries to China during periods of low supply from the Northern Hemisphere. In addition to the world's leading producers, a number of countries are increasing their export potential, adapting production processes to global market needs (Kim *et al.*, 2025). Serbia is the main European producer of sour cherries, a substantial part of which is exported to the EU. The main problems are dependence on weather conditions and yield fluctuations (Kljajić *et al.*, 2024). Moldova is also focused on processing and exporting cherries to the EU and Commonwealth of Independent States, but the development of the industry is hindered by a lack of investment and limited access to modern technologies (Ceban & Lucaşenco, 2023). Iran is experiencing an increase in production due to government programmes to support horticulture and expand irrigation systems, which contributes to an increase in exports to the Persian Gulf and Europe, but competition from Turkey and the United States remains substantial (Kazempour Kahriz *et al.*, 2025).

Italy is a traditional cherry producer in Europe, focusing on the domestic market and exporting to EU countries. Despite the stable level of production, Italian farmers face competition from cheaper suppliers. The strategy of exporters is aimed at expanding their presence in the EU countries through marketing campaigns and focusing on premium product quality (Della Casa *et al.*, 2019). Argentina takes advantage of its seasonal advantage by supplying cherries to the world market during a period of product shortages in the Northern Hemisphere. The main buyer of Argentine cherries is China, which buys considerable volumes in winter (Jaureguiberry & Tappata, 2022). South Korea is a small producer but a large-scale importer, focusing on supplies from Chile and the United States. Consumers in Korea have high requirements for the quality and environmental standards of products, which forces exporters to comply with strict labelling and quality control requirements (Shin & Ji, 2021). Pakistan has considerable potential for the development of the cherry sector, but a lack of investment, weak infrastructure, and limited logistics opportunities do not allow this potential to be fully realised. Further development of the industry will depend on improving transport corridors, attracting investors, and adapting to international certification standards (Spies, 2023).

The global cherry market continues to expand, concentrating in countries with favourable agroclimatic conditions and access to major markets. Turkey, the United States, and Chile remain the largest producers and exporters, while countries with less developed logistics infrastructures, such as Kyrgyzstan and Pakistan, face difficulties in entering global markets. China remains the main driver of demand, encouraging manufacturers to adopt the latest technologies, improve logistics, and meet strict quality standards.

Cherry demand in China and its impact on the international market. China is the world's largest importer of cherries, which determines global trends in the production and trade of this product. The structure of consumption in the Chinese market differs substantially from other countries and is characterised by seasonality of demand, the influence of consumer preferences, and the specific features of customs regulation. The main suppliers to the Chinese market are Chile, the United States, Australia, and Uzbekistan, with Chile occupying the dominant share of imports (Lei, 2018). The Chinese cherry market shows clearly defined seasonal dynamics, which affects pricing and import volumes. The main period of increased demand occurs during the winter months, especially during the Chinese New Year period, when cherries are associated with well-being and prosperity. This creates a high demand for premium products supplied by Chile, taking advantage of the seasonal benefit (Ye, 2023).

Research of consumer preferences in China shows that the main criteria for choosing cherries are size, colour, freshness, and sweetness. Large, dark red varieties with a high sugar content are most popular, which affects the pricing policy and competitive advantages of suppliers (Zhang *et al.*, 2024). The growing demand for organic and environmentally certified products remains an important factor. Consumers in major cities such as Beijing, Shanghai, and Guangzhou are willing to pay a higher price for premium cherries, which encourages producers to adapt their products to market requirements (Chen *et al.*, 2023). Chile remains the undisputed leader among cherry exporters to China, providing more than 90% of the imports of this product. Due to optimised logistics solutions, specifically, the Cherry Express programme, Chilean manufacturers substantially reduce transportation time, which allows them to maintain the quality and freshness of products when entering the Chinese market (Lei, 2018). The United States ranks second in terms of cherry shipments, but faces trade barriers and high duties that limit the competitiveness of American products. Despite the high quality and safety standards, additional costs of import customs clearance make products less accessible to Chinese consumers, which reduces their market share (Ye, 2023). Australia occupies an important place among suppliers, focusing mainly on the premium segment. The proximity to China and short transport route provides competitive advantages in the speed of delivery, which helps maintain quality and increase the sales time of products. Australian cherries are in demand among Chinese consumers due to their high cultivation standards and strict quality control (Li *et al.*, 2022). Central Asian countries, particularly Uzbekistan, are seeking to expand their presence in the Chinese market, but face numerous logistical difficulties. The lack of efficient infrastructure, the long duration of transportation, and strict sanitary requirements limit the ability of these countries to enter large-scale sales markets (Chen *et al.*, 2023). Argentina is gradually expanding its presence in the Chinese market, using a seasonal preference strategy similar to the Chilean export model. Since Argentine production falls between December and February, deliveries coincide with peak demand in China, especially during the holiday period. Despite this, the country's export opportunities still remain limited because of the high logistics costs, distance from major commercial ports, and the need to adapt products to Chinese sanitary standards (Jaureguiberry & Tappata, 2022). However, the Argentinian government is actively working to sign new trade agreements and improve transport infrastructure, which can contribute to the growth of exports to China (Table 6).

***Table 6**. Major cherry suppliers to the Chinese market (2024)*

Country	Share in China's imports (%)	Main advantages	Main restrictions
Chile	90.2%	Seasonal advantage, fast logistics	High transportation costs
USA	5.3%	High-quality products	Trade barriers, high duties
Australia	2.5%	Geographical proximity, premium quality	Limited production volumes
Uzbekistan	1.2%	Low production cost	Logistical difficulties, strict standards
Argentina	0.8%	Seasonal advantage, strategic export in winter	High logistics costs, the need to adapt to Chinese standards

***Source:** compiled by the authors based on W. Li et al. (2022)*

China's customs policy is one of the critical factors regulating cherry imports. For some countries, in particular, the United States, customs rates remain high, which reduces the competitiveness of products. For example, in 2023, customs duties on American cherries were 25%, which substantially limited their availability to Chinese consumers. As of 2024, China's customs tariffs on imports of American Cherries remain high, which continues to limit its competitiveness in the Chinese market. For Chile, which has favourable trade agreements with China, customs tariffs were reduced, which provided for a substantial increase in exports. This allows Chilean manufacturers to compete on price and increase their market presence. In addition to duties, China imposes strict sanitary and phytosanitary requirements on imported products. Cherries must meet safety standards, pass thorough phytosanitary control, and meet the requirements for residual pesticide levels. This creates additional barriers for countries seeking to enter the Chinese market.

China remains the biggest driver of global cherry demand, and this trend will continue in the coming years. Further market growth will be driven by an increase in the share of premium and organic products, which corresponds to changing consumer preferences and increased quality requirements. An important factor will be the optimisation of logistics supply chains, which will help reduce delivery time and improve product safety. Therewith, China will actively strengthen the role of domestic production, expanding the area under cherry orchards and introducing new agricultural technologies. Much attention will be paid to the development of marketing strategies aimed at the younger generation of consumers who demonstrate a high demand for high-quality and branded products. Despite substantial opportunities, the market remains highly competitive, and countries seeking to expand exports to China must adapt their strategies to meet demand and regulatory requirements. In the future, it is possible to further increase the share of Uzbekistan and other Central Asian countries in Chinese imports, which may change the distribution of the market and increase competition among exporters.

Logistics and trade barriers to cherry exports: A comparative analysis of Kyrgyzstan and Chile. Logistics and trade barriers are crucial factors for successful cherry exports, especially to strategic markets such as China. They cover aspects of transportation, storage, sanitary, and phytosanitary requirements, customs procedures, and marketing strategies. Chile has a well-established logistics system and a well-developed infrastructure to support exports, while Kyrgyzstan faces substantial obstacles that limit its opportunities in the international market. Transportation is one of the most important stages of the cherry supply chain. Chile has a state-of-the-art maritime logistics network, which enables efficient delivery of products to China and reduces delivery time by sea. This minimises product losses and improves its quality at the time of receipt to consumers. The use of cold chains and a modified gas medium during transportation can substantially extend the shelf life of cherries, which is a crucial factor for long-distance export (Cabañas *et al.*, 2023). Kyrgyzstan, on the contrary, mainly uses motor transport due to its remoteness from seaports and an insufficiently developed logistics infrastructure, which substantially increases the delivery time up to 40 days. Transportation costs in Kyrgyzstan remain substantially higher, reaching USD 900/tonne, which is almost twice the logistics costs of Chile, where this figure is USD 500/tonne. This substantially reduces the competitiveness of Kyrgyz exports on the international market. The lack of specialised warehouses with cooling systems leads to high product losses during transportation.

Sanitary and phytosanitary barriers are another challenge for cherry exporters. Chile has a well-developed quality control system that allows its products to meet international standards. The country has modern methods of pre-harvest monitoring, strict control of pesticide residues and pest control technologies, which lower the risks of returning products from customs (VanWoerkom *et al.*, 2022). Kyrgyzstan has serious problems with compliance with China's phytosanitary requirements. The lack of modern laboratories, long certification procedures, and cases of detection of quarantine organisms in product batches caused delays and even refusal to import Kyrgyz cherries to China in 2023. In 2024, the volume of exports to China decreased by 86.32%, which indicates increased control and non-compliance with the requirements of the importer (Table 4). Customs procedures and regulatory barriers also play an important role in determining the competitiveness of exporters. Chile has favourable terms of trade with China, including preferential tariffs and simplified customs procedures. Due to the signed free trade agreements, Chilean products quickly pass customs clearance, which ensures the stability of supplies. Instead, Kyrgyzstan faces high customs tariffs and lengthy certification procedures, reducing its competitiveness. In 2023, several shipments of Kyrgyz cherries were returned due to non-compliance with China's phytosanitary standards, which led to a further reduction in exports. Analysis of sanitary compliance and customs clearance refusals shows substantial differences between Chile and Kyrgyzstan (Fig. 1).

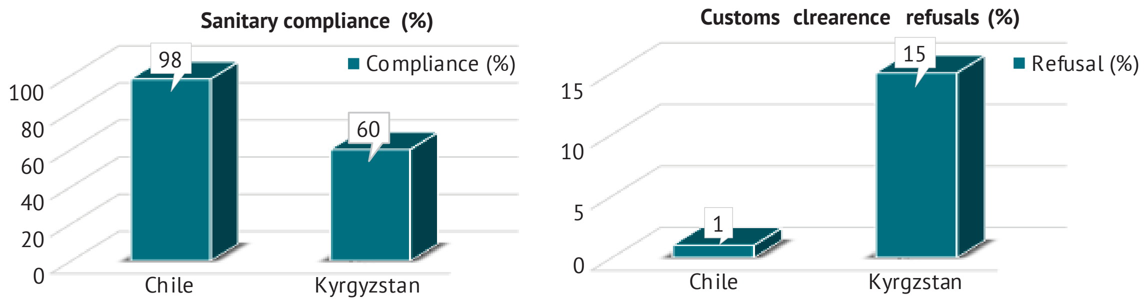

Figure 1. *Comparison of sanitary compliance and customs clearance failure rate (%) between Chile and Kyrgyzstan*
Source: *compiled by A.H. VanWoerkom et al. (2022)*

The results confirm key issues limiting cherry exports from Kyrgyzstan. The high level of refusals in customs clearance and the low level of compliance with sanitary standards require the implementation of measures to improve the quality control system, adapt to international standards, and optimise logistics procedures. It is necessary to expand cooperation with international certification organisations and introduce modern technologies for packaging and storing products to increase the competitiveness of Kyrgyz cherries. Marketing strategies are an important element of export support, and in this aspect, Chile is substantially ahead of Kyrgyzstan. Chilean manufacturers actively use advertising campaigns and partnerships with major retail chains in China. The "Cherries from Chile" campaign includes promotion through social networks

WeChat and Douyin, online sales, and cooperation with Chinese electronic platforms (Chiang *et al.*, 2021). This ensures high brand awareness and consumer confidence. In turn, Kyrgyz exporters do not have well-established marketing strategies and are practically absent from the information space of China, which substantially complicates the promotion of their products.

An analysis of logistics and trade barriers to exports showed a substantial advantage of Chile in all key aspects. Chilean producers have access to efficient transport infrastructure, international marketing, and simplified customs procedures, which allows them to maintain stable export volumes. Instead, Kyrgyzstan faces challenges such as inefficient logistics, a lack of specialised laboratories for product certification, high customs costs, and weak marketing policies. It is necessary to invest in the development of logistics, adaptation of products to international standards and promotion of Kyrgyz cherries in foreign markets through marketing initiatives to improve the situation.

Strategies for the development of cherry exports from Kyrgyzstan: Adaptation to the requirements of the Chinese market. Expanding cherry exports from Kyrgyzstan to China is a promising direction for the development of the country's agricultural sector. However, successful entry into the Chinese market requires adaptation to its regulatory, logistics, marketing, and trade requirements. The analysis of world experience, in particular, the example of Chile, allows identifying effective approaches to improving the production and sales chain, which will contribute to increasing the competitiveness of Kyrgyz products (Nikolić *et al.*, 2021). One of the main requirements of China for cherry imports is compliance with sanitary and phytosanitary standards. Products must meet international standards for the absence of pests, pesticide residues, and phytopathogens. Sanitary certification is a prerequisite for export, and the process of obtaining it is often complicated due to the lack of proper laboratory facilities for product quality control in Kyrgyzstan (Uzenbaev *et al.*, 2019). In addition, China imposes strict packaging requirements: containers must be sealed, transport-resistant, and contain appropriate markings indicating the country of origin, harvest date, and storage conditions (Kantaroğlu & Demirbaş, 2020). Given that consumers in China prefer large, juicy fruits with a high sugar content, selection research and the introduction of modern storage technologies can be key factors for successful export development.

Logistical challenges remain one of the most substantial barriers to Kyrgyz cherries entering the Chinese market. Unlike Chile, which has an efficient sea transportation system, Kyrgyzstan is forced to use road and rail transport, which substantially increases delivery time and logistics costs (Ivanova *et al.*, 2023). Optimisation of logistics chains, in particular, the use of refrigerated containers, will allow maintaining the quality of products on the way to the consumer. One possible solution is to create direct trade routes, which will reduce the costs and risks associated with transit through third countries. Marketing strategies also play an important role in export development. Kyrgyz cherry currently has no established brand on the international market, which limits its attractiveness to consumers (Song & Shi, 2020). Adapting marketing campaigns to the preferences of Chinese consumers who prefer premium products increases demand. Effective methods can be to promote products through Chinese online platforms, such as JD.com and Alibaba, cooperation with local distributors, and participation in international food exhibitions. In addition, cultural aspects should be accounted for: in China, cherries are often associated with luxury and festive events, which can become the basis for developing marketing campaigns aimed at the premium market segment.

Trade mechanisms play an important role in ensuring sustainable exports. Conclude bilateral agreements that simplify the import and export procedure would reduce customs barriers. The successful example of Chile demonstrates that government support for exporters, subsidising certification, and developing transport infrastructure substantially contribute to the expansion of sales markets. Kyrgyzstan can adapt this experience by expanding cooperation with Chinese regulators, implementing state support programmes for producers, and attracting international investment in the field of agricultural studies. The experience of Chile, as well as other major exporters, such as the United States and Turkey, shows the need for an integrated a Ivanova approach to the development of the industry. The main areas of reform may include improving cultivation technologies, increasing the level of mechanisation of farms, creating modern logistics hubs, and integrating into international trade networks. Studies show that high export efficiency is achieved through a combination of state regulation, investment promotion, and the introduction of innovative horticultural management methods (Canan & Torun, 2025).

Thus, the development of cherry exports from Kyrgyzstan to China is possible if the production and logistics processes are comprehensively adapted to international standards. Introduction of modern agricultural technologies, optimisation of logistics, effective marketing, and active state support are key factors for the country to reach a competitive level. Based on the experience of Chile, Kyrgyzstan can implement a strategy for the long-term development of the industry, which will contribute to economic growth and strengthen the country's position in the international market.

DISCUSSION

The global cherry market continues to grow, and China remains its major consumer, defining requirements for exporters. Chile's experience shows that successful entry into the Chinese market depends on efficient logistics, compliance with sanitary standards, and strategic marketing. Kyrgyzstan has natural prerequisites for increasing exports, but faces a number of restrictions that require a systematic solution. The results of the study showed a substantial gap in the scale of cherry production and exports between Kyrgyzstan and Chile. The dynamics analysis confirmed stable production growth in Chile, where in 2024, the volume reached 641 thousand tonnes, which was consistent with the conclusions of P. Bamber and K. Fernandez-Stark (2016), who emphasised the effectiveness of government support, mechanised harvesting, and access to infrastructure. Thereby, Kyrgyzstan did not show similar growth, maintaining low production indicators, which coincides with the data obtained by A. Shaiyldaeva *et al*. (2024), stressing the impact of a lack of investment, a small area of plantings, and the absence of modernised cultivation technologies.

Logistical barriers remained a substantial problem for Kyrgyzstan. The transportation time to China reached 40 days, which was substantially higher than in Chile (22 days). This was consistent with the conclusions of V. Tudela *et al*. (2023), who underlined the importance of developed infrastructure for the competitiveness of fruit exports. The high failure rate in customs clearance of Kyrgyz products (15%) confirmed the need to improve quality control, which was in line with the study by S. Yunusov and H. Demirsoy (2024), where it was noted that Central Asian countries face similar problems due to non-compliance with importer standards. The findings of the study confirmed that the competitiveness of cherry exporters was determined not only by production volumes but also by the ability to adapt to the requirements of international markets. Turkey, as noted by H. Arısoy *et al*. (2023), took advantage of its geographical location and developed agricultural infrastructure to boost exports. A similar strategy was used by the United States, which, according to G. Lang (2017), focused on the premium market segment. Chile, due to efficient logistics, increased export supplies, which was consistent with the results of this study. Moldova and Serbia, according to A. Ceban and E. Lucaşenco (2023) and N. Kljajić *et al*. (2024), gradually expanded exports using strategic partnerships with the EU. In this context, Kyrgyzstan had the potential to expand exports, but, unlike other countries, it remained poorly integrated into international trade networks (Dooranov *et al*., 2024). It is necessary to modernise production, simplify logistics, and improve state support to increase competitiveness. In Italy, as stated by R. Della Casa *et al*. (2019), improving marketing strategies and logistics solutions contributed to the expansion of sales markets. Argentina, as presented by F. Jaureguiberry and M. Tappata (2022), used public-private partnerships to support exports, which ensured the stability of the sector. In South Korea, according to S. Shin and S. Ji (2021), the demand for imported cherries was formed due to consumer preferences focused on quality and environmental standards, which gave a competitive advantage to countries with high cultivation technologies. As presented by M. Spies (2023), Pakistan developed agricultural exports through infrastructure projects, while Kyrgyzstan had similar difficulties, but did not implement system solutions to overcome them.

An important factor in shaping global demand remained the structure of China's imports, which, as stated by L. Lei (2018), continued to show dynamic growth. However, as the results of this study showed, Kyrgyzstan was not represented among stable suppliers due to the lack of trade agreements and limited compliance with sanitary standards. Advantages of Chinese consumers in the cherry segment, examined by Z. Ye (2023), confirmed that the growing demand was focused on high-quality products that had a clear market position. Chile used these characteristics to strengthen its presence, while Kyrgyzstan did not implement targeted marketing strategies, which did not allow it to compete on equal terms. This confirmed the need to develop specialised adaptation programmes to the Chinese market to improve export potential.

Methods of preserving the quality of cherries and their impact on export competitiveness remain important aspects of international trade. As proven by C. Cabañas *et al*. (2023), the use of a modified gas medium in combination with an antagonistic yeast substantially improved the shelf life of cherries, which ensured successful long-distance export. This technology was widely used in Chile, reducing product losses, while in Kyrgyzstan, such methods were not implemented, which created risks of spoilage during transportation. Phytosanitary control and the use of pesticides were also instrumental in shaping the export strategy, as confirmed by A. VanWoerkom *et al*. (2022), analysing the effect of residual chemicals after cherry processing on export potential. Excessive use of insecticides could restrict access to international markets due to tougher regulatory requirements, which agrees with the difficulties that Kyrgyzstan faced when passing sanitary control in China. Therewith, the Chinese market, according to A. Chiang *et al*. (2021) demonstrated a high sensitivity of consumers to the quality and environmental friendliness of cherries, which contributed to an increase in demand for products with proven cultivation standards.

Research on the economic efficiency of cherry cultivation conducted by S. Nikolić *et al*. (2021) pointed out that countries with a developed system of producer support showed better results in production costs and export profitability. This supplemented the conclusions about Chile's competitiveness, while Kyrgyzstan, due to the lack of systematic support, faced high production and logistics costs, hindering export opportunities. The efficiency of cherry production largely depended on the management of crop losses and the introduction of modern agricultural technologies. A study by M. Kantaroğlu and N. Demirbaş (2022) confirmed that substantial product losses in Turkey were due to insufficient mechanisation and low investment in post-harvest processing, which limited the country's export potential. A similar situation was observed in Kyrgyzstan, where transportation and storage losses remained high due to the lack of efficient logistics solutions.

Analysis of the sensory characteristics of cherries performed by I. Ivanova *et al*. (2023) showed that compliance with organoleptic parameters was a determining factor in the success of products on the European market. This aspect could be critical for Kyrgyzstan in expanding exports to China, as Chinese consumers prefer high-quality products with optimal levels of hardness, colour, and sweetness. Climatic factors also affected production efficiency (Ivanova *et al.*, 2021). High yields in Chile were achieved through the introduction of irrigation technologies and adaptation of varieties, which is consistent with the findings of G. Bujdosó and K. Hrotkó (2017), which affirmed that technological innovation is crucial for stable production. According to Z. Song and X. Shi (2020), the climate substantially affected yields in north-western China, which stimulated the adaptation of new plant protection methods. This experience can be used in Kyrgyzstan to minimise the risks associated with unstable weather conditions. The analysis of the results obtained confirmed that the success of cherry exports was largely determined by the level of adaptation to international quality standards, logistics capabilities, and state support for production. Comparison with other countries showed that Kyrgyzstan has a substantial potential for expanding exports, but requires comprehensive improvement of cultivation technologies, optimisation of logistics, and increased integration into world trade networks.

CONCLUSIONS

The study identified substantial differences between Chile and Kyrgyzstan in cherry production and exports due to the level of mechanisation, logistics, and government support. Kyrgyzstan, despite its natural potential, has limited opportunities to enter the international market, while Chile shows stable export growth due to the integrated development of the industry. The dynamics of cherry production indicated a substantial increase in volumes in Chile from 397 thousand tonnes in 2022 to 641 thousand tonnes in 2024, which confirms the effectiveness of the implemented agricultural technologies. Kyrgyzstan, on the other hand, showed stagnation, reducing production from 6.4 thousand tonnes in 2022 to 4.12 thousand tonnes in 2024. The main factors hindering the development of the industry in Kyrgyzstan are insufficient mechanisation, limited investment, and weak integration into the international trading system.

Export analysis confirmed Chile's dominance in the Chinese market. In 2024, China accounted for 92.36% of all Chilean cherry exports, while Kyrgyzstan's contribution remained minimal – only 0.4%. Chilean suppliers increased their exports to China from 358 thousand tonnes in 2022 to 592 thousand tonnes in 2024, while Kyrgyzstan exported only 1.65 tonnes in 2024, which is 86.32% less than in 2023. The reasons for these dynamics were non-compliance with sanitary standards, high cost of logistics, and difficulties in customs clearance. Logistics barriers substantially limit the competitiveness of Kyrgyz products. The time to transport cherries to China from Kyrgyzstan was 40 days, which is almost twice as long as from Chile (22 days). Logistics costs in Kyrgyzstan also remained high at USD 900/tonne, which is substantially higher than in Chile (USD 500/tonne). Sanitary barriers proved to be another substantial problem: the compliance of Kyrgyz products with China's phytosanitary requirements in 2024 was only 60%, which led to 15% of refusals in customs clearance, while in Chile, this figure was at the level of 1%.

The Chilean experience showed that government support, investment in technology, and effective marketing strategies are key factors for successful exports. Chile actively uses advertising campaigns and cooperates with Chinese retail chains, which contributes to increasing demand for its products. However, Kyrgyzstan does not have a developed marketing strategy, which limits its ability to expand the market. It is necessary to introduce technological modernisation, improve the logistics system, and expand international trade agreements to strengthen Kyrgyzstan's position in the international market. Optimisation of transportation, development of product branding strategies, and adaptation to Chinese requirements can increase the competitiveness of Kyrgyz cherries. Further research should focus on mechanisms for integrating Kyrgyz producers into global supply chains and developing effective financial instruments to support farmers. Limitations of the study were incomplete access to detailed Chinese customs reports and limited official data on logistics costs in Kyrgyzstan, which could affect the accuracy of the export potential assessment. Improving the competitiveness of Kyrgyz Cherries requires improving logistics, creating refrigerated warehouses, adapting to China's sanitary requirements, and expanding trade agreements. Simplification of customs procedures and development of marketing strategies will contribute to stable exports. Further studies may assess the impact of government support and market diversification.

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CONFLICT OF INTEREST

None.

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Порівняльний аналіз галузі черешні в Киргизстані та Чилі та стратегії розвитку ринку в Китаї

Мяолун Чжоу
Докторант
Киргизький національний університет імені Жусупа Баласаґина
720033, вул. Фрунзе, 547, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0001-8707-1500
Джапар Алибаєв
Доктор економічних наук, професор
Киргизький національний університет імені Жусупа Баласаґина
720033, вул. Фрунзе, 547, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0003-0931-9846
Хуаньін Сюй
Докторант
Киргизький національний університет імені Жусупа Баласаґина
720033, вул. Фрунзе, 547, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0008-6627-1782
Хаохэ Юань
Докторант
Киргизький національний університет імені Жусупа Баласаґина
720033, вул. Фрунзе, 547, м. Бішкек, Киргизька Республіка

Анотація. Мета дослідження – провести порівняльний аналіз виробництва та експорту черешні в Киргизстані та Чилі, оцінити їх конкурентоспроможність на світовому ринку, а також визначити ключові бар'єри та можливості для розширення експорту до Китаю. Аналіз базувався на статистичних даних щодо виробництва та експорту черешні, оцінці логістичних витрат, митних процедур та державної підтримки, а також розрахунку частки експорту та темпів зростання поставок на китайський ринок. Результати показали суттєві відмінності між Киргизстаном та Чилі у розвитку галузі черешні. У 2024 році виробництво черешні в Чилі досягло 641 тис. тон, тоді як в Киргизстані цей показник становить лише 4,12 тис. тон, що відображає суттєву різницю в масштабах виробництва та рівні технологічного розвитку. Чилі забезпечила 92,36 % китайського імпорту черешні, використовуючи ефективні торговельні механізми, оптимізовану логістику та державні стимули, тоді як експорт з Киргизстану залишається нестабільним і обмеженим. Високі логістичні витрати в Киргизстані (900 доларів США за тонну) порівняно з Чилі (500 доларів США за тонну) знижують конкурентоспроможність продукції. Відсутність сучасних транспортних коридорів, складських приміщень та належного холодильного обладнання суттєво ускладнює стабільний експорт до Китаю, що призводить до високих втрат продукції під час транспортування. Аналіз також показав, що жорсткі санітарні вимоги, сертифікація та фітосанітарний контроль створюють додаткові бар'єри для виходу киргизької продукції на міжнародний ринок, що вимагає стратегічних змін у державній політиці та залучення інвестицій у модернізацію галузі. Дослідження продемонструвало, що конкурентоспроможність експортерів черешні визначається рівнем логістичної інфраструктури, ефективністю торговельних механізмів та відповідністю міжнародним вимогам, що свідчить про необхідність оптимізації логістики, створення холодильних складів та спрощення митного оформлення для збільшення експорту з Киргизстану

Ключові слова: конкурентоспроможність; логістика; санітарні вимоги; торговельні бар'єри; митне оформлення; контроль якості

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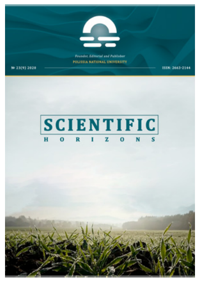

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Analysis of production factors determining agricultural productivity in Cuispes

Manuel Antonio Morante Dávila
Master
Research Institute of Economics and Development
of the National University Toribio Rodriguez de Mendoza of Amazonas
01001, 304 University Str., Chachapoyas, Peru
https://orcid.org/0000-0003-3098-9019

Alex Javier Sánchez Pantaleón
Master
Research Institute of Economics and Development
of the National University Toribio Rodriguez de Mendoza of Amazonas
01001, 304 University Str., Chachapoyas, Peru
https://orcid.org/0000-0001-5708-272X

Irma Dolores Montenegro Rios
Master
Research Institute of Economics and Development
of the National University Toribio Rodriguez de Mendoza of Amazonas
01001, 304 University Str., Chachapoyas, Peru
https://orcid.org/0000-0001-5445-2190

Maritza Revilla Bueloth
Master
Research Institute of Economics and Development
of the National University Toribio Rodriguez de Mendoza of Amazonas
01001, 304 University Str., Chachapoyas, Peru
https://orcid.org/0000-0002-8275-8696

Oscar Chavez Espinoza*
Master
Research Institute of Economics and Development
of the National University Toribio Rodriguez de Mendoza of Amazonas
01001, 304 University Str., Chachapoyas, Peru
https://orcid.org/0000-0002-6865-4815

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*Corresponding author

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Abstract. This study aimed to evaluate the impact of productive factors – Capital, Labour, Knowledge, Technology, Management, and Land – on agricultural productivity in the district of Cuispes. A sample of 50 producers was analysed using a quantitative approach and PLS-SEM models, and further assessed across four productive groups through R statistical software, using ordinary least squares (OLS) and analytic hierarchy process (AHP) models. The results indicate that land fertility plays a fundamental role in the production process. PLS analysis reveals that Management, Technology, and Knowledge exhibit moderate and low positive correlations of 0.680, 0.632, and 0.341, respectively, whereas Capital and Labour show negative correlations of 0.252 and 0.400 with productivity. Group B excels in Land, Capital, and Technology (AHP: 0.44), demonstrating significant productive potential. OLS results confirm that the combination of Technology and Land is critical to agricultural success. Group D performs well in Knowledge and Technology (AHP: 0.25), and OLS identifies it as the second most significant group in terms of Technology use. Groups A and C score lower (AHP: 0.10 and 0.25), with a negative impact according to OLS; these groups require improvements in production methods and management practices to become more competitive in the market. It is concluded that Group B is the most productive sector, followed by Group D, both representing the most profitable activities in the district. Certain production factors should therefore be developed further, and public or private institutions should strengthen agricultural productivity through targeted public policies

Keywords: PLS analysis; analytic hierarchy process; ordinary least squares; capital; management; technology

INTRODUCTION

Agricultural productivity is a fundamental driver of economic development and food security on a global scale. Its enhancement not only ensures a stable food supply but also promotes social welfare, generates employment, and supports equitable income distribution within rural communities. A comprehensive understanding of the factors influencing agricultural productivity is essential for improving production efficiency, advancing long-term sustainability, and guaranteeing fair access to vital resources. This need becomes particularly urgent in light of the escalating global food demand driven by population growth, coupled with pressing environmental challenges such as soil degradation and climate change. As such, research into the determinants of agricultural productivity remains both timely and critical.

Agriculture, as a resource-intensive sector, depends heavily on the strategic management of production inputs – Capital, Labour, Management, Knowledge, and Technology – to sustain productivity. According to Z. Zhou *et al.* (2024), effective coordination of these resources is pivotal for sustained production growth. Notably, J. Chavas and C. Nauges (2020) highlight the transformative role of technological advancement in enhancing agricultural efficiency, particularly in increasing crop yields. Their research further underscores that capital investment, especially in the form of access to financial services, enables farmers to adopt modern machinery and advanced farming techniques. Despite these advancements, many farmers continue to face structural barriers that constrain productivity growth. K. Chacón and D. Gutman (2022) identify limited access to modern agricultural technologies as a significant limiting factor. Similarly, the intensifying effects of climate change, documented by W. Shah *et al.* (2024), pose increasing risks to consistent agricultural output.

As noted by A. Weyori *et al.* (2018), the broader economic contribution of agriculture is contingent upon the efficient utilisation of production factors, where these are deficient, consequences include reduced output, technical inefficiencies, and hindered economic progress. W. Shah *et al.* (2023) support this view, suggesting that without ongoing improvements in key inputs, agriculture becomes vulnerable to stagnation. Land, in particular, remains a critical yet problematic resource. Farmers recognise soil fertility as a major determinant of productivity. However, as L. Nkurunziza *et al.* (2020) argue, challenges such as restricted access to arable land, inadequate education, and weak technological integration persist, undermining both productivity and sustainability in rural areas. In recent years, the competitiveness of the agricultural sector has increasingly been evaluated through the lens of local production capacity and the strategic deployment of endogenous resources. As M. Kobylińska (2021) observes, an emerging trend among farmers is the adoption of organic practices intended to improve yields while preserving ecological integrity. Profitability in this context, as shown by F. Tenchini and C. de Freitas (2024), depends on the optimal use of production factors to enhance logistics, infrastructure, and the management of agricultural knowledge, thereby facilitating market access for high-quality outputs. This transition is supported by H. Xiong *et al.* (2023), who emphasise that agroecological practices, which blend traditional knowledge with scientific advancements, offer a viable pathway for optimising productivity while maintaining environmental stewardship.

Overall, the literature strongly indicates that agricultural productivity is shaped by a dynamic interplay of multiple production factors. By analysing these determinants, both public policymakers and private sector stakeholders can devise more effective strategies to foster efficiency, resilience, and sustainability in agriculture. Therefore, the present study focused on identifying the specific drivers of agricultural productivity in the district of Cuispes, with particular attention to land management, the application of agricultural knowledge, technology adoption, efficient use of capital, farm management practices, and the role of human labour. The insights derived from this investigation are intended to support the development of informed production strategies tailored to the needs of rural agricultural systems.

MATERIALS AND METHODS

Study area. The area of investigation was the district of Cuispes, one of the twelve districts that comprise the Province of Bongará, in the Department of Amazonas, northern Peru. It is bordered by the districts of Florida to the north, Jumbilla to the east, San Carlos and Jazán to the south, and Shipasbamba to the west. The district of Cuispes spans approximately 110.72 square kilometres and features varied terrain, including elevated areas, plains, and altitudes ranging from 1,000 metres above sea level to more than 1,690 metres in its highest regions. The population density is approximately 7.8 inhabitants per square kilometre, and the total population is estimated to exceed 700 residents. The study population consisted of 50 farmers, divided into four productive groups: Group A: crops such as arracacha, yucca, potato, and vituca; Group B: coffee; Group C: gherkin, beans, maize, pineapple; Group D: banana and avocado. The following hypotheses were proposed.

H1: Adequate land management influences productivity in the agricultural sector.

H2: Enhanced application of agricultural knowledge increases productivity in the agricultural sector.

H3: The adoption of technology influences productivity in the agricultural sector.

H4: Efficient use of capital influences productivity in the agricultural sector.

H5: Effective farm management influences productivity in the agricultural sector.

H6: The human labour factor influences productivity in the agricultural sector.

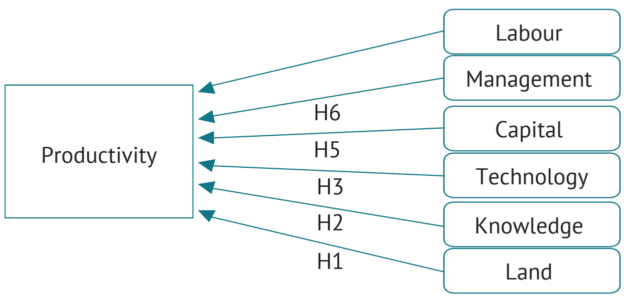

***Figure 1**. Research design*
***Source:** authors' compilation*

Data collection. For data collection, a random sampling method was implemented, targeting the most relevant hamlets in terms of production. The necessary permissions were obtained before the commencement of data collection, with the purpose of the research clearly explained and confidentiality and data security guaranteed. Verbal consent was obtained from the main authorities of the Cuispes district, and farmers engaged in diverse agricultural activities were randomly selected to complete a paper-based questionnaire. Prior to this, concepts related to the productive factors influencing agricultural yields were explained, thereby ensuring the validity of the questionnaire and the reliability of the data collected. The questionnaire comprised two sections: the first gathered sociodemographic information, while the second focused on productive factors and the productivity of agricultural activities. The latter was assessed using a five-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree), as proposed by authors such as Y. VegaSampayo *et al.* (2022). The study adhered to the principles outlined in the American Sociological Association's Code of Ethics (1997).

A basic mixed-methods approach was adopted to examine the relationship between productivity factors and farm improvement. This approach was structured to identify, define, and analyse the key factors influencing agricultural productivity. Data collection was conducted via a questionnaire survey administered in March 2024 to a sample of farmers from the district of Cuispes. The analysis employed the PLS-SEM method, hierarchical process analysis (AHP), and the ordinary least squares model to quantitatively examine the impact of productive factors on agricultural outputs.

Data analysis. PLS-SEM was employed to evaluate the productive factors influencing agricultural activity and their impact on productivity enhancement. The data were analysed across four productive groups using R statistical software, incorporating OLS and AHP models to identify the most influential factors in each group and to determine the most significant agricultural activity in the district of Cuispes. The research relied on data obtained through the survey application, and the reliability of the dataset was validated with a Cronbach's alpha coefficient exceeding 0.78 (HerreraGuerra *et al.,* 2023). Data were processed using Smart PLS, R, and Excel software to facilitate a clearer and more detailed analysis.

RESULTS AND DISCUSSION

In the analysis of agricultural productivity in Cuispes, it was identified that land management and land quality are key factors that contribute to improved productive performance, while Technology and Knowledge exert a comparatively lower influence. The PLS-SEM model confirmed the relevance of Management and Technology for productivity but found no significant effect from Labour or Land. AHP and OLS analyses identified coffee as the crop with the greatest productive potential, followed by plantain, thereby suggesting that improvements in Technology and Management are necessary to optimise production.

To estimate potential bias in the structural equation model (PLS-SEM), in this study authors applied tests of internal consistency and construct reliability, such as Cronbach's alpha, composite reliability, and average variance extracted (AVE). These tests are widely accepted in the quantitative research literature. The values initially obtained did not fully support the validity of the SEM model, indicating that certain variables may have been omitted that are necessary to establish the model's viability. The results are presented in Table 1, where Cronbach's alpha, composite reliability and AVE are reported for each construct within the model.

***Table 1**. Reliability and construct validity*

	CA	(rho_a)	(rho_c)	AVE
Capital	0.700	0.724	0.766	0.624
Labour	0.739	0.777	0.851	0.658
Knowledge	0.71	0.757	0.818	0.692
Land	0.866	0.949	0.912	0.775
Management	0.876	0.893	0.905	0.616
Production	0.879	0.885	0.912	0.674
Technology	0.853	0.853	0.895	0.632

***Note:** CA – Cronbach's Alpha; (rho_a) – composite reliability; (rho c) – composite reliability; AVE – average variance extracted*
***Source:** compiled by the authors*

Table 1 shows the internal reliability measures for assessing the coherence of the indicators that constitute each latent variable. These are considered acceptable Cronbach's alpha, composite reliability rho_a values exceeding 0.7. The degree to which indicators of a latent variable share a high proportion of variance is considered satisfactory when the AVE exceeds 0.5. These criteria allow the researcher to determine whether the selected constructs are well-defined and whether the indicators are appropriate. The results from the external model indicate that the constructs – Capital, Knowledge, Land, Management, Production, and Technology – meet the criteria of the measurement model criteria. Thus, the selected latent variables and their associated indicators are deemed reliable and valid for use in a PLS-SEM analysis. Table 2 presents the discriminant validity of the constructs in the measurement model, assessed using the Heterotrait-Monotrait Ratio (HTMT). Values below the critical threshold of 0.85 indicate satisfactory discriminant validity (Hair *et al.*, 2019).

***Table 2**. Heterotrait-Monotrait Ratio analysis*

	Capital	Labour	Knowledge	Management	Production
Capital					
Labour	0.637				
Knowledge	0.248	0.382			
Management	0.415	0.344	0.598		
Production	0.643	0.295	0.480	0.755	
Technology	0.279	0.626	0.804	0.632	0.720

***Note:** this table presents the HTMT values between different constructs in the measurement model, used to assess discriminant validity in PLS-SEM*
***Source:** compiled by the authors*

The construct Capital and Knowledge presents an HTMT value of 0.248, reflecting a significant conceptual distinction between the two. Similarly, Labour and Knowledge yield have an HTMT of 0.382, which also indicates adequate discriminant validity. In addition, Capital and Management show an HTMT of 0.415, while Production and Management report a value of 0.480 – both well below the critical threshold – underlining a clear differentiation between these pairs of constructs. However, the HTMT between Knowledge and Technology is 0.804, suggesting a possible conceptual overlap. Although this value remains below the commonly accepted limit of 0.85, it indicates a potential interrelation or shared dimensions in either conceptualisation or measurement.

The productive factors and their relationship with productivity were evaluated using the PLSSEM algorithm. Some external loadings of the indicators were found to be non-significant for certain constructs and were therefore removed to enhance the model's validity. Figure 2 illustrates the relationships between the latent variables and their observable indicators within the measurement model. The high values of the retained external loadings confirm a strong association between the constructs and the productivity indicators (Hair *et al.,* 2019).

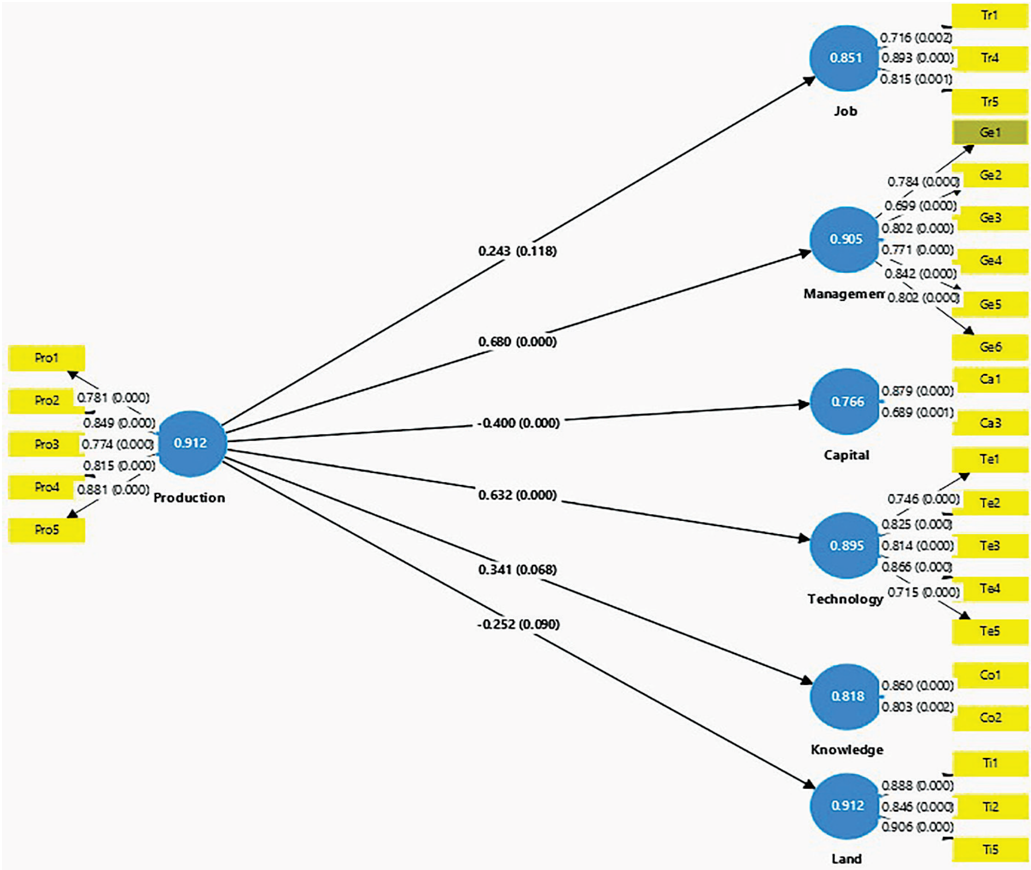

Figure 2*. Measurement results and structural model – SmartPLS*

Source: *compiled by the authors*

Evaluation of the structural model using PLS-SEM, based on the data presented in Figure 2, showed that after the removal of some indicators to improve model feasibility, the latent constructs Management and Technology exhibited a statistically significant influence on productivity. The retained indicators for Management (loadings: 0.79, 0.69, 0.80, 0.77, 0.84, 0.80) and Technology (loadings: 0.74, 0.82, 0.81, 0.86, 0.71) all demonstrated external loadings exceeding 0.7, indicating a strong relationship with productivity outcomes. By contrast, the constructs Labour and Land, although supported by indicators with high external loadings (Labour: 0.71, 0.89, 0.81; Land: 0.80, 0.84, 0.90), did not show a statistically significant influence on productivity in this study (Table 3). These findings suggest that while Capital, Management and Technology are key determinants of productivity improvements, Labour, Knowledge and Land may not exert such a strong direct impact. The results underscore the importance of prioritising effective management practices and the adoption of advanced technologies in strategies aimed at enhancing agricultural productivity.

Table 3*. Results of hypothesis testing*

Hypothesis	t-value	p-value	Decision
Production → Capital	3.696	0.000	Accept
Production → Labour	1.564	0.118	Reject
Production → Knowledge	1.829	0.068	Reject
Production → Land	1.695	0.090	Reject
Production → Management	7.841	0.000	Accept
Production → Technology	4.954	0.000	Accept

Source: *compiled by the authors*

Table 3 presents an analysis of the structural relationships between the constructs in the PLSSEM model, showing both significant and non-significant results for several hypotheses. Hypotheses indicating positive relationships between Production and Capital ($t = 3.696$, $p = 0.000$), Management ($t = 7.841$, $p = 0.000$), and Technology ($t = 4.954$, $p = 0.000$) were accepted, suggesting that production has a statistically significant and positive influence on these constructs. In contrast, hypotheses linking Production to Labour ($t = 1.564$, $p = 0.118$), Knowledge ($t = 1.829$, $p = 0.068$), and Land ($t = 1.695$, $p = 0.090$) were rejected due to a lack of statistical significance, as their p-values exceed the 0.05 threshold (Table 4). These findings demonstrate that, although production exerts a strong influence on Capital, Management and Technology, it does not have a statistically significant effect on Labour, Knowledge, or Land. This underscores the importance of recognising the variability in the influence of production factors when analysing productivity.

***Table 4**. Analytic hierarchy process and ordinary least squares analysis*

AHP	Analytic hierarchy process						
	Stie	Stra	Scapi	Stec	Scono	Sges	Prioritisation
A	0.25	0.27	0.14	0.07	0.19	0.3	0.21
B	0.55	0.37	0.57	0.57	0.2	0.41	0.44
C	0.08	0.13	0.06	0.12	0.07	0.14	0.1
D	0.13	0.23	0.23	0.25	0.54	0.15	0.25
Weighting	0.18	0.17	0.16	0.15	0.15	0.19	
OLS	Ordinary least squares						Intercept
A	−4.41	−4.41	11.17	−5.69	0	0	−3.1
B	0.28	−0.28	−4.04	2.49	−3.53	−0.4	13.61
C	0.16	0.16	−0.33	0.04	−0.52	1.21	−4.22
D	−0.17	−0.17	−0.86	0.51	0.44	−0.14	8.33

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

Table 4 presents the analytic hierarchy process applied to agricultural production in the district of Cuispes. Group B, corresponding to coffee cultivation, received the highest score of 0.44. This alternative excelled in key productive factors such as Land, Capital, and Technology, suggesting that coffee cultivation is not only viable but also has considerable potential for optimisation. These findings imply that increased investment in Technology and land management could lead to substantial productivity gains. In second place, Group D, which refers to banana production, achieved a score of 0.25. This alternative performed particularly well in the areas of Knowledge and Technology, highlighting the importance of training programmes and technology transfer in improving efficiency and outputs for these crops. However, its relatively modest performance overall signals the need to enhance management and marketing strategies to maximise production outcomes. By contrast, Groups C and A, corresponding to cucumber and plantain, recorded lower scores of 0.10 and 0.25, respectively. Although these crops contribute to the local economy, the findings suggest that their management strategies require reassessment. Identifying areas for improvement and adopting more sustainable and efficient agricultural practices will be essential for enabling these crops to compete more effectively in the market.

From the OLS approach, it can be observed that Group B not only ranks highest in the hierarchical analysis but also explains agricultural activity in the district more effectively. In this model, the interaction between Technology and Land emerges as a critical determinant factor for the success of agricultural production success. This correlation suggests that enhancing access to advanced technologies and implementing efficient land management practices could serve as effective strategies to increase agricultural output. Group D, which represents banana production, is identified as the second most significant agricultural activity and also demonstrates strong performance in the use of technology. In contrast, Groups A and C exhibit a negative influence on agricultural activities, implying that their current methods may be inefficient and require comprehensive revision. The analysis of combining the AHP and OLS models indicates that both approaches offer complementary insights into agricultural productivity in Cuispes. The integration of qualitative and quantitative analyses provides a more comprehensive understanding, underscoring the necessity of implementing strategies to enhance resource management, foster technological innovation, and prioritise capacity-building for farmers to optimise agricultural production in the region. Both models underscore the importance of effective resource management, highlighting Group B as the leading alternative for productivity gains, followed by Group D. This finding implies that while AHP prioritises strategic alternatives, OLS provides contextual explanations for the suboptimal utilisation of certain production factors. Therefore, the combination of both models offers a holistic framework for improving agricultural productivity by addressing both the prioritisation of interventions and the optimisation of specific factors in agricultural activities.

Productive factors such as Land, Labour, Capital, Technology, and Knowledge are fundamental to the development of agricultural activity, as they influence both the efficiency and sustainability of farming systems (Pérez-Fernández *et al.,* 2018). In this context, the organisation of farmers is essential for enhancing responsiveness, transparency, and efficiency, thereby optimising agricultural productivity (Ataei *et al.,* 2024). Furthermore, the diversification of agricultural systems and the integration of value-added activities make it can improve productivity through more efficient use of available resources (Cáceres & Gras, 2020). The results obtained confirm the importance of Capital, Management, and Technology in enhancing agricultural productivity in the Cuispes district. This finding is consistent with the results of X. Zhang *et al.* (2023), who highlighted that the adoption of modern technologies and effective resource management optimises land and water use efficiency. Similarly, M. Dimitrijević (2023) demonstrated that investment in agricultural infrastructure and access to credit are key determinants of increased productivity.

However, in contrast to the findings of S. Liu *et al.* (2023), in the present study, factors such as Land and Knowledge did not show a significant influence ($p > 0.05$). This may be explained by barriers to accessing and efficiently utilising these resources, suggesting that the mere availability of Land or Knowledge is not sufficient to improve productivity unless complemented by appropriate training and technical support. In specific crops, the results indicate that for arracacha, cassava, and potato, Capital and Labour are the most influential factors, which aligns with the findings of A. Díaz Díaz and J. Toscano (2022), emphasised that investment in equipment and the efficient use of the Labour force are essential for agricultural profitability. However, in the case of coffee, it was found that Capital has a negative impact, suggesting inefficiencies in its management, contrasting with the results of M. Di Leginio *et al.* (2024), who reported a positive effect of Capital in highvalueadded crops. In crops such as maize, beans, and cucumber, Technology and Labour were identified as the determining factors, in line with M. Tomas-Simin snd D. Janković (2014), who found that the adoption of technology improves productivity on small farms. However, Capital and Knowledge had negative effects, which may be attributed to deficiencies in their application or ineffective Management. On the other hand, in crops such as banana and avocado, Management and Land emerged as key factors, consistent with J. Salinas Vásquez *et al.* (2023), who highlighted the importance of effective planning and access to quality land for agricultural success. The adoption of modern technologies and efficient management practices are presented as a fundamental strategy for increasing agricultural productivity in similar contexts. Additionally, data-driven decision-making, farmer-to-farmer cooperation, and social innovation can transform production processes and contribute to sustainable agricultural development.

CONCLUSIONS

This research provides significant theoretical contributions through the validation of the PLSSEM model, highlighting the key productive factors that influence agricultural productivity. The results show that Capital, Management, and Technology are determinants of farmers' productive performance, aligning with previous studies and supporting the use of linear regression for different groups of agricultural activities. Specifically, Capital and Labour are critical in Group A; Knowledge, Labour, and Technology in Group B; Labour and Technology in Group C; and Land, Management, and Technology in Group D. These findings underscore that the most relevant productive factors vary by farming activity, suggesting the need for further research to identify the most profitable factors in each case. In terms of practical implications, this study highlights the importance of policies that promote equitable access to resources such as Capital and Technology, alongside training strategies in agricultural management. Such policies would enhance the efficiency, competitiveness, and sustainability of the agricultural sector, particularly benefiting farmers in the Cuispes district. However, factors such as Land, Knowledge, and Labour did not show a significant impact on production, which invites a reconsideration of financial support and the development of strategies tailored to the specific needs of each activity.

In terms of limitations, the study is constrained by the limited availability of prior research on productive factors and their impact on agricultural production, hindering a comprehensive comparison. Moving forward, it is recommended that future research broaden its focus to achieve a deeper understanding of these factors, particularly concerning farmers' awareness of their significance. This would support more technologically advanced and sustainable agricultural development, enhancing both yields and the socioeconomic conditions of rural communities.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Аналіз виробничих факторів, що визначають сільськогосподарську продуктивність у Куїспесі

Мануель Антоніо Моранте Давіла
Магістр
Науково-дослідний інститут економіки та розвитку
Національного університету Торібіо Родрігеса де Мендоси, Амазонас
01001, вул. Університетська, 304, м. Чачапояс, Перу
https://orcid.org/0000-0003-3098-9019

Алекс Хав'єр Санчес Панталеон
Магістр
Науково-дослідний інститут економіки та розвитку
Національного університету Торібіо Родрігеса де Мендоси, Амазонас
01001, вул. Університетська, 304, м. Чачапояс, Перу
https://orcid.org/0000-0001-5708-272X

Ірма Долорес Монтенегро Ріос
Магістр
Науково-дослідний інститут економіки та розвитку
Національного університету Торібіо Родрігеса де Мендоси, Амазонас
01001, вул. Університетська, 304, м. Чачапояс, Перу
https://orcid.org/0000-0001-5445-2190

Маріца Ревілья Буелот
Магістр
Науково-дослідний інститут економіки та розвитку
Національного університету Торібіо Родрігеса де Мендоси, Амазонас
01001, вул. Університетська, 304, м. Чачапояс, Перу
https://orcid.org/0000-0002-8275-8696

Оскар Чавес Еспіноза
Магістр
Науково-дослідний інститут економіки та розвитку
Національного університету Торібіо Родрігеса де Мендоси, Амазонас
01001, вул. Університетська, 304, м. Чачапояс, Перу
https://orcid.org/0000-0002-6865-4815

Анотація. Метою дослідження була оцінка впливу виробничих факторів (капіталу, праці, знань, управління та землі) на сільськогосподарську продуктивність у районі Куїспес. У вибірку увійшли 50 виробників, аналіз яких здійснювався з використанням кількісного підходу та моделей структурного моделювання на основі часткових найменших квадратів (PLS-SEM). Дані були згруповані у чотири виробничі групи та проаналізовані за допомогою статистичного програмного забезпечення R із використанням методів звичайних найменших квадратів (OLS) і ієрархічного процесного аналізу (AHP). Результати засвідчили, що родючість ґрунту була основоположним фактором у виробничому процесі фермерів. PLS-аналіз показав, що фактори управління, технологій та знань мали помірну і слабку позитивну кореляцію з продуктивністю (0,680; 0,632 і 0,341 відповідно), тоді як капітал і праця виявили негативну кореляцію (-0,252 і -0,400). Група B вирізнялася найвищими показниками за факторами земля, капітал і технології (AHP: 0,44), що вказувало на високий виробничий потенціал; результати OLS підтвердили, що поєднання технологій і землі було ключовим для досягнення аграрного успіху. Група D вирізнялася показниками знань і технологій (AHP: 0,25), а OLS визначив її як другу за значущістю діяльність у контексті застосування технологій. Натомість групи A і C продемонстрували низькі оцінки (AHP: 0,10 та 0,25), а результати OLS вказали на негативний вплив, що вимагало покращення виробничих методів і управлінських підходів для підвищення конкурентоспроможності. У підсумку було встановлено, що група B виявилася найбільш продуктивним сектором, за нею йшла група D – обидві становили найбільш репрезентативні та прибуткові види діяльності в районі Куїспес. Таким чином, окремі виробничі фактори потребували подальшого розвитку, а державні та приватні інституції мали б сприяти підвищенню сільськогосподарської продуктивності через відповідні публічні політики

Ключові слова: аналіз PLS; ієрархічний процесний аналіз; метод звичайних найменших квадратів; капітал; управління; технології

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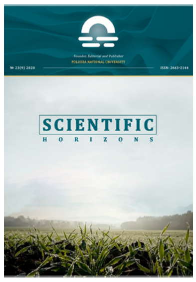

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Irrigation systems as a factor in increasing productivity in agricultural regions of Ukraine

Nataliia Markova*
PhD in Agricultural Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0001-6169-6978

Iryna Smirnova
PhD in Agricultural Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-8976-3818

Yurii Zadorozhnii
Senior Lecturer
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0003-3499-7753

Maksym Horbunov
Graduate Student
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0009-0009-5387-2631

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Abstract. The research relevance is determined by the need to analyse the efficiency of irrigation systems in the agricultural regions of Ukraine against the background of increasing climate change and moisture deficit, which affect the stability of agricultural production. The study aimed to determine the impact of irrigation on the productivity of major crops (sunflower, wheat and winter rape) and to assess the economic efficiency of introducing irrigation technologies in arid regions of Ukraine. The study used agronomic and economic methods of analysis. The irrigation efficiency was determined by comparing crop yields under different water supply regimes. The cost-effectiveness assessment included an analysis of the costs of installing and operating irrigation systems concerning the increase in yields and product quality. The study determined that the use of irrigation increased the yield of sunflower by 28-48%, winter wheat by 15-25%, and rapeseed by 25-35%. Optimal water supply contributed to an increase

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**Corresponding author*

in the protein and gluten content of wheat grain and an increase in the oil level of rapeseed. An analysis of the economic efficiency of irrigation showed that the payback period depended on the type of system: drip irrigation provided the highest yield increase with minimal water consumption, while sprinklers required higher operating costs. Irrigation was substantial in increasing crop productivity in the arid regions of Ukraine. Adaptive irrigation technologies, including automated water management systems, proved to be the most effective. The introduction of modern irrigation methods will help optimise the water balance of soils, reduce the negative impact of drought and increase the economic profitability of agricultural production

Keywords: agriculture; primary sector of economy; water balance; yield; sunflower; winter wheat; winter rape; economic profitability; adaptive technologies

INTRODUCTION

The research relevance is determined by the need to improve irrigation systems in Ukraine against the backdrop of global climate change rising average annual temperatures and increasing frequency of droughts, which significantly limit crop productivity, especially in the southern regions. Water shortages and soil degradation due to excessive water consumption require the development of adaptive water management methods that would optimise the water balance of soils, reduce moisture losses and improve product quality. In addition, the destruction of hydraulic structures, such as the Kakhovka hydroelectric power plant, exacerbates the problem of water supply and requires the restoration and modernisation of irrigation infrastructure for sustainable agricultural production. The issue of efficient use of irrigation systems was widely covered in the scientific literature, in particular in the context of adapting agricultural production to climate change, optimisation of water balance and increase in the economic profitability of crops. S. Tegipko and I. Dimov (2024) studied the introduction of modern irrigation system management technologies and their impact on agricultural productivity. The researchers determined that the use of automated irrigation systems contributed to increased water use efficiency and reduced water losses, which had a positive impact on yields and product quality. The problem of distribution of irrigated land in Ukraine was analysed by N.A. Prokopenko (2023). The researcher determined that most of these areas are concentrated in regions with critical moisture levels, which required the expansion of irrigated areas to ensure stable agricultural production.

At the same time, the environmental impact of irrigation was studied by S.I. Demianenko (2022). The author noted that excessive irrigation can lead to soil salinisation and loss of soil fertility. To reduce this negative impact, it was proposed to introduce adaptive irrigation methods that would take into account the balance of water consumption and soil quality. The problem of restoring land use systems after the destruction of hydraulic structures was a key issue in the research of V.V. Yuzva (2024). The author highlighted that military operations have significantly complicated the provision of agriculture with the necessary water resources, which necessitated the development of a strategy for modernising irrigation infrastructure.

International scientific literature has also extensively studied approaches to efficient water use in irrigated agriculture. S. Attard *et al.* (2024) determined that the use of water-saving technologies in regions with developed irrigation infrastructure increased yields without increasing water consumption. Y. Heiba *et al.* (2024) demonstrated that the use of drip irrigation in combination with precise soil moisture monitoring technologies could significantly reduce water consumption and increase crop productivity at the same time. Climate change and its impact on the functioning of irrigation systems were analysed by H. Zhou *et al.* (2024). The authors proved that even with increased investment in agriculture, the instability of the water balance could decrease agricultural productivity. The effectiveness of different irrigation methods in arid regions was studied by E.T. Ebstu and M. Muluneh (2025). The study proved that drip irrigation in combination with optimised fertilisation schemes ensured maximum productivity with minimal water use. A. Cholik *et al.* (2025) conducted a study on water use in the irrigation system of the Seuseupan region. The researchers determined that effective water management could significantly reduce water consumption and increase crop yields, which is important for maintaining sustainable agricultural production.

The issue of international cooperation in the development of irrigation systems was addressed by O.M. Mohish and O.B. Myhailyuk (2024). The authors noted that the integration of advanced water conservation technologies from international experience could increase the efficiency of the Ukrainian agricultural sector and improve its competitiveness. M.S. Kavunichenko (2024) studied the impact of European integration processes on the development of agriculture in Ukraine, emphasising that the introduction of modern irrigation technologies could ensure higher production profitability and improve product quality. The consequences of the destruction of the Kakhovka hydroelectric power plant were analysed by Y. Dorosh *et al.* (2024). The authors determined that the loss of the reservoir significantly reduced the area of irrigated land in the southern regions, which required a revision of the water management strategy to adapt agriculture to new conditions. Despite the available research, the long-term environmental impacts of irrigation, the impact of different irrigation technologies on product quality, and their economic feasibility on farms of different sizes remain insufficiently understood.

The study aimed to assess the impact of irrigation technologies on the yield and quality characteristics of crops (sunflower, winter wheat and rapeseed), as well as to determine the economic feasibility of their implementation in the arid regions of Ukraine.

MATERIALS AND METHODS

The study of the efficiency of irrigation systems in increasing crop productivity was based on an integrated approach that included agronomic, economic and environmental methods. The object of the study was irrigation systems and their impact on the yield and quality of sunflower (*Helianthus annuus* L.), winter wheat (*Triticum aestivum* L.) and winter rape (*Brassica napus* L.). The experimental plots were in the Southern Steppe zone of Ukraine at the Educational and Research Centre of Mykolaiv National Agrarian University from 2022 to 2024. The research was conducted under three irrigation regimes: no irrigation (control), optimal irrigation and excessive irrigation.

Standardised agronomic methods were used to assess crop productivity, including harvesting from the plots of record, subsequent determination of the crop weight and conversion of the data per hectare. The quality parameters of grain products were analysed in the laboratory: the protein and gluten content of wheat grain was determined by the Kjeldahl method based on the analysis of total nitrogen, while the oil content of rapeseed was estimated by the hexane extraction method with subsequent determination of the mass fraction of fat. The photosynthetic activity of plants was determined using a portable gas analyser LI-6400XT, which was used to record the level of CO_2 assimilation under different irrigation regimes, assessing the impact of water supply on the efficiency of photosynthetic processes. The cost-effectiveness of irrigation technologies was calculated based on an analysis of capital and operating costs. Capital costs included the cost of installing drip and sprinkler irrigation systems while operating costs included water supply, electricity and maintenance costs. Additional gross income from irrigation was defined as the difference between the yields on irrigated and rainfed plots multiplied by the market value of the product (1):

$$\Delta D = (Y_{germ} - Y_{rainfed}) \times P, \quad (1)$$

where ΔD – additional income, UAH/ha; Y_{germ} – crop yield under irrigation, t/ha; $Y_{rainfed}$ – crop yield on the rainfed field, t/ha; P – market price of the product, UAH/t.

The payback period of investments in irrigation systems was calculated as the ratio of capital expenditures to the average annual net profit generated by irrigation (2):

$$T_{payback} = \frac{C_{cap}C_{cap}}{P_{net}P_{net}}, \quad (2)$$

where $T_{payback}$ – payback period, years; C_{cap} – capital costs, UAH/ha; P_{net} – average annual net profit from irrigation, UAH/ha.

ROE was defined as the ratio of net profit to capital expenditure expressed as a percentage (3):

$$ROI = \left(\frac{C_{cap}}{P_{net}}\right)\left(\frac{C_{cap}}{P_{net}}\right) \times 100\%, \quad (3)$$

where ROI – return on investment ratio, %.

The environmental impact of irrigation was assessed by analysing soil salinity using a soil conductivity meter (EC-meter). The water balance of the soil was monitored using tensiometers and Decagon GS3 moisture sensors. Statistical data processing was conducted in the RStudio software environment using agricolae packages for analysis of variance (ANOVA). The difference between the groups was considered statistically significant at the level of p<0.05 by Student's t-test. The study was based on an analysis of scientific papers on the impact of irrigation on crop productivity, the economic efficiency of irrigation systems and their environmental impact. Data on sunflower, winter wheat and rapeseed yield under different irrigation regimes (non-irrigated conditions, optimal irrigation, excessive irrigation) were studied. The quality characteristics of the products, such as protein and gluten content in wheat grain and oil content in rapeseed, was emphasised. The environmental impact of intensive irrigation was also analysed, including the risk of soil salinisation and changes in the water balance.

The study compared the efficiency of different types of irrigation systems, such as drip irrigation and sprinklers. The cost-effectiveness of irrigation systems was assessed by comparing the costs of implementing and operating these technologies with the increase in yields and product quality. Environmental impact of intensive irrigation was emphasised. The prospects for the introduction of adaptive irrigation technologies that incorporate climate change and the dynamics of crop water consumption was analysed in the study. The use of precision irrigation, automated water management systems and innovative approaches to optimising soil water balance were emphasised. Adaptive irrigation systems based on energy-saving solutions and precise water management were noted to ensure an optimal balance between irrigation costs and crop yields.

RESULTS

Influence of irrigation systems on productivity and ecological balance in the Southern Steppe of Ukraine. Irrigation is one of the key factors in stabilising yields and improving the quality of agricultural products in conditions of unstable moisture. The use of irrigation systems helps to compensate for moisture deficits, which is critical in regions with an arid climate, such as the Southern Steppe of Ukraine. The rational use of irrigation optimises the water balance of plants, improves photosynthetic activity and efficient absorption of nutrients (Pichura *et al.*, 2024). Modern approaches to assessing irrigation efficiency address agronomic, economic and environmental parameters. Agronomic efficiency is determined by yield growth, product quality and crop resistance to changes in water regime. The economic assessment involves analysing the profitability of technologies, including irrigation costs, additional agronomic measures and profitability gained through increased yields. The environmental component includes optimising the use of water resources, preventing secondary salinisation of soils and maintaining their fertility (Havrysh *et al.*, 2020).

Assessment of the long-term environmental impacts of irrigation is an important aspect of water management. The long-term use of irrigation systems in regions with a moisture deficit can lead to the accumulation of salts in the soil profile, which negatively affects its physical and chemical properties. In addition, changes in the water regime led to the transformation of agroecosystems, including changes in the species structure of vegetation and soil microbiota (Borovyk *et al.*, 2024). This requires the development of adaptive measures aimed at maintaining ecological balance under intensive irrigation.

Irrigation has a significant impact on the growth and development of sunflower, winter wheat and rapeseed. Sunflower (*Helianthus annuus* L.) is a relatively drought-resistant crop, but under conditions of limited water supply, the leaf surface area decreases, the development of the root system slows down and the period of active photosynthesis is reduced. The introduction of adaptive irrigation systems can increase the yield of this crop by 20-30% due to improved water management and longer growing seasons. Winter wheat (*Triticum aestivum* L.) has high requirements for water supply, especially in the tillering, earing and earing phases. Water deficit during these critical periods can lead to a decrease in the number of productive shoots, a reduction in ear length and a decrease in grain filling. The use of irrigation can increase the yield of winter wheat by 28-48%, as well as improve the quality characteristics of the grain, in particular the protein and gluten content (Korkhova *et al.*, 2023). Winter rapeseed (*Brassica napus* L.) is a crop that responds positively to irrigation, especially in the phases of germination, germination and spring vegetation recovery. Optimal water supply contributes to the development of a powerful root system, increase of biomass and accumulation of oil in seeds. Research shows that irrigation can increase rapeseed yields by 25-35% compared to rainfed conditions, as well as increase the oil content in seeds to 45-47% (Kovalenko *et al.*, 2024). Thus, irrigation increases crop productivity, especially in conditions of natural precipitation deficit. The use of modern irrigation system management technologies allows to optimise water consumption, increase photosynthesis efficiency and ensure stable production of high-quality products.

Sunflower: productivity potential under different irrigation regime. Sunflower (*Helianthus annuus* L.) is one of the leading oilseed crops in Ukraine, especially in the Southern Steppe, where climatic conditions are often characterised by insufficient moisture. The introduction of efficient irrigation systems can significantly increase the productivity of this crop, providing optimal conditions for plant growth and development. According to the study, sunflower has high plasticity and can adapt to changes in moisture supply, but lack of moisture negatively affects its productivity, which is confirmed by the study of the adaptability of different hybrids under conditions of insufficient moisture (Yeremenko *et al.*, 2020). The sunflower hybrids P64HE133 and P64LE25 are highly adaptable to different growing conditions. P64LE25 is characterised by stable yields in different agroclimatic conditions, excellent resistance to root lodging and high tolerance to rust and diseases of leaves and heads. Under irrigated conditions, these hybrids demonstrate an improved morphological structure, including an increase in leaf surface area and the development of a more powerful root system. This contributes to more efficient absorption of water and nutrients and ensures higher productivity compared to rainfed conditions. At the same time, under non-irrigated conditions, there is a reduction in plant size, which can limit their yield potential.

Soil moisture levels directly affect the photosynthetic activity of sunflowers. With optimal irrigation, a stable water balance is maintained, which contributes to an increase in the intensity of photosynthesis, efficient stomatal functioning and better carbon dioxide absorption. In addition, sufficient water supply helps to reduce the temperature of the leaf surface, which has a positive effect on enzymatic processes and the overall metabolism of plants. In contrast, in dry conditions without irrigation, photosynthetic activity decreases due to stomatal closure and reduced transpiration, which is a defensive response to water deficit (Zymaroieva *et al.*, 2021). The results of the study confirm that the introduction of irrigation significantly increases sunflower yields, but the effectiveness of this measure depends on compliance with the optimal irrigation regime. The largest yield increase was noted under optimal irrigation conditions, while excessive water supply, although providing some yield increase, is accompanied by an increased risk of disease development and deterioration of seed quality. Given these factors, it is necessary to maintain a balanced irrigation regime that ensures maximum productivity gains without adverse effects on the plant organism and crop quality.

Data analysis shows that the use of irrigation systems has a significant impact on sunflower yields. Under non-irrigated conditions, plant productivity is lowest due to limited soil moisture, which negatively affects the growth and development of the plant organism. Optimal irrigation provides the highest yields, which is explained by the improvement of physiological processes, including photosynthetic activity and efficient nutrient absorption. At the same time, excessive irrigation, although leading to an increase in yields compared to natural moisture conditions, has certain negative consequences, such as reduced seed quality and an increased risk of plant disease (Table 1).

***Table 1**. Influence of different irrigation regimes on sunflower productivity in 2022-2024 on average*

Irrigation mode	Yield (t/ha)	Increase in yield (%)	Additional observations
No irrigation (control)	2.5	–	Reduced leaf surface area, lower photosynthetic activity
Optimal irrigation	3.7	48%	Increased leaf surface area, high photosynthetic activity
Excessive irrigation	3.2	28%	Increased risk of disease development, reduced seed quality

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

Thus, the introduction of rational irrigation practices is a key factor for realising the productivity potential of sunflower hybrids P64HE133 and P64LE25 in the Southern Steppe of Ukraine. Optimal water supply helps to improve physiological processes, increase photosynthetic activity and provide consistently high yields, which makes these technologies promising for increasing production efficiency.

Winter wheat: the impact of irrigation systems on grain yield and quality. Winter wheat is one of the key grain crops in Ukraine, and its productivity largely depends on the level of water availability and the efficiency of irrigation systems. Research has demonstrated that the use of irrigation not only stabilises yields but also improves grain quality by increasing protein and gluten content (Lykhovyd, 2023). Optimal irrigation contributes to the formation of a productive stem, improves the structure of the ear and ensures a fuller grain filling. The varieties Duma Odeska and Osnova Odeska are characterised by high yields and adaptability to different growing conditions. The genetic characteristics of these varieties provide them with high resistance to lodging, which is a substantial factor in growing technologies under conditions of moisture deficit. One of the key elements of high productivity is the ability of plants to effectively use moisture during periods of moisture deficit. Studies have demonstrated that these varieties demonstrate better drought tolerance compared to other commercial wheat varieties, due to their deeper root system and better adaptive response to changes in the water regime (Korkhova *et al*., 2023).

Irrigation has the greatest impact on winter wheat yields during the critical stages of development: tillering, earing and heading. Insufficient water supply during these periods can significantly reduce the number of productive shoots, limit plant growth and negatively affect grain fullness. The introduction of irrigation during these phases not only increases yields but also improves the quality characteristics of grain, which is a key factor in increasing its technological value for the baking industry (Pichura *et al*., 2024). Table 2 summarises the main indicators of grain yield and quality depending on the level of moisture. The data obtained confirm that optimal irrigation provides the highest yields and improves the biochemical composition of grain and its marketable characteristics. At the same time, excessive irrigation, while contributing to yield growth, does not maximise the improvement of quality indicators, in particular protein and gluten levels, which are important for the food value of wheat.

***Table 2**. The impact of irrigation on the yield and quality of winter wheat grain in 2022-2024 on average*

Parameter	No irrigation (control)	Optimal irrigation	Excessive irrigation
Yield (t/ha)	5.2	7.8	7.2
Protein content (%)	11.8	14.5	13.9
Gluten (%)	24.5	31.2	30
Weight of 1000 grains (g)	38.5	43.2	42

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

The results confirm that optimal irrigation contributes to the most efficient use of water resources, ensuring a balance between productivity and grain quality. The high protein and gluten content of grain obtained under conditions of rational water supply is an important indicator of its suitability for bakery production. At the same time, excessive irrigation, while increasing yields, is accompanied by a decline in grain quality and can create risks of waterlogging. Thus, the use of irrigation systems in the cultivation of winter wheat can increase not only yields but also grain quality indicators. The most effective is the use of irrigation in critical phases of growth and development, which helps to maximise the genetic potential of the crop and ensures high productivity under conditions of stable water supply.

Winter rape: adaptability and productivity in irrigated conditions. Winter rapeseed (*Brassica napus* L.) is one of the leading oilseed crops in Ukraine, and its productivity largely depends on the level of water supply and the efficiency of irrigation technologies. In the Southern Steppe of Ukraine, irrigation is a critical factor that contributes not only to increasing yields but also to improving seed quality. Tempo and Clavir CL rape hybrids are highly adaptable to different levels of water supply. Tempo is characterised by rapid autumn development, which can efficiently use autumn moisture reserves and form a strong root system before entering winter. The hybrid has increased disease resistance and good winter hardiness. Clavir KL, in turn, is a high-yielding hybrid with good yield potential and high oil content. Research demonstrated that under conditions of sufficient water supply, these hybrids form an optimal crop structure with high photosynthetic apparatus productivity, which contributes to the accumulation of dry matter and increase in yield (Kovalenko *et al.*, 2024).

Irrigation has a positive effect on the accumulation of rapeseed biomass, which directly affects its yield. Under optimal moisture levels, yields can increase by 20-30% compared to rainfed conditions. Irrigation also has an important impact on the quality characteristics of seeds, on the oil content. Optimal water supply allows to achieve the maximum oil content, while in dry conditions this metric is significantly reduced. One of the key factors in rapeseed productivity is the development of the root system. A deep and branched root system allows plants to use soil moisture more efficiently, reducing dependence on short-term water shortages. Irrigation conditions promote intensive growth of the root system, which ensures improved absorption of moisture and nutrients. Analysis of the data shows that optimal irrigation ensures maximum yields and improves seed quality, including oil content. At the same time, excessive irrigation, while contributing to biomass growth, leads to a decrease in the efficiency of water use, slightly reducing the oil content of seeds. It is also worth noting that an expanded root system with optimal irrigation allows plants to better withstand short-term droughts, which is an important factor in yield stability (Table 3).

***Table 3**. The impact of irrigation on winter rape productivity on average for 2022-2024*

Irrigation mode	Yield (t/ha)	Oil content (%)	Root system length (cm)
No irrigation (control)	2.8	42.5	95
Optimal irrigation	4.1	46.8	125
Excessive irrigation	3.6	45.1	110

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

Thus, the use of irrigation technologies in the cultivation of winter rape not only increases its yield but also improves the quality of seeds. Tempo and Clavir CL hybrids demonstrate high efficiency under conditions of optimal water supply, which is confirmed by the data on the increase in their yield and oil content. Irrigation also promotes the development of a strong root system, which provides plants with resistance to dry periods and efficient use of water resources.

Physiological and biochemical parameters of crops under irrigated conditions. Irrigation affects the fundamental physiological and biochemical processes of plants, including photosynthetic activity, transpiration and dry matter accumulation. Ensuring an optimal water regime helps to improve the efficiency of assimilation processes, which directly affects crop productivity. Photosynthetic activity is a key indicator of plant productivity, as it determines the rate of organic matter synthesis (Oliynyk *et al.*, 2020). Studies have shown that irrigation helps to maintain the optimum level of photosynthetic potential through improved water supply. The chlorophyll content (Chl a+b) in sunflower leaves under irrigation increased by 15-22%, in winter wheat by 18-25%, and in rapeseed by 20-27% compared to rainfed conditions. This indicates the maintenance of a stable state of chloroplasts and an increase in the activity of the photosynthetic apparatus. The intensity of photosynthesis in irrigated crops increased by an average of 20-35%, depending on the crop. The largest increase in this indicator was observed in rapeseed and winter wheat, due to their high sensitivity to soil moisture. Improved water supply contributed to active carboxylation, increased productive leaf apparatus and a general increase in photosynthetic productivity.

Transpiration is an important process that maintains plant temperature and regulates the absorption of mineral elements (Boiko *et al.*, 2024). Data analysis demonstrated that under irrigation conditions, the average transpiration rate for sunflowers was 5.8-6.5 mmol/m^2/s, which is 10-15% higher than in rainfed crops. In winter wheat, this figure reached 4.2-5.1 mmol/m^2/s, and in rapeseed 5-5.8 mmol/m^2/s. The increased intensity of transpiration with sufficient moisture indicates active water exchange and improved regulation of the heat balance of plants. This is an important factor in increasing the resistance of crops to high temperatures, which is typical for arid regions. The accumulation of dry matter is an integral indicator of the efficiency of growth processes. Irrigation promotes more intensive synthesis of organic compounds, which has a positive impact on the structure of the crop. The dry matter content of irrigated sunflower crops was 44-48%, which is 8-12% higher than under rainfed conditions. In winter wheat, this figure increased to 56-62%, ensuring better grain filling. In rapeseed, the dry matter content increased to 40-44%, which contributed to an increase in seed oil content (Pichura *et al*., 2024). Thus, the use of irrigation contributes to the improvement of the physiological and biochemical parameters of crops, providing optimal water supply, increased photosynthetic activity and improved crop quality. The use of efficient irrigation systems reduces drought stress, increases plant resilience and ensures high productivity under unstable water conditions.

Comparative assessment of the economic efficiency of irrigation. Irrigation is a strategically important factor in agriculture, especially for water-scarce regions such as the Southern Steppe of Ukraine. Its implementation helps to increase yields, improve product quality and reduce risks associated with climate change. At the same time, the use of irrigation systems requires significant financial investments, which requires a comprehensive analysis of their economic efficiency. The calculation of the costs of installing and operating different irrigation systems shows that drip irrigation, although requiring a higher initial investment, is more cost-effective in the long run due to reduced water and electricity consumption. Sprinkler systems, in turn, have lower capital costs but are more expensive to maintain (Table 4).

Table 4*. Estimated cost of installation and operation of irrigation systems*

Parameter	Drip irrigation	Sprinkler systems
Installation cost (thousand UAH/ha)	45-60	75-90
Annual operating costs (thousand UAH/ha)	5-8	12-15
Water consumption (m^3/ha)	2,500-3,500	5,000-7,000
Electricity consumption (kWh/ha)	450-600	1,000-1,400
Average yield increase (%)	20-35	15-30

Source: *compiled by the authors*

The impact of irrigation on yields depends on the crop. The largest increase in productivity is observed in winter wheat, where the yield increase reaches 2.3-2.8 t/ha. For rapeseed, this figure is 1.2-1.7 t/ha, and for sunflower – 1-1.5 t/ha. Accordingly, the economic effect of using irrigation also varies depending on the crop, which is confirmed by the calculations of additional profit (Table 5).

Table 5*. The impact of irrigation on yields and profitability*

Crop	Yield with irrigation, Y_{germ} (t/ha)	Yield without irrigation, $Y_{rainfed}$ (t/ha)	Price (UAH/t)	Additional yield (t/ha)	Additional income (UAH/ha)	Payback period (years)	ROI (%)
Winter wheat	7.8	5.2	7,000	2.6	18,200	2.75	36.4
Sunflower	3.7	2.5	21,000	1.2	25,200	1.98	50.4
Winter rape	4.1	2.8	15,000	1.3	19,500	2.56	39

Source: *compiled by the authors*

Regarding the obtained indicators, it is determined that the payback period of irrigation systems is one of the key factors in deciding on their implementation. The fastest payback period for drip irrigation is 1.7-2.4 years on average, while for sprinklers this period is 3-4.4 years (Table 6).

Table 6*. Payback calculation*

System	Capital expenditures, C_{cap} (UAH/ha)	Net profit, P_{net} (UAH/ha)	Payback, $T_{payback}$ (years)	ROI (%)
Drip irrigation	50,000	21,000	2.38	42
Sprinkler irrigation	35,000	15,000	2.33	43

Source: *compiled by the authors*

Thus, the results of the analysis demonstrated that although the introduction of irrigation systems requires significant financial resources, they are economically justified due to the steady increase in yields and incomes. The most efficient option for farms with limited water resources is drip irrigation, which provides a quick payback and minimises water and electricity consumption. Sprinkler systems may be appropriate for large areas where flexibility in water supply is required, but their cost-effectiveness is lower due to higher operating costs. The choice of the optimal system should be based on the agricultural and climatic conditions of the region, the financial capacity of the farm and the availability of water resources.

Environmental impact analysis of irrigation systems. The use of irrigation has a significant impact on the ecological state of agricultural landscapes, changing the physical and chemical properties of the soil, its microbiological composition and water balance. Rational water management helps to maintain soil productivity, while inefficient irrigation methods can lead to soil degradation, salinisation and structural disruption. Studies of the impact of irrigation on soil microbiota have shown that under conditions of regular moisture, the activity of microorganisms increases. In particular, the content of nitrogen-fixing bacteria increased by 12-18% compared to rainfed conditions, which contributed to the accumulation of available nitrogen for plants. At the same time, excessive moisture created a favourable environment for the development of fungal infections, which could negatively affect the phytosanitary condition of crops (Merza *et al*., 2023; Zamani *et al*., 2021).

Changes in the chemical composition of the soil under irrigation were manifested in an increase in the electrical conductivity of the soil solution, which indicated the accumulation of salts. Depending on the source of irrigation water, after 3-5 years of intensive use of irrigation, the salinity level increased by 20-30%, which led to a decrease in the availability of phosphorus and potassium, as well as deterioration of soil structural properties. One of the positive aspects was the stabilisation of the humus content: constant moisture supply contributed to the uniform decomposition of organic matter and active humification, which had a positive effect on soil fertility (Cepeda *et al*., 2024; Corwin, 2021). The dynamics of soil moisture content depended on the irrigation technology used. The analysis showed that drip irrigation ensures an even distribution of moisture in the arable layer (0-30 cm) at the level of 70-80% of the lowest moisture capacity, which is optimal for most crops. At the same time, the use of sprinklers resulted in uneven moisture, especially in the upper soil horizons, where the moisture content was 55-65% of the lowest moisture capacity. This caused uneven water consumption by plants and contributed to increased evaporation, which reduced irrigation efficiency (Khondoker *et al*., 2023).

Thus, the implementation of irrigation systems requires comprehensive environmental monitoring to prevent soil degradation. The optimal solution is to use drip irrigation, which minimises the risk of salinity, promotes even moisture distribution and maintains the stability of the microbiological environment. The use of water with a controlled salinity level and adaptive irrigation regimes helps to reduce the negative impact on ecosystems and maintain soil fertility in the long term.

International experience and prospects of adaptive irrigation. Studying international experience of using irrigation systems in regions with similar climatic conditions is important for optimising water use in Ukraine. In the United States (California, Texas), Spain, Israel and Australia, modern irrigation technologies are actively used to increase yields and reduce water consumption. Precision irrigation methods, remote soil moisture monitoring, and automated irrigation systems that ensure even distribution of moisture and optimise water consumption are highly effective (Didkovska, 2023). The introduction of such technologies could become a promising area for the agricultural regions of Ukraine. Increased climate change, rising average annual temperatures, changes in precipitation distribution and an increase in the frequency of droughts necessitate the introduction of adaptive water management systems (Shahini, 2024). Such technologies are already being actively used in Spain and Australia, where deficit irrigation is practised, which involves optimising irrigation rates without reducing yields. Israel has implemented systems for the reuse of treated water, which can reduce freshwater consumption by 40-50%. Similar approaches can be effective in Ukraine, especially in the southern regions with limited water resources.

Drip irrigation, automated systems and soil moisture sensors play an important role in improving irrigation efficiency. Drip irrigation, which is widely used in the US and Spain, can reduce water losses by 30-50%, ensuring that the root zone of plants is moistened. Automated monitoring systems that evaluate soil moisture, evaporation and weather conditions can reduce water use without sacrificing yields. Studies show that the use of such technologies can increase yields by 15-30%, depending on the crop and growing conditions. For example, in the United States, the introduction of precision irrigation has increased corn yields by 20-40%, and in Spain – wheat productivity by 15-30% (Ivaniuta *et al*., 2020). In addition, such systems have a positive impact on the physical and chemical properties of soils, contributing to the preservation of humus and reducing the risk of secondary salinisation.

The results of the study show that the efficiency of irrigation technologies in Ukraine is in line with general international trends. However, to increase the productivity and efficiency of water use, it is necessary to adopt the world's advanced technologies: precision irrigation and remote humidity monitoring will help optimise water consumption, and the use of energy-saving irrigation systems will reduce electricity consumption by 20-30%, and the introduction of deficit irrigation will reduce irrigation volumes with minimal impact on yields. Another promising area is the use of treated wastewater for irrigation, which is actively used in Israel and Spain and could be useful for Ukraine, especially in industrial regions with water shortages. Thus, international experience confirms the effectiveness of modern irrigation systems and the feasibility of their implementation in Ukraine. The use of precise water management, adaptive irrigation regimes and water reuse technologies will reduce the pressure on water resources and ensure stable yields in the face of climate change.

DISCUSSION

A study of the effectiveness of irrigation systems in the Southern Steppe of Ukraine confirmed their importance for stabilising yields and improving product quality under conditions of natural moisture deficit. The results correlate with the findings of other scientific studies on the impact of irrigation on agricultural productivity and its environmental impact. The results of this study confirmed that the use of irrigation technologies helps to increase the yield of sunflower, winter wheat and winter rapeseed by 15-35%, depending on the crop and the level of water supply. Similar trends were observed in the study by P. Lykhovyd (2021), which noted that the lack of precipitation in Ukraine significantly affects the yield of major crops, and an increase in irrigated areas is needed to ensure stable production. At the same time, according to a study by X. Cao *et al.* (2021), the efficiency of water use in the agricultural sector is closely related to the level of implementation of modern irrigation technologies, in particular drip and differentiated irrigation, which can significantly improve the economic performance of farms.

The study confirmed that optimal irrigation contributes to an increase in photosynthetic activity, root system development and product quality. T. Zhang *et al.* (2021) also demonstrated that the use of different irrigation methods in arid regions affects grain quality and corn yields, and the most effective were drip and subsurface irrigation systems, which reduce water consumption and ensure uniform plant development. Similar conclusions were reached in this study, as excessive irrigation led to waterlogging of the soil, increased risk of disease development and reduced economic efficiency of crops. The cost-effectiveness analysis demonstrated that irrigation is a justified measure in arid regions, but the cost of its implementation can be a significant limiting factor. A study by N. Merza *et al.* (2023) confirmed that the profitability of irrigated agriculture depends not only on yield growth but also on the level of water supply costs, which can reduce economic feasibility in farms with insufficiently developed infrastructure. This study also determined that excessive irrigation costs can lead to a decrease in the level of profitability, therefore it is necessary to introduce resource-saving water management methods to increase economic efficiency.

The environmental impact assessment confirmed that excessive irrigation contributes to the accumulation of salts in the soil profile, which can negatively affect its fertility in the long term. Similar conclusions were drawn by M. Khondoker *et al.* (2023), noting that the increase in soil salinity due to the excessive use of irrigation systems is one of the global problems of agriculture, which requires adaptive approaches to water use, particularly the use of desalination technologies. The findings of this study also confirmed that to prevent soil degradation, it is necessary to implement adaptive management of irrigation systems that incorporate the balance between crop productivity and environmental sustainability. The use of modern irrigation technologies has a positive impact on the productivity of agricultural systems (Yeraliyeva *et al.*, 2017). The study by Y.V. Cepeda *et al.* (2024) confirmed that technical modernisation of irrigation systems can significantly increase the efficiency of water use, reduce moisture loss and improve the environmental situation. This study also determined that the rational management of irrigation systems helps to stabilise yields and minimise water losses, which is important in regions with limited water resources.

The analysis of the economic efficiency of irrigation confirmed that optimal water supply provides the highest profitability of agricultural production, but excessive irrigation can lead to higher water supply costs and reduced economic feasibility. Similar findings were obtained in the study by O. Zamani *et al.* (2021), stating that the implementation of water conservation policies and efficient water pricing is an important tool for increasing the productivity of the agricultural sector. The study established that the efficiency of water use directly depends on the optimisation of irrigation technologies and the rational use of water resources. An analysis of the environmental impacts of irrigation has shown that excessive water use contributes to soil salinity, which can negatively affect long-term land fertility. A study by D.L. Corwin (2021) also confirmed that climate change and intensive irrigation are causing an increase in soil salinity, which requires adaptive approaches to water use. The study determined that to prevent soil degradation, it is necessary to use methods of optimal water balance and integrated water management.

An assessment of promising irrigation methods has confirmed that the use of alternative energy sources for water supply can help improve the economic efficiency of irrigation systems. The study by J. Rana *et al.* (2021) demonstrated that the use of solar energy for irrigation systems can significantly reduce electricity costs and increase the financial sustainability of agricultural enterprises. Similar conclusions were obtained in this study, as the economic efficiency of irrigation significantly depends on the level of energy and water supply costs. Rational management of irrigation systems requires the introduction of modern technologies for monitoring and automated control of soil moisture. S. Alharbi *et al.* (2024) confirmed that the use of technological solutions, such as remote soil moisture monitoring and automated irrigation systems, increases water use efficiency and minimise moisture losses. The study also noted that the introduction of precision irrigation and automated water management systems is a promising area for optimising water use in arid regions.

The results of the study are consistent with the findings of B. Golla (2021), stating that agricultural production in arid regions largely depends on water use efficiency, and the use of adaptive irrigation technologies helps to improve crop productivity. This paper confirmed that optimisation of irrigation technologies can ensure stable production in the face of climate change and reduced natural moisture. The obtained results confirm that the introduction of modern irrigation methods contributes to the optimal distribution of moisture in the soil, reducing its evaporation and improving the overall condition of agrocenoses. Similar conclusions were drawn by S. Lin *et al.* (2024), noting that the combination of drip irrigation with mulching not only improves the water supply of plants but also increases the efficiency of fertiliser use, which has a positive impact on cotton yields. This study also confirmed that the optimal combination of water and mineral nutrition helps to maximise crop potential while reducing unproductive water losses. A comparison of the results obtained with previous scientific studies confirmed that further development of irrigation systems should be aimed at introducing energy-efficient and environmentally friendly irrigation technologies. Optimisation of the water regime and adaptation of irrigation technologies to specific agricultural and climatic conditions will ensure a stable level of crop productivity without a negative impact on the environment.

CONCLUSIONS

Irrigation is a key factor in stabilising yields and improving product quality in conditions of unstable water supply. Optimal water supply increases the photosynthetic activity of plants (by 20-35%), increases the chlorophyll content (by 15-27%) and improves the water regime, which has a positive impact on their productivity. The study demonstrated that the use of irrigation ensures optimal absorption of nutrients and the development of a powerful root system, which contributes to the increase of crops' resistance to drought conditions. The study determined the use of irrigation provides an increase in yield: for sunflower – optimal irrigation by 48%, excessive irrigation by 28%; winter wheat – by 15-25%, winter rape – by 25-35%. In addition, the content of dry matter and oil in the seeds increases, which improves the quality of the products. Studies have confirmed that irrigation can reduce the impact of stress factors associated with moisture deficit while maintaining the productive potential of plants.

The economic evaluation of irrigation systems confirmed their financial feasibility. It was found that the average payback period for irrigation is 1.7-4.4 years, depending on the type of system and crop. The use of adaptive water management technologies allows optimising irrigation costs, which increases the overall profitability of production. At the same time, the study determined that excessive irrigation can be accompanied by increased water supply costs and an increased risk of secondary soil salinisation. An analysis of the environmental impacts demonstrates the need for rational water management. It has been established that intensive irrigation without appropriate control causes accumulation of salts in the soil (by 20-30%), changes in its physical and chemical properties, and disruption of the water balance. At the same time, the use of adaptive irrigation methods stabilised the humus balance, improve the microbiological activity of the soil and maintain its fertility in the long term.

Comparison with international experience has confirmed the effectiveness of modern irrigation technologies, including precision irrigation, automated moisture monitoring and deficit irrigation, which are actively used in the US, Spain, Israel and Australia. These technologies help to minimise water consumption, increase irrigation efficiency and reduce the burden on water resources. Adaptation of such approaches, including the introduction of energy-saving systems, precision irrigation using moisture sensors, as well as the use of reuse and recycling technologies for irrigation, is promising for Ukraine. The results of the study compiled recommendations for the further development of irrigated agriculture. The rational management of irrigation systems should be based on the principles of adaptive water use, considering the needs of specific crops and agroclimatic conditions. It is advisable to introduce automated humidity control systems, apply deficit irrigation and use precise water supply systems to optimise water resources. Further research could conduct an empirical verification of the identified patterns in the field and developing integrated approaches to managing irrigation systems in the face of climate change. A promising direction is the integration of modern technologies for moisture monitoring, precision agriculture and economic optimisation of irrigation to ensure sustainable development of the agricultural sector of Ukraine.

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CONFLICT OF INTEREST

None.

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Зрошувальні системи як фактор підвищення продуктивності в аграрних регіонах України

Наталія Маркова
Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-6169-6978
Ірина Смірнова
Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-8976-3818
Юрій Задорожній
Старший викладач
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0003-3499-7753
Максим Горбунов
Аспірант
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0009-0009-5387-2631

Анотація. Актуальність дослідження зводиться до необхідності аналізу ефективності зрошувальних систем в аграрних регіонах України на фоні посилення змін клімату та дефіциту вологи, що впливають на стабільність сільськогосподарського виробництва. Метою дослідження було визначити вплив зрошення на продуктивність основних сільськогосподарських культур (соняшника, пшениці та ріпаку озимих) та оцінити економічну ефективність впровадження зрошувальних технологій у посушливих регіонах України. У дослідженні використовувалися агрономічні та економічні методи аналізу. Визначення ефективності зрошення здійснювалося шляхом порівняння врожайності культур за різних режимів водозабезпечення. Оцінка економічної ефективності включала аналіз витрат на встановлення та експлуатацію зрошувальних систем у співвідношенні до приросту врожайності та підвищення якості продукції. Було встановлено, що застосування зрошення дозволило підвищити врожайність соняшника на 28-48 %, пшениці озимої – на 15-25 %, а ріпаку – на 25-35 %. Оптимальне водозабезпечення сприяло збільшенню вмісту білка та клейковини у зерні пшениці, а також підвищенню рівня олії в насінні ріпаку. Аналіз економічної ефективності зрошення показав, що термін окупності залежав від типу системи: краплинне зрошення забезпечувало найвищий приріст врожайності при мінімальних витратах води, тоді як дощувальні установки потребували більших експлуатаційних витрат. Зрошення відіграло важливу роль у підвищенні продуктивності сільськогосподарських культур у посушливих регіонах України. Найбільш ефективними виявилися адаптивні технології зрошення, що включали автоматизовані системи управління водними ресурсами. Впровадження сучасних методів зрошення сприятиме оптимізації водного балансу ґрунтів, зменшенню негативного впливу посухи та підвищенню економічної рентабельності агровиробництва

Ключові слова: сільське господарство; первинний сектор економіки; водний баланс; врожайність; соняшник; пшениця озима; ріпак озимий; економічна рентабельність; адаптивні технології

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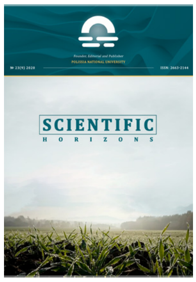

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Cost structure in Kazakhstan's grain farming and methods of its optimisation

Galymzhan Kerimbek
PhD in Economic Sciences, Professor
Al-Farabi Kazakh National University
050040, 71 Al-Farabi Ave., Almaty, Republic of Kazakhstan
https://orcid.org/0000-0003-0563-8399

Katira Mamutova*
PhD in Economic Sciences, Associated Professor
Mukhtar Auezov South Kazakhstan University
160012, 5 Tauke Khan Ave., Shymkent, Republic of Kazakhstan
https://orcid.org/0000-0003-0676-1620

Aizhan Oralbayeva
PhD in Economic Sciences, Associated Professor
Korkyt Ata Kyzylorda University
120014, 29A Aiteke bi Str., Kyzylorda, Republic of Kazakhstan
https://orcid.org/0000-0002-9233-8599

Zhanymgul Baimukasheva
PhD in Economic Sciences, Associated Professor
Aktobe Regional University named after K.Zhubanov
030000, 34 Aliya Moldagulov ave., Aktobe, Republic of Kazakhstan
https://orcid.org/0000-0002-2593-2520

Gulmira Nurbayeva
PhD in Economic Sciences, Associated Professor
Toraighyrov University
140008, 64 Lomov Str., Pavlodar, Republic of Kazakhstan
https://orcid.org/0000-0001-7006-4403

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Abstract. The optimisation of costs in Kazakhstan's grain farming is a pressing issue driven by the need to enhance the economic efficiency of agricultural production amid rising resource costs and increasing competition in the international market. The objective of this study was to substantiate approaches to reducing costs in grain farming by analysing cost structures and assessing the effectiveness of technological and economic measures. The study employed variation statistics, regression analysis, econometric modelling, cost-benefit analysis, and investment profitability calculations to evaluate the efficiency of various production strategies. The research

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*Corresponding author

findings demonstrated that the key directions for cost optimisation included the introduction of minimum tillage technologies, particularly no-till and strip-till systems, automation of agrotechnical processes, rational use of fertilisers and plant protection products, as well as the utilisation of digital platforms for product sales. An analysis of statistical data for 2020-2024 indicated that the adoption of minimum tillage technologies contributed to a 50-60% reduction in fuel costs, a 20-25% decrease in machinery depreciation costs, and a 15-20% reduction in labour costs. Automated agricultural management systems enabled an 18-22% reduction in fertiliser and plant protection product costs due to precise resource distribution. Optimisation of logistical processes and constructing grain storage facilities contributed to a 12-18% reduction in product losses during transportation and a 10-15% decrease in logistics costs. The use of digital platforms for product sales ensured a 40-50% reduction in transaction costs and a 60% decrease in buyer search costs. The overall effect of implementing the proposed measures allowed for a 12-17% reduction in grain production costs, depending on farm scale and applied technologies. The proposed recommendations were aimed at reducing production costs, ensuring the financial stability of the agricultural sector, and enhancing the competitiveness of Kazakhstan's grain farming

Keywords: economic efficiency; technological innovations; minimum tillage; agricultural automation; resource management

INTRODUCTION

The rise in costs in Kazakhstan's grain farming is influenced by several factors, including increasing fuel and lubricant prices, rising costs of agrochemicals and seeds, changes in state agricultural policy, and climatic fluctuations affecting yield levels. In the context of global competition, effective management of cost structures is one of the key factors in ensuring the financial stability of the agricultural sector. The implementation of modern agrotechnologies, precision farming methods, and digital platforms plays a particularly significant role in optimising resource use and improving agricultural enterprise productivity. The lack of a systematic approach to cost reduction in grain production may lead to a decline in the competitiveness of Kazakhstan's agricultural products in the international market, necessitating the development of scientifically grounded strategies for optimising production costs.

Research on the optimisation of farming technologies and the enhancement of agricultural production efficiency encompasses various aspects of economic, environmental, and agrotechnical feasibility. The introduction of zero tillage technology in small farms in Kyrgyzstan, as analysed in the study by A. Tadjiev *et al.* (2023), demonstrated a 23% reduction in soil preparation costs and a 15% overall decrease in production costs. However, it was accompanied by an increase in hired labour costs (by 13%) and herbicide costs (by 15%). Moreover, the long-term effects of the technology on soil productivity, yield levels, and farm financial stability remained unassessed, along with macroeconomic factors influencing its effectiveness. The study by S. Turebayeva *et al.* (2022) assessed the productivity of winter wheat under direct seeding and various fertilisation schemes in arid regions of Southern Kazakhstan. It was established that phosphorus fertiliser application accelerated grain ripening, while the combination of nitrogen and phosphorus fertilisers prolonged the growing season, and the lowest production costs were observed with the use of growth stimulants with microelements. However, the long-term effects of the technology on soil fertility, economic risks associated with fluctuating agrochemical prices, and potential climatic variations that could impact the profitability of this method were not considered.

The research by S.B. Kenenbaev *et al.* (2021) examined resource-saving farming systems in South-Eastern Kazakhstan, focusing on soil moisture retention and soil fertility improvement. However, the study lacked a detailed economic efficiency analysis of the implemented technologies, including a comparison of costs and profitability of different tillage methods. The absence of an assessment of financial stability impacts on farms, as well as the social aspects of adapting new methods, limited the practical applicability of the findings.

The optimisation of water use through drip irrigation and the application of mineral fertilisers in South-Eastern Kazakhstan was the subject of a study by A.S. Sembayeva *et al.* (2025). The study recorded an increase in maize (*Zea mays* L.) yield ranging from 0.87 to 2.85 t/ha. However, it lacked an analysis of the long-term impact of these technologies on the physico-chemical properties of the soil, particularly potential salinisation processes. Additionally, the economic accessibility of these technologies for local farmers, which could influence their widespread adoption, remained unassessed. The study by N. Suleimenova *et al.* (2021) examined the environmental sustainability and productivity of rapeseed (*Brassica napus* L.) in South-Eastern Kazakhstan under shallow chisel tillage (mini-till). It was found that this approach increased yield by 21.3% and provided an additional income of 29.3 thousand tenge/ha. However, the study did not consider potential risks such as weed and pathogen accumulation, the impact of climate change on the technology's effectiveness, or comparisons with alternative rapeseed cultivation methods.

B.J. Olorunfemi and S.E. Kayode (2021) analysed post-harvest grain losses and the efficiency of modern storage technologies. The authors noted that the use of metal silos, improved bags, and wooden storage facilities helped reduce losses caused by pests and mould. They also emphasised the importance of implementing automated inventory management systems. However, economic barriers to adopting these technologies, their accessibility to small farmers, and the environmental aspects of long-term grain storage were not assessed, which could affect their real efficiency under different farming conditions. R.K. Zhapayev *et al.* (2023) studied the physico-chemical properties of soil and water balance under different tillage methods in South-Eastern Kazakhstan. It was established that zero tillage contributed to moisture retention (29.8-54.8 mm) but increased soil density (1.32-1.33 g/cm^3) and reduced nitrate nitrogen content. The highest yield (1.76 t/ha) was recorded with minimum tillage, confirming its effectiveness in rainy conditions. However, the long-term impact of soil compaction on fertility and the potential consequences of reduced nitrate nitrogen content for future yields remained unassessed.

The study by A.E. Kokenova *et al.* (2022) focused on grain production management processes and their economic efficiency. It proposed methods for diagnosing production problems and modelling factors influencing enterprise productivity. However, the study lacked empirical analysis of the effectiveness of the proposed strategies under real conditions and did not account for macroeconomic factors or the risks of implementing new management approaches. The issue of rational use of dark chestnut soils in Northwestern Kazakhstan was explored in the study by Z.M. Gumarova *et al.* (2025). It considered possibilities for restoring fallow land through the use of black fallow and leguminous crops. However, the study lacked an economic analysis of the profitability of these measures and the long-term impact of different tillage methods. Social aspects of their implementation and the influence of climate change were also insufficiently explored. A separate area of research is innovative agricultural management in Kazakhstan, studied by Z. Taishykov *et al.* (2023). Key directions were identified, including the introduction of modern technologies, financing agricultural science, genomic selection, and the optimisation of agrotechnical processes. However, the study lacked a detailed economic analysis of these innovations, risk assessments for small and medium-sized farms, and comparative analysis with countries possessing similar agroclimatic conditions.

The aim of the study was to develop scientifically grounded approaches to optimising the cost structure in Kazakhstan's grain farming based on an analysis of the main components of the cost base, an assessment of the efficiency of technological and economic solutions, and the modelling of strategies for reducing production costs.

MATERIALS AND METHODS

The study is analytical and aimed at assessing the cost structure in Kazakhstan's grain farming and developing strategies for its optimisation. The timeframe covers the period from 2020 to 2024, allowing for an evaluation of cost structure changes and the effectiveness of applied technological and economic measures. The research is based on the analysis of statistical data, economic calculations, and optimisation scenario modelling. Primary and secondary data were obtained from multiple sources to ensure a comprehensive analysis of the issue. The main sources of statistical data included the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), Food and Agriculture Organization (2024), the World Bank (n.d.), and the Organisation for Economic Co-operation and Development (2023).

The study applied methods of variation statistics to analyse the distribution of costs in Kazakhstan's grain farming. The arithmetic means of expenses for specific resources (fuel, fertilizers, seeds, labour costs) and their standard deviation were determined, allowing for an assessment of the stability and variability of the cost structure across different regions of the country. The reliability of differences between cost groups was evaluated using Student's t-test at a significance level of $p \leq 0.05$. To identify the relationship between costs and economic efficiency, econometric analysis was applied, particularly regression modelling. Models were developed to establish dependencies between material cost levels and grain yields, enabling an assessment of the impact of specific cost categories on overall farm productivity. Correlation analysis identified interdependencies between the level of mechanisation in production processes and the share of labour costs. Additionally, to evaluate the economic feasibility of technological innovations and management strategies, the Cost-Benefit Analysis method was used. A comparative analysis of costs for traditional and innovative soil cultivation methods (conventional plowing, No-Till, Strip-Till) was conducted to assess their profitability. The Return-on-Investment analysis was also applied to determine the economic impact of implementing automated agricultural management systems and digital platforms for grain sales.

The interpretation of results was based on a comparison of obtained statistical indicators with data from previous years and international standards in grain production, particularly the provisions of the Codex Alimentarius (1963) and the regulations of the International Grains Council (n.d.). Analysing cost structure dynamics made it possible to identify key factors influencing production costs and the financial stability of farms. The results of optimisation scenario modelling were considered from the perspective of their potential impact on the long-term sustainability of Kazakhstan's agricultural sector. The assessment of the effectiveness of economic measures and technological innovations took into account not only direct changes in cost structure but also prospects for increasing the competitiveness of the grain sector in the international market. The obtained results allowed for the formulation of well-founded recommendations for cost optimisation in Kazakhstan's grain farming. Identified correlations between cost levels and production efficiency contribute to the development of effective management strategies aimed at reducing production costs. The analysis of the economic feasibility of technological solutions and financial mechanisms enables the determination of the most promising development directions for the industry, considering modern challenges.

RESULTS

Analysis of cost structure in Kazakhstan's grain farming. The cost structure in Kazakhstan's grain farming is shaped by the interaction of technological, economic, and natural-climatic factors. The main components of the cost base include material expenses, particularly expenditures on fertilizers, seeds, and plant protection products, which have the greatest impact on production costs. A significant share of expenses also consists of energy costs, including fuel and electricity expenditures, which are highly dependent on fluctuations in energy prices. Labour costs and depreciation expenses create additional financial burdens on producers, especially considering seasonal employment fluctuations and the need to modernise agricultural machinery. Analysing the structure of these expenses allows for an assessment of the capital intensity of grain production and the identification of ways to improve its economic efficiency.

The dynamics of costs in Kazakhstan's grain farming reflect a trend toward an increasing share of material expenses, which may be linked to rising resource prices and stricter requirements for ensuring stable yields. At the same time, there is a decline in the share of labour costs, which may indicate an increasing level of mechanisation and automation in production processes (Tolepbergen, 2022). Different regions of Kazakhstan demonstrate variations in cost structure due to soil and climatic conditions, resource accessibility, and applied agrotechnologies. Evaluating these factors helps determine regional differences in production costs of grain crops and opportunities for their optimisation. Expenditures on fertilizers, seeds, and plant protection products are key components of the material base of production, determining the cost price and productivity of the agricultural sector. The analysis of cost distribution over the period from 2020 to 2024 allows for an assessment of key trends in resource use and the identification of directions for their optimisation (Fig. 1).

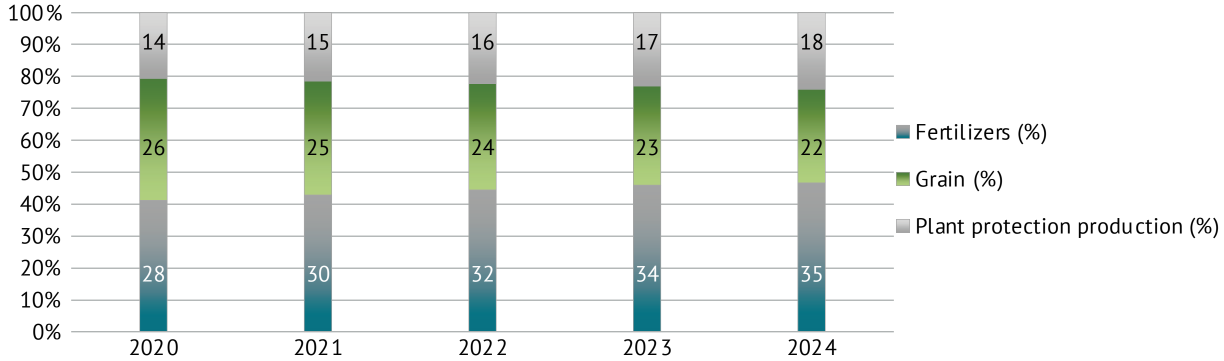

***Figure 1**. Distribution of expenditures on material resources in Kazakhstan's grain farming (%)*
***Source:** created by the authors based on Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), Food and Agriculture Organization (2024), Organisation for Economic Co-operation and Development (2023), World Bank (n.d.)*

During the analysed period, a steady increase in fertilizer costs was observed, which may result from the intensified use of mineral fertilizers to maintain stable yields. This trend was also influenced by changes in soil chemical composition and the need for increased micronutrient application to preserve soil fertility. At the same time, the adaptation of precision farming technologies enabled agricultural enterprises to optimise fertilizer application, reducing losses and increasing efficiency. The reduction in the share of seed costs is associated with the improvement of breeding methods, which ensure the development of high-yielding varieties with enhanced agronomic characteristics. The introduction of more drought- and disease-resistant crops reduces the need for reseeding and increases the efficiency of seed material use. The increase in plant protection costs is likely linked to the spread of pests and diseases, necessitating more intensive use of pesticides and fungicides to maintain yields.

Fuel and lubricants represent another significant component of the cost structure. Given the vast areas of cultivated land in Kazakhstan, fuel expenses can account for 15-20% of total costs. Fluctuations in oil and petroleum product prices directly impact this cost segment. Depreciation costs related to the use of agricultural machinery and equipment also constitute a substantial share of total expenditures. Depending on the intensity of machinery use and its cost, depreciation charges may reach 10-15% of total expenses. This highlights the importance of efficient asset management and investment in modern equipment. Labour costs form another crucial component of the cost structure. Due to the seasonal nature of grain farming, labour expenses may vary, but on average, they account for approximately 10% of total costs. Wage levels, the availability of skilled workers, and working conditions influence this indicator. An analysis of the dynamics of cost structure changes from 2020 to 2024 reveals a trend of rising expenditure on material resources, particularly fertilisers and fuel, which is associated with global price fluctuations (Fig. 2).

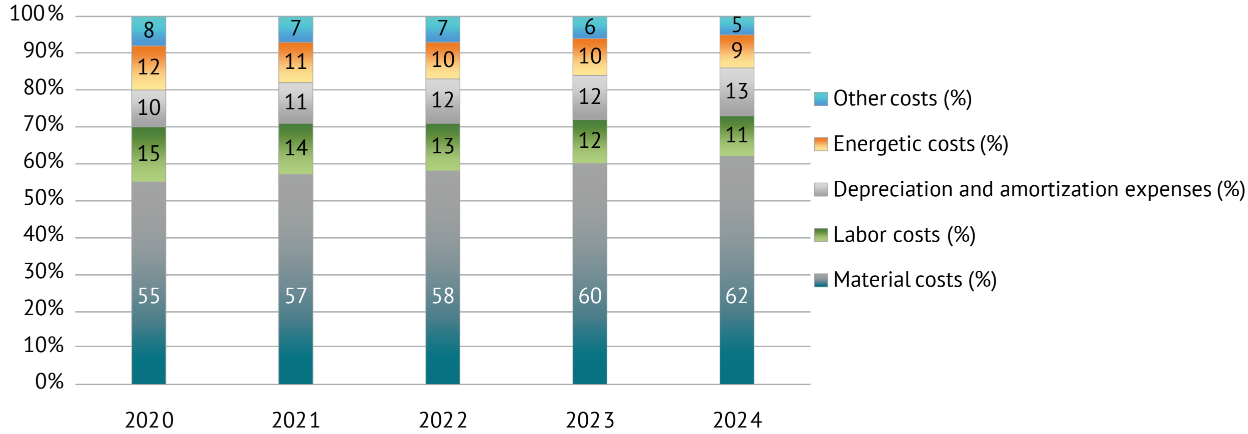

***Figure 2**. Cost structure in Kazakhstan's grain farming (%)*

***Note:** material costs include expenditure on seeds, fertilisers, and plant protection products. Energy costs cover fuel and electricity expenses. Other costs include administrative expenses, equipment repair, and maintenance costs*

***Source:** created by the authors based on Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), Food and Agriculture Organization (2024), Organisation for Economic Co-operation and Development (2023), World Bank (n.d.)*

Figure 2 demonstrates a growing share of material costs in the overall cost structure of grain production, which may be attributed to rising prices for fertilisers and plant protection products. At the same time, the share of labour and energy costs has declined, which may indicate improvements in production efficiency and the adoption of energy-saving technologies. The increase in depreciation costs may be linked to the renewal of agricultural machinery and the implementation of modern production technologies. Regional differences in cost structure are also significant. In northern Kazakhstan, where most grain production is concentrated, fuel and depreciation costs are higher due to the larger cultivated areas. In southern regions, where climatic conditions allow for higher yields, expenditure on fertilisers and plant protection products tends to be higher due to the more intensive cultivation technologies. Macroeconomic factors such as inflation, exchange rate fluctuations, and government policies influence the cost levels of grain production. The depreciation of the national currency may lead to higher prices for imported material resources, increasing overall production costs. Government support in the form of subsidies and preferential loans can partially offset these negative impacts.

Technological innovations as a factor in cost optimisation in grain production. The adoption of technological innovations is one of the key areas for improving resource efficiency in Kazakhstan's grain production. The cost of grain production largely depends on the level of mechanisation, the use of modern soil cultivation methods, and the implementation of digital technologies. The use of no-till and strip-till techniques reduces fuel and lubricant consumption and minimises the number of mechanical treatments, contributing to lower production costs. The introduction of precision farming systems based on spatial data analysis enhances the efficiency of agrotechnical processes and promotes rational resource use. The choice of technology determines fuel and lubricant consumption levels, machinery wear and tear, labour requirements, and final production costs. Traditional ploughing remains a widely used method, but its high energy intensity and cost encourage the adoption of alternative approaches (Angon *et al.*, 2023). No-till (Jiang *et al.*, 2021) and strip-till (Różewicz, 2022) techniques reduce the number of mechanical treatments, lower fuel consumption, and optimise resource use. Table 1 presents a comparative analysis of costs for three main soil cultivation methods.

Table 1. *Comparative analysis of costs for traditional ploughing, No-Till, and Strip-Till in Kazakhstan*

Indicator	Traditional Technology	No-till	Strip-till
Fuel costs (litres/ha)	25	10	15
Machinery depreciation costs ($/ha)	20	15	18
Labour costs ($/ha)	30	20	22
Total costs ($/ha)	75	45	55

Source: *created by the authors based on Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), Food and Agriculture Organization (2024), Organisation for Economic Co-operation and Development (2023), World Bank (n.d.)*

The comparative analysis results show a significant difference in cost levels between traditional ploughing and modern soil cultivation methods. The primary factor in cost reduction is lower fuel and lubricant expenses, which is particularly evident in no-till technology. This is due to the elimination of ploughing and the reduced number of machineries passes across the field, which also minimises agricultural equipment wear and tear. Although strip-till technology requires slightly higher machinery depreciation costs compared to no-till, it remains economically viable due to the optimal balance between soil structure preservation and efficient fertiliser application in the root zone. The reduction in labour costs in no-till and strip-till systems indicates a decreased need for fieldwork, which serves as an additional cost-saving factor. The lower per-hectare costs in farms using no-till and strip-till confirm the economic feasibility of transitioning to minimal soil cultivation. This serves as a key argument for implementing resource-saving technologies in Kazakhstan's grain production, particularly given the rising prices of energy resources and the need to optimise agricultural enterprises' cost bases. The development of digital technologies in grain farming enhances the accuracy of agro-production process monitoring. The use of Big Data, AI, and Internet of Things enables the analysis of large volumes of data on crop conditions, moisture levels, and the need for fertilisers or plant protection products. Kazakhstan is expanding the use of automated crop monitoring systems, which ensure precise application of agrochemicals and minimise unproductive costs. The implementation of GPS navigation and remote field sensing sensors reduces yield losses by enabling timely responses to adverse factors. The introduction of automated management systems for agrotechnical processes is an important step towards improving efficiency and reducing costs in Kazakhstan's grain farming sector. These systems optimise resource use, lower expenditure on fuel, fertilisers, and plant protection products, and enhance labour productivity. Figure 3 presents a comparative analysis of cost structures before and after the introduction of automated management systems.

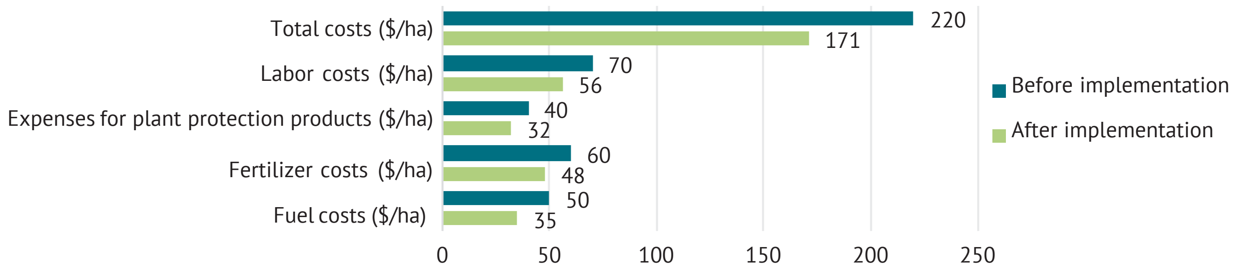

Figure 3. *Changes in the cost base of farms following the implementation of automated agricultural process management systems*

Source: *created by the authors based on Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), Food and Agriculture Organization (2024), Organisation for Economic Co-operation and Development (2023), World Bank (n.d.)*

An analysis of the data presented in Figure 3 indicates a significant reduction in production costs following the introduction of automated systems. In particular, fuel costs decreased by 30%, which may be attributed to the optimisation of machinery routes and the reduction of unnecessary operations. Fertiliser and plant protection costs each decreased by 20%, indicating more precise dosing and targeted application of these resources due to automated systems. Labour costs also declined by 20%, likely resulting from the automation of routine processes and a reduced need for manual labour. Overall, the implementation of automated agricultural process management systems led to a 22.3% reduction in total costs per hectare. This highlights the economic feasibility of investing in such technologies to enhance the competitiveness and profitability of grain farms in Kazakhstan.

The impact of technological innovations on the cost base of farms is confirmed by statistical data, which show a trend towards reducing production costs in farms that apply precision farming and automated systems. The reduction in fuel and lubricant expenses, along with optimised fertiliser and plant protection costs, contributes to lowering production costs by 10-15%. At the same time, integrating modern technologies ensures stable yield levels and allows farms to remain profitable even during adverse weather conditions. The development of digital platforms for agribusiness management contributes to reducing transaction costs and improving the efficiency of logistics operations in Kazakhstan's grain sector. The use of blockchain technologies to monitor grain supply chains enhances market transparency and reduces risks for producers. The improvement of technological processes, based on production data analysis, contributes to better yield predictability and cost optimisation. The expanded application of technological innovations in Kazakhstan's grain production ensures cost structure optimisation and more efficient resource use. The introduction of modern agrotechnologies helps reduce production costs, increase yields, and promote the long-term sustainability of the agricultural sector. This creates a foundation for further developing economically efficient farming models that ensure the stability of agricultural production in a competitive market environment.

Economic strategies for cost management in Kazakhstan's grain sector. The economic efficiency of grain farming largely depends on optimising costs related to production resources, transportation, storage, and product sales. Cost management involves implementing modern economic strategies aimed at improving resource efficiency and reducing production costs. In Kazakhstan, with its vast arable land and developed grain industry, key optimisation areas include cost standardisation, efficient land resource management, reducing transaction costs, and integrating digital technologies in logistics and grain marketing. Cost standardisation involves establishing optimal resource consumption norms per unit of land or production, helping to reduce overuse and improve production planning. The introduction of a differentiated approach to fertiliser and plant protection application, based on agrochemical soil analysis, minimises costs and enhances agrochemical efficiency (Sivojiene *et al.*, 2021). The use of remote sensing data in resource management enables more accurate assessment of plant water and nutrient needs.

The choice of soil tillage technology plays a crucial role in optimising the cost burden on Kazakhstan's grain farms. The cost of cultivating major crops largely depends on agroecological conditions, soil characteristics, and the intensity of applied technologies. The tillage method affects resource consumption, particularly fuel, fertilisers, and labour costs, ultimately determining the overall production cost (Dolia & Shevchenko, 2024). Table 2 presents a comparative analysis of wheat and barley cultivation costs depending on soil type and tillage technology.

***Table 2**. Comparative analysis of grain crop cultivation costs in Kazakhstan by soil type and tillage technology*

Crop	Soil type	Tillage technology	Fuel costs ($/ha)	Fertilizer costs ($/ha)	Labour costs ($/ha)	Total costs ($/ha)
Winter wheat	Chernozem	Conventional	50	60	70	220
		No-till	35	48	56	171
	Chestnut	Conventional	55	65	75	235
		No-till	38	52	60	180
Spring barley	Chernozem	Conventional	45	55	65	205
		Strip-till	40	50	60	190
	Chestnut	Conventional	50	60	70	215
		Strip-till	42	53	63	195

***Note:** chernozem soils are characterised by high natural fertility, significant humus content, and good water retention capacity, allowing for reduced fertiliser application and increased efficiency of traditional and minimal tillage technologies. Chestnut soils have lower humus levels, a higher tendency to dry out, and require additional fertiliser and moisture input to maintain stable yields. This results in higher cultivation costs for grain crops in such conditions, making no-till and strip-till technologies particularly suitable for conserving soil moisture and optimising production costs*

***Source:** created by the authors based on Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), Food and Agriculture Organization (2024), Organisation for Economic Co-operation and Development (2023), World Bank (n.d.)*

The analysis of the data in Table 2 demonstrates that grain cultivation costs depend not only on the tillage technology used but also on soil type. On chestnut soils, total costs for both winter wheat and spring barley cultivation are higher compared to chernozem soils. This may be due to lower natural fertility, the need for increased fertiliser application, and additional measures to improve soil structure. At the same time, the introduction of minimal tillage technologies, particularly no-till and strip-till, contributes to cost reductions, making these technologies a viable option for resource-efficient farming. The application of no-till technology significantly reduces the costs of winter wheat cultivation regardless of soil type. This is due to lower fuel and lubricant costs and reduced manual labour requirements resulting from fewer mechanical operations. The use of strip-till in spring barley production also demonstrates economic advantages, as it helps reduce fertiliser costs and optimise agrochemical use through localised application. Given the presented data, minimal tillage technologies can be recommended as an effective tool for reducing production costs and enhancing the resilience of agricultural production in Kazakhstan.

Optimising logistics costs is a key strategy for reducing total expenses in grain production. Transport costs can constitute a significant share of total costs, particularly given the large distances between production regions and export hubs. The use of automated logistics management systems enables route optimisation and minimises transport expenses. The construction of grain storage facilities close to production areas reduces interregional transportation needs and crop losses during transit. Minimising grain losses during harvesting and storage is another crucial economic aspect of cost management. The implementation of modern combine harvesters with loss control systems, automated aeration, and humidity control in grain storage facilities helps reduce product losses and improve quality (Kulazhanov *et al.*, 2024). The use of microclimate monitoring technologies in elevators contributes to optimising energy costs associated with drying and storing grain.

Reducing transaction costs is another area of production cost optimisation in Kazakhstan's grain sector. The consolidation of small and medium-sized farms into cooperative formations helps lower procurement, financing, and product marketing costs. The use of digital platforms for direct contracts between producers and consumers reduces intermediary costs and enhances price transparency in the grain market. Financial instruments such as crop insurance, credit financing, and government subsidies help mitigate risks and ensure production stability. Hedging mechanisms help reduce the impact of grain price fluctuations on farm profitability. Government support programmes, including subsidies for fertiliser purchases, machinery acquisition, and insurance, help alleviate the financial burden on producers. The introduction of digital platforms for grain sales has a significant impact on reducing transaction costs in agricultural enterprises. Digitalisation enables process automation, reduces the number of intermediaries, and increases transaction transparency. Figure 4 presents a comparative analysis of transaction costs in farms before and after the introduction of digital platforms.

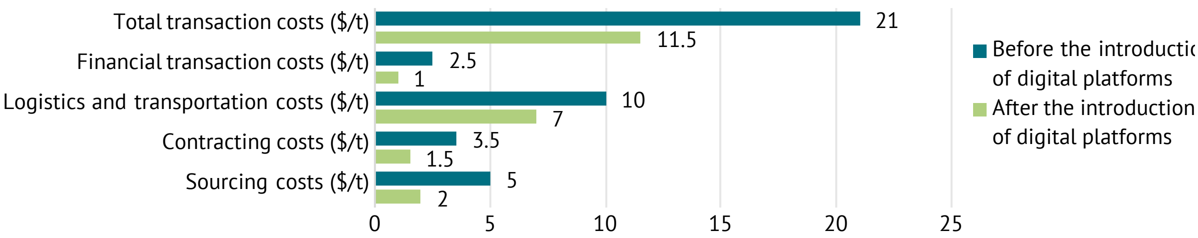

Figure 4. *Comparative analysis of transaction costs in agricultural enterprises before and after the implementation of digital platforms for grain sales*

Source: *created by the authors based on Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), Food and Agriculture Organization (2024), Organisation for Economic Co-operation and Development (2023), World Bank (n.d.)*

An analysis of the statistical data presented in Figure 4 revealed that the introduction of digital platforms significantly reduces transaction costs in agricultural enterprises. Specifically, the costs associated with finding buyers decrease by 60%, demonstrating the effectiveness of digital solutions in establishing direct connections between producers and consumers. Contracting costs are reduced by 57% as digital platforms simplify and automate the documentation processes for agreements. Moreover, logistics and transportation costs decrease by 30% due to route optimisation and the use of modern supply chain management systems. Financial transaction costs drop by 60% thanks to the integration of electronic payment systems, ensuring fast and secure transactions. Overall, total transaction costs per ton of grain decline by 45%, enhancing the competitiveness of agricultural enterprises and contributing to their sustainable development. Thus, cost management in Kazakhstan's grain sector requires a comprehensive approach, including resource utilisation regulation, logistics optimisation, transaction cost reduction, and the adoption of modern digital technologies. The implementation of economically justified strategies increases the competitiveness of Kazakhstan's grain products and ensures the sustainable development of the agricultural sector in a fluctuating economic environment.

Recommendations for cost optimisation in Kazakhstan's grain sector. An analysis of the cost structure in Kazakhstan's grain sector has shown that the key factors influencing production costs are expenses for fuel, fertilizers, wages, transportation, and crop storage. The introduction of advanced agricultural technologies, digital solutions, and financial mechanisms can significantly reduce production costs and improve the economic efficiency of farms. Given this, it is necessary to summarise the obtained data and assess the potential economic impact of implementing various cost optimisation strategies. Effective management of production resources requires a systematic approach that includes technological process modernisation, logistics improvements, and strengthening the financial stability of agricultural enterprises. To structure the results, Table 3 has been compiled, summarising the main cost optimisation strategies and their impact on key economic indicators.

***Table 3**. Key cost optimisation strategies in Kazakhstan's grain sector and their impact on economic indicators*

Optimisation strategy	Measures	Impact on economic indicators
Technological innovations	Adoption of precision farming, No-Till and Strip-Till technologies, automation of agro-technical processes	Reduction in fuel costs (-20-30%), fertilizer costs (-15-20%), and labor costs (-10-15%); decreased equipment wear
Rational resource management	Agrochemical soil analysis, targeted fertilizer and pesticide application, selection of adapted seeds	Reduction in fertilizer costs (-15%) and plant protection costs (-10%); increase in yield (+5-10%)
Logistics optimisation	Construction of grain storage facilities, optimisation of transportation routes, automated storage monitoring	Reduction of transport losses (-12-18%); decrease in logistics (-10-15%)
Financial mechanisms	State subsidies, crop insurance, preferential lending	Increase in modernisation investments (+15-20%); reduction of financial risks
Digital platforms	Trade automation, blockchain for transaction control, formation of cooperatives	Reduction in transaction costs (-40-50%); decrease in buyer search costs (-60%)

***Note:** all indicators are calculated based on statistical data analysis and expert evaluations regarding the impact of implemented technologies and economic measures in Kazakhstan's grain sector*
***Source:** created by the authors based on Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), Food and Agriculture Organization (2024), Organisation for Economic Co-operation and Development (2023), World Bank (n.d.)*

Data analysis indicates that the greatest economic impact is achieved through technological innovations and digital solutions. In particular, the application of precision farming, No-Till, and Strip-Till technologies significantly reduces costs for fuel, fertilizers, and labour, increasing production profitability. The automation of agro-technical processes helps minimise equipment wear and extend its lifespan, reducing long-term depreciation costs. Optimisation of material resources, particularly the rational use of fertilizers and plant protection products, not only cuts costs but also enhances the environmental efficiency of farms. Targeted fertilizer application and adaptation of seed materials to local climate conditions contribute to preserving soil fertility, ensuring stable yields in the long run. At the same time, logistics solutions such as the construction of modern grain storage facilities and transportation automation help minimise product losses and improve its quality.

The use of financial mechanisms and digital platforms allows for significant reductions in operational costs and enhances product sales efficiency. State subsidies and preferential lending stimulate investments in agricultural sector modernisation, while digital platforms ensure market transparency and simplify contract agreements. This reduces transaction costs and improves access to international markets for Kazakhstan's grain. Overall, the implementation of comprehensive cost optimisation measures strengthens the financial stability of enterprises and solidifies Kazakhstan's position as a leading global grain producer.

DISCUSSION

The findings confirm that the implementation of modern technological and managerial solutions has contributed to the reduction of production costs in Kazakhstan's grain sector. Minimal tillage methods, particularly No-Till and Strip-Till, have helped lower fuel and equipment depreciation costs, as evidenced by statistical calculations. The automation of agro-technical processes has facilitated more efficient distribution of fertilizers and plant protection products, reducing expenses. Logistics optimisation, including improved transport routes and the development of grain storage facilities, has led to lower losses during storage and transportation. Economic cost management mechanisms, such as financial instruments and digital platforms, have decreased transaction costs and improved profitability. However, the efficiency of implemented measures varied depending on farm scale, regional characteristics, and access to innovative technologies, requiring adaptation of optimisation strategies to specific production conditions.

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The economic efficiency of the grain sector largely depended on logistics process optimisation and technological innovations (Kim *et al.*, 2025). The study by D. Prajapati *et al.* (2022) examined sustainable grain supply chain models, considering economic, environmental, and social factors such as transportation costs, carbon emissions, and product damage risks. This research focused on Kazakhstan's regional characteristics, the development level of grain logistics, and the digitalisation of supply processes. It was established that an integrated cost management approach contributed to reduced production costs, aligning with the conclusions of the analysed study, but with an added evaluation of specific financial and technological mechanisms in local conditions.

The development of digital financial mechanisms in agriculture helped reduce transaction costs and enhance the economic stability of Kazakhstan's grain enterprises. Similar issues were explored in the study by X. Guo *et al.* (2023), which assessed the impact of digital financial technologies on farmer incomes in China's leading grain regions. It was found that digital platforms improved access to credit resources, expanded entrepreneurial opportunities, and optimised financial flows. The difference in this research was the focus on the impact of digital technologies on the cost structure of grain production in Kazakhstan, particularly their role in financing the agricultural sector and improving product sales mechanisms.

Soil quality played a key role in increasing agroecosystem productivity and grain production efficiency. The study by I.C. Mendes *et al.* (2021) developed the Soil Quality Index for Fertility and Biological Assessment, combining chemical and biological indicators. It was found that optimal soil enrichment with organic carbon and macronutrients contributed to higher yields. While this research confirmed the effectiveness of various fertilisation methods, the main emphasis was on the economic impact of minimum tillage and precision farming technologies, ensuring cost optimisation in grain production. A key factor in the development of Kazakhstan's grain sector was not only the implementation of modern technologies but also the activation of entrepreneurial activity among farmers. The study by Y. Pan *et al.* (2024) examined the interaction between farmers' entrepreneurship and economic growth in China's agricultural sector, showing that innovative entrepreneurial activity contributed to regional economic development in areas with similar urbanisation levels. The analysis confirmed the importance of entrepreneurship in agriculture, aligning with the findings of this study. However, Kazakhstan's research focused on cost optimisation mechanisms through digital financial tools and logistics improvements, complementing conclusions of Y. Pan *et al.*

The effective functioning of the grain industry was determined by the choice of farming system, which influenced both cost levels and the long-term stability of agricultural production. The study by G. Han *et al.* (2021) found that the main motives for Iowa (USA) farmers transitioning to organic farming were economic benefits, environmental responsibility, occupational safety, and traditional farming methods. The analysis confirmed that most farmers considered this transition justified, although the public health aspect did not always meet expectations. The study of Kazakhstan took into account the economic feasibility of implementing modern agro-technologies; however, the primary focus was on cost optimisation through digitalisation and the introduction of precision farming technologies.

The sustainability of the grain industry depended not only on economic and technological factors but also on social aspects, particularly the issue of generational renewal among farmers (Yaheliuk *et al.*, 2024). The study by S.F. Conway *et al.* (2021) analysed the influence of the behavioural patterns of older generations of farmers on the transfer of farms to the next generation. The authors found that financial incentives were not always effective due to the deeply rooted perception of farming as a lifelong profession, which complicated the process of exiting the sector. The study confirmed that the workforce structure of farms influenced cost management efficiency and readiness to implement modern technologies. Unlike S.F. Conway *et al.*, the main focus was on economic and technological factors in cost optimisation; however, the obtained results indicated the necessity of considering demographic trends when developing long-term strategies for the development of Kazakhstan's grain industry.

The integration of digital technologies into Kazakhstan's grain industry was viewed as one of the key tools for improving cost management efficiency and optimising production processes. The study by C. Ayim *et al.* (2022) confirmed the effectiveness of information and communication technologies in enhancing farmers' access to agronomic information, although their implementation was limited by low digital literacy and weak infrastructure. Cost analysis in Kazakhstan's grain industry demonstrated that the use of Big Data, artificial intelligence, and automated platforms contributed to reducing production costs through more precise resource allocation. A distinctive feature of this study was its focus on the economic efficiency of digital solutions, assessing their real impact on the cost structure of the agricultural sector.

Technological innovations also played an important role in increasing the productivity and sustainability of the grain industry (Bulgakov *et al.*, 2020). The study by N. Khan *et al.* (2021) examined the potential of modern technologies, such as the Internet of Things, artificial intelligence, and autonomous systems, in transforming food systems. The authors emphasised the importance of appropriate regulatory policies for the successful implementation of innovations. The conducted study confirmed the effectiveness of digital technologies in reducing costs in Kazakhstan; however, the main emphasis was on modelling cost structures and assessing the profitability of innovations, taking regional characteristics into account.

Logistical processes were critical to the efficiency of the grain industry, as transportation and storage of grain accounted for a significant share of costs. The study by E. Mardaneh *et al.* (2021) proposed a decision-support system for selecting optimal grain storage and distribution strategies. It was found that storing the harvest directly on farms contributed to reducing losses and increasing profitability. The study confirmed the importance of logistical solutions in reducing costs in Kazakhstan while also focusing on regional infrastructure characteristics and the digitalisation of supply processes. The preservation of grain quality largely depended on the efficiency of logistical solutions. The study by Y.J. Kim and B.K. Lee (2022) analysed containerised logistics as an alternative to traditional grain storage and transportation, identifying its advantages in reducing losses due to spoilage and pest infestation. However, the authors noted that containerised logistics required significant initial investments. The study confirmed the feasibility of improving logistical processes in Kazakhstan, but the main focus was on assessing the financial efficiency of different transportation approaches and the potential of digital platforms in supply chain management.

Rationalising grain storage was a crucial factor in cost optimisation in the grain industry. The study by K.A. Rosentrater (2022) examined the economic aspects of storage, including the choice between on-farm storage and terminal elevators, as well as the impact of storage on overall production profitability. The author emphasised that investments in grain storage should be economically justified, considering market prices and planning horizons. The conducted study confirmed that an effective storage system contributed to reducing losses and increasing the profitability of farms in Kazakhstan; however, the focus was on adapting digital technologies to inventory management.

Enhancing the sustainability of the grain industry required a comprehensive approach that included not only economic efficiency but also environmental aspects. The study by A. Gohin (2023) evaluated the ability of the French food system to adapt to the European Union's Green Deal requirements, particularly regarding the reduction of fertilizer and pesticide use. It was found that such changes were possible without significant economic losses for farmers, provided there was effective government support. The conducted study considered similar aspects, but the emphasis was on adapting cost optimisation strategies to Kazakhstan's agro-climatic conditions, the availability of financial mechanisms, and the role of digital technologies in reducing production costs. Assessing the impact of technological innovations and climatic factors is an important aspect of the sustainability of the grain industry (Krychkovska *et al.*, 2025). The study by I.A. Baig *et al.* (2024) used econometric analysis to identify a positive correlation between rainfall levels, CO_2 emissions, and wheat yields, as well as the significant effect of modern agro-technologies. The study of Kazakhstan assessed the impact of precision farming and automated systems, focusing on their economic feasibility. Unlike I.A. Baig *et al.*, the primary emphasis was on financial mechanisms that facilitated cost structure optimisation.

Macroeconomic factors determined the strategies for developing the agricultural sector. The study by Â. Belletti and S. Schneider (2023) analysed Brazil's and China's export relations, considering institutional factors and Food Regimes. Kazakhstan also studied macroeconomic aspects, including government regulation and market fluctuations. The difference was the focus on regional mechanisms for cost optimisation. The impact of macroeconomic variables on agricultural production was assessed in S.B. Akpan and A.A. Umoren (2021), where the ARDL model showed that, in the long term, key determinants were per capita income, land use density, the consumer price index, and the exchange rate. The study of Kazakhstan also examined cost dynamics, credit accessibility, and government support, but the main emphasis was on technological and logistical solutions for cost optimisation, complementing the findings of S.B. Akpan and A.A. Umoren.

The study confirmed that the implementation of technological innovations, logistics optimisation, and the use of digital financial mechanisms contributed to cost reduction in Kazakhstan's grain industry. Methods of minimal tillage, automation of agro-technical processes, digital platforms, and improvements in logistical solutions ensured increased production efficiency, reduced losses, and lower transaction costs. At the same time, macroeconomic factors, such as government regulation, financial support, and market fluctuations, influenced the stability of the sector. The obtained results aligned with international research findings; however, the emphasis was placed on regional specifics and the economic feasibility of implementing innovative solutions in local conditions.

CONCLUSIONS

The study demonstrated a new approach to cost optimisation in Kazakhstan's grain industry through a comprehensive analysis of cost structures, an assessment of the impact of technological and economic factors, and the modelling of strategies for their reduction. The obtained results made it possible to establish interconnections between key cost components, the level of mechanisation of production processes, and the application of innovative technologies, which contributed to substantiating ways to improve the economic efficiency of the sector. The analysis of cost structures in Kazakhstan's grain industry showed that the largest share of total costs was attributed to material resources, particularly fertilizers, seeds, and plant protection products, due to the need to maintain stable yields and adapt to changing agro-climatic conditions. At the same time, a trend of decreasing labour costs was observed, indicating a gradual increase in mechanisation and automation. Regional differences in cost structures were identified, depending on resource accessibility, soil-climatic characteristics, and the adoption of modern agro-technologies.

Research on technological innovations has shown that the implementation of minimum tillage, particularly No-Till and Strip-Till, allowed for a reduction in fuel costs by 50-60%, depreciation expenses by 20-25%, and labour costs by 15-20%. The use of automated agricultural management systems contributed to a more efficient allocation of resources, ensuring a reduction in fertilizer and plant protection costs by 18-22%. The evaluation of economic cost management strategies confirmed the effectiveness of financial mechanisms, logistical solutions, and digital platforms. Optimising logistics through the improvement of transport routes and the construction of grain storage facilities reduced product losses during transportation by 12-18% and overall logistics costs by 10-15%. The use of digital platforms facilitated a reduction in transaction costs by 40-50% and a decrease in buyer search costs by 60%, thereby enhancing the competitiveness of grain products.

The research faced several limitations, including insufficient statistical data detailing, which complicated the assessment of long-term changes in cost structures. The analysis of technological innovations was based on selective data, which might have affected the representativeness of the results. The impact of state support and regulatory mechanisms on cost optimisation requires further study. Additionally, climate risks, which can significantly influence the effectiveness of implemented measures in the future, were not fully considered. The developed recommendations for cost optimisation in Kazakhstan's grain farming sector included the adoption of modern technologies, adaptation of logistical schemes, and the expansion of digital solutions for production process management and product marketing. Future research may focus on assessing the long-term impact of technological changes on the cost of grain production, adapting economic strategies to various agricultural production models, and developing mechanisms to enhance the efficiency of state support for the agricultural sector.

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CONFLICT OF INTEREST

None.

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Структура витрат у зерновому господарстві Казахстану та методи її оптимізації

Галимжан Керімбек
Кандидат економічних наук, професор
Казахський національний університет імені Аль-Фарабі
050040, просп. Аль-Фарабі, 71, м. Алмати, Республіка Казахстан
https://orcid.org/0000-0003-0563-8399
Катіра Мамутова
Кандидат економічних наук, доцент
Південно-Казахстанський університет імені Мухтара Ауезова
160012, просп. Тауке Хана, 5, м. Шимкент, Республіка Казахстан
https://orcid.org/0000-0003-0676-1620
Айжан Оралбаєва
Кандидат економічних наук, доцент
Кизилординський університет імені Коркит ата
120014, вул. Айтеке бі, 29А, м. Кизилорда, Республіка Казахстан
https://orcid.org/0000-0002-9233-8599
Жанимгуль Баймукашева
Кандидат економічних наук, доцент
Актюбінський регіональний університет імені К.Жубанова
030000, просп. Алія Молдагулова, 34, м. Актобе, Республіка Казахстан
https://orcid.org/0000-0002-2593-2520
Гульміра Нурбаєва
Кандидат економічних наук, доцент
Торайгиров університет
140008, вул. Ломова, 64, м. Павлодар, Республіка Казахстан
https://orcid.org/0000-0001-7006-4403

Анотація. Оптимізація витрат у зерновому господарстві Казахстану є актуальною проблемою, зумовленою необхідністю підвищення економічної ефективності сільськогосподарського виробництва в умовах зростання вартості ресурсів і посилення конкуренції на міжнародному ринку. Метою даного дослідження було обґрунтування підходів до зниження витрат у зерновому господарстві шляхом аналізу структури витрат та оцінки ефективності технологічних і економічних заходів. Для оцінки ефективності різних виробничих стратегій було використано методи варіаційної статистики, регресійного аналізу, економетричного моделювання, аналізу витрат і вигод, а також розрахунки інвестиційної прибутковості. Результати дослідження показали, що ключовими напрямками оптимізації витрат є впровадження технологій мінімального обробітку ґрунту, зокрема систем no-till та strip-till, автоматизація агротехнічних процесів, раціональне використання добрив та засобів захисту рослин, а також використання цифрових платформ для продажу продукції. Аналіз статистичних даних за 2020-2024 роки показав, що впровадження технологій мінімального обробітку ґрунту сприяло скороченню витрат на паливо на 50-60 %, амортизаційних витрат на техніку – на 20-25 %, витрат на оплату праці – на 15-20 %. Автоматизовані системи управління сільським господарством дозволили скоротити витрати на добрива та засоби захисту рослин на 18-22 % завдяки точному розподілу ресурсів. Оптимізація логістичних процесів та будівництво зерносховищ сприяли скороченню втрат продукції під час транспортування на 12-18 % та зменшенню логістичних витрат на 10-15 %. Використання цифрових платформ для продажу продукції забезпечило скорочення транзакційних витрат на 40-50 %, а витрат на пошук покупців – на 60 %. Загальний ефект від впровадження запропонованих заходів дозволив знизити собівартість виробництва зерна на 12-17 %, залежно від масштабу господарства та застосованих технологій. Запропоновані рекомендації спрямовані на зниження виробничих витрат, забезпечення фінансової стабільності аграрного сектору та підвищення конкурентоспроможності зернового господарства Казахстану

Ключові слова: економічна ефективність; технологічні інновації; мінімальний обробіток ґрунту; автоматизація сільського господарства; управління ресурсами

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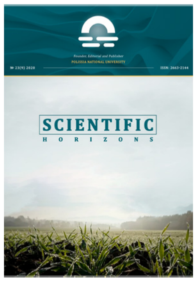

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Optimisation of credit strategies in the agro-industrial complex under conditions of market instability

Dias Babash*
Doctoral Student
Zhetysu University named after Ilyas Zhansugurov
040009, 187A Zhansugurov Str., Taldykorgan, Republic of Kazakhstan
https://orcid.org/0009-0001-3425-0804

Daniyar Kaldiyarov
Doctor of Economic Sciences, Professor
Zhetysu University named after Ilyas Zhansugurov
040009, 187A Zhansugurov Str., Taldykorgan, Republic of Kazakhstan
https://orcid.org/0000-0002-0181-2962

Gulnar Tuleshova
PhD in Economic Sciences
Zhetysu University named after Ilyas Zhansugurov
040009, 187A Zhansugurov Str., Taldykorgan, Republic of Kazakhstan
https://orcid.org/0009-0001-4717-0969

Zhanar Turalina
PhD in Economic Sciences
City Scientific and Methodological Center of New Technologies in Education of Almaty
050007, 62 Sh. Kaldayakov, Almaty, Republic of Kazakhstan
https://orcid.org/0000-0003-2249-9124

Olessya Lemechshenko
Master of Sciences
Zhetysu University named after Ilyas Zhansugurov
040009, 187A Zhansugurov Str., Taldykorgan, Republic of Kazakhstan
https://orcid.org/0000-0002-8907-9768

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Abstract. The purpose of this study was to analyse the problems of lending to the agro-industrial complex of Kazakhstan and to develop a methodology for its sustainable financing. The study was based on a systematic approach, including theoretical analysis of economic and financial factors, comparative analysis of international practices, as well as the development of subsidy, insurance, and monitoring methods to optimise the sustainability of lending to the agro-industrial complex. The findings of the

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**Corresponding author*

study revealed that ensuring the sustainability of lending to agro-industrial complex requires a comprehensive approach, including the integration of mechanisms of state regulation, market instruments, and risk management methods. The analysis of existing practices of agro-industrial complex financing in Kazakhstan revealed that the key problems continue to be the high cost of borrowed funds (in 2024 the loan rate was 6% for soft loans, and reached 25-27% in the case of commercial loans), limited access of small and medium-sized farmers to credit resources, as well as the underdevelopment of agricultural risk insurance mechanisms. In this context, the study confirmed the effectiveness of such instruments as interest rate subsidies, state credit guarantees, and the expansion of preferential lending programmes for agricultural producers. According to the findings, this enabled small farmers to access financing in the amount of 10 billion tenge and increase production capacity by 15-20%. Additionally, the study found that in an unstable macroeconomic environment, regular monitoring of macroeconomic factors and adaptation of credit policy to changes in financial markets are significant, as a tonne of grain cost around 80,000 tenge in 2020 and could reach 135,000 tenge by 2024. The use of digital platforms and analytical tools to assess risks and forecast market trends can greatly improve the efficiency of agribusiness credit management. Furthermore, international practices in agricultural finance, particularly models of credit support used in developed and transition economies, can be adapted to the conditions of Kazakhstan, considering the specific features of its agricultural sector and financial system. The obtained findings provided a basis for improving the mechanisms of lending to the agro-industrial complex, increasing the availability of financial resources for agricultural producers, and minimising credit risks in conditions of economic instability

Keywords: macroeconomic factors; subsidies; insurance; agricultural products; currency fluctuations; financing; interest rates

INTRODUCTION

The agro-industrial complex (AIC) plays a key role in the economy, providing food security, employment, and export potential. Its development depends on the availability of financing, long-term investments, and the stability of credit mechanisms. High capital intensity, seasonality, and income instability make the sector less attractive to lending institutions, while macroeconomic instability, volatile interest rates, and poorly developed agricultural risk insurance force farmers to turn to short-term loans with high costs. Measures to subsidise interest rates, develop insurance mechanisms, and improve risk management are required to increase the sustainability of financing. The use of international practices will enable the creation of a stable financial system that supports the modernisation of the agricultural sector, increases its competitiveness, and reduces the influence of external economic factors.

One of the principal factors affecting the sustainability of lending to the agro-industrial complex is the difficulty of forecasting risks associated with market volatility (Boiko *et al.*, 2024). R. Tazhibayeva (2021) noted the effects of market fluctuations on credit availability for agrarians, emphasising the significance of state support for agribusiness, but without considering long-term market volatility and its impact on risk forecasting under volatile conditions. G. Esimkhan *et al.* (2024) also considered risks associated with market volatility, focusing on short-term price changes and their effects on financial flows of agricultural producers, but the study did not address the factors of predicting long-term market trends, which limited the applicability of its findings in conditions of uncertainty and high volatility inherent in modern agricultural markets.

External factors such as changes in international trade and global economic crises also significantly affect the sustainability of agribusiness lending (Luchechko & Gordiichuk, 2023). M. Afolabi *et al.* (2021) examined the effects of external economic instability on credit availability of agrarians, revealing the value of risk diversification using currency hedges, but without considering the effects of global economic crises on long-term credit strategies, which limited its application in the face of global uncertainty. R. Sodoma *et al.* (2021) highlighted the influence of international trade on agrarian credit, emphasising the significance of foreign trade for the agribusiness sector as well as the role of international financial institutions in supporting agribusiness, but without considering the relationship between external economic shocks and internal economic conditions, making the conclusions insufficiently precise for real-world application. T.G. Abdulova *et al.* (2022) examined the state of bank lending to agricultural enterprises in Kazakhstan, identifying problems of access to credit and noting insufficient financial support to the agribusiness sector, but without addressing the influence of macroeconomic factors, which limited the generalisability of the findings.

Instability of financial institutions also poses a serious threat to the sustainability of lending to the agro-industrial complex, as economic shocks in the banking sector can lead to limited availability of credit resources and increase the cost of borrowing for agricultural producers. S. Khalatur *et al.* (2023) focused on analysing the impact of banking system crisis on the availability of financial resources for agribusinesses, identifying key risks for agrarians in the context of instability of financial institutions, but not considering the long-term effects of such crises, thus limiting the scope of application of their findings. J. Glauber *et al.* (2021) investigated the measures taken by public and private financial institutions to ensure the sustainability of agricultural credit in the face of financial shocks, but without considering the possibility of integrating the latest financial instruments, which limited the practical relevance of the findings for the development of the agricultural sector in the long term. Y. Liu *et al.* (2022) analysed the effects of financial crises on financial institutions working with the agricultural sector and proposed a series of methods to stabilise lending, but without assessing the impact of financial risks specific to the agricultural sector, which limited the accuracy of the proposed solutions for agribusiness in the context of global economic instability.

The purpose of the present study was to develop an effective methodology for assessing and optimising the sustainability of agribusiness lending under conditions of market instability. To fulfil this purpose, the objectives of the study included the analysis of the current problems of lending to agribusiness associated with market volatility, instability of financial institutions and external economic factors; development of recommendations to improve credit mechanisms for agrarians, including the optimisation of state support programmes, and the use of alternative financial instruments that help reduce risks and improve the availability of credit resources to agricultural producers.

MATERIALS AND METHODS

The methodology for assessing and optimising the sustainability of lending to the agro-industrial complex was based on a comprehensive study of financial, institutional, and macroeconomic factors affecting the availability and stability of credit resources in the agro-industrial complex, as well as on market mechanisms and risk management. The study employed a systematic approach that allowed considering the interconnection of various elements of financial infrastructure, such as credit institutions, state regulators, and agrarian enterprises. The study was based on a comprehensive analysis of materials that included official statistical data, regulations, strategic documents, and reports of state and international organisations handing the issues of financing and lending of the agro-industrial complex. This approach helped to assess the current state of the lending system in the agricultural sector, as well as to identify internal and external factors affecting its stability and efficiency. Particular attention was paid to the study of international best practices aimed at increasing the availability of financial resources for agricultural producers, development of risk minimisation tools, as well as the application of public and private financing mechanisms.

The principal sources of information included data from the National Bank of Kazakhstan (n.d.), specifically, reports on monetary policy, official statistical compilations and analytical reports containing information on the dynamics of interest rates, the structure of the loan portfolio of second-tier banks, and the volume of financing of the agro-industrial complex. The study also used the materials from the Ministry of Agriculture of the Republic of Kazakhstan (n.d.), including annual reports on the development of the agrarian sector, strategic documents related to the financial support of agrarians, and regulations governing the procedure for subsidising interest rates and granting soft loans to agricultural producers. Additionally, the Ministry of National Economy of the Republic of Kazakhstan (n.d.) reports containing macroeconomic indicators, forecasts on inflation, exchange rate, and other factors affecting the availability of credit resources for agribusiness, as well as open data from the Bureau of National Statistics (n.d.) were studied. The study used analytical materials from Agrarian Credit Corporation (n.d.), including information on existing agricultural finance programmes, as well as reports from Baiterek National Managing Holding Joint Stock Company (n.d.), which coordinates government policy on agricultural finance.

International sources included statistics and analytical publications of the World Bank Group (n.d.), specifically, reports on the investment climate in Kazakhstan and assessment of the stability of financial institutions, as well as reports of the International Monetary Fund (IMF) (n.d.), containing macroeconomic assessments of the sustainability of the country's credit system. A significant role in the analysis was played by the materials of the Food and Agriculture Organisation of the United Nation (FAO), including reports on sustainable development of the agricultural sector and adaptation of agricultural producers to economic instability (Resolution of the Government of the Republic of Kazakhstan No. 960, 2021). To examine the international practices of crediting the agro-industrial complex, the study used the reports of the Organisation for Economic Co-operation and Development (OECD) (n.d.), which analysed the mechanisms of agricultural support in countries with developed and transition economies. The study also considered the research of the European Bank for Reconstruction and Development (EBRD) (n.d.) on the issues of financing the agro-industrial sector in the countries of Central Asia, as well as publications of the Asian Development Bank (ADB) (n.d.), which included recommendations for improving agricultural policy and access to financial resources.

RESULTS

Kazakhstan's agro-industrial complex is a strategically significant sector of the economy that ensures internal food security and a considerable share of the country's exports. In 2024, the contribution of the agro-industrial complex to the gross domestic product (GDP) was about 5.2-5.5%, which is equivalent to more than KZT 4.8 trillion. Therewith, this indicator showed a steady upward trend despite macroeconomic challenges. The structure of agricultural production in Kazakhstan is mainly represented by crop production (about 60% of total production), livestock breeding (38%), and agro-processing (2%). One of the most competitive segments of the agro-industrial complex is the grain sector, which provides Kazakhstan with a strong position in the world market. According to the Food and Agriculture Organisation of the United Nations (n.d.), Kazakhstan ranks 7th in the world in wheat exports, behind such leaders as the USA, Canada, and the European Union (EU). In 2024, wheat exports were estimated at ~8.5 million tonnes, with the geography of supply covering over 30 countries, including Uzbekistan, China, Afghanistan, and Iran.

The flour milling industry deserves special attention, where Kazakhstan consistently ranks 1st in the world in flour exports. In 2024, Kazakhstan's flour exports reached 1.9 million tonnes, which was greater than its nearest competitors such as Turkey. The high export potential is explained not only by favourable climatic conditions for growing durum wheat, but also by the developed network of milling complexes, most of which are located in Northern and Southern Kazakhstan. Apart from its economic role, Kazakhstan's agriculture plays a vital social function. The sector employs more than 1.3 million people, which is over 20% of the economically active population of the country. The dependence of rural regions on agro-industrial production is particularly strong: for instance, in Kostanay and North Kazakhstan regions, up to 45% of the employable population is working in agriculture.

At the same time, despite its promising potential, Kazakhstan's agro-industrial complex faces a series of financial constraints, among which the excessive cost of loans continues to be one of the key problems. The average interest rate on loans in Kazakhstan ranges from 12-25% per annum, which is significantly higher than in some other agricultural countries (Table 1). For instance, the EU has preferential loan programmes with rates of 2-5% per annum.

***Table 1**. Indicators of lending to the agro-industrial complex of Kazakhstan in 2021-2024*

Indicator	2021	2022	2023	2024
Volume of investments in agriculture	KZT 704.8 bn	KZT 853.5 bn	KZT 910 bn	KZT 980 bn
Average interest rate on agricultural loans	15.9-18%	15.9-20%	6% (preferential) and 22-25% (commercial)	6% (preferential) and 25-27% (commercial)
Volume of lending to agriculture (including soft and commercial loans)	KZT 600 bn	KZT 725 bn	KZT 800 bn	up to KZT 900 bn
Total volume of concessional lending	KZT 400 bn	KZT 510 bn	KZT 550 bn	Over KZT 600 bn
Number of loans issued	~20,000	~22,000	~22,000-23,000	up to 25,000
Share of concessional loans in the total volume of lending to the agro-industrial complex	65-70%	70%	70-75%	about 75%
Volume of overdue debt (share of non-performing loans)	14-15%	13-15%	~13%	~11-12%

***Source:** compiled by the authors of this study based on Olzhas Bektenov on support for farmers: For the first time the volume of preferential lending has reached 580 billion tenge (2024); A. Tishchenko (2024); Agricultural lending in the Republic of Kazakhstan for 2021 (2021)*

Several factors contribute to the elevated interest rate environment in Kazakhstan. Agriculture continues to be a high-risk sector for banks and other lenders due to the seasonality of production, dependence on weather conditions, and fluctuations in commodity prices. Furthermore, inflation in Kazakhstan has historically been high, reaching 20.3 per cent. in 2022 and 11.8 per cent. in 2023, forcing banks to set interest rates accordingly. In 2024, inflation in Kazakhstan slowed to 8.6% compared to 9.8% in 2023. During this period, food prices rose by 5.5%, non-food prices – by 8.3%, and paid services – by 13.3% (Bureau of National Statistics, 2025). Despite the decline in the overall inflation rate, the significant surge in prices of paid services continued to put pressure on the financial sector, forcing banks to maintain corresponding interest rates. Furthermore, commercial banks are limited in long-term financing of the agro-industrial complex, as agrarian projects require a long payback period, and the banking system is oriented towards short- and medium-term loans. Access to credit is particularly problematic for small and medium-sized farms, which do not hold sufficient collateral assets. Banks require collateral covering 120-150% of the loan amount, which often becomes an insurmountable barrier for farmers. Land that could be used as collateral is state-owned and leased to farmers in Kazakhstan, which complicates lending. In addition, the market value of agricultural equipment used as collateral is estimated by banks at a discount of up to 50%, which limits the size of possible loans. Another factor complicating lending is the lack of flexibility in loan programmes. Most commercial loans in Kazakhstan are issued for terms of 1 to 5 years, which does not always meet the real needs of agricultural producers. For instance, to purchase machinery or build livestock complexes, long-term loans for 7-10 years with a grace period are needed, but such offers are practically absent in the market.

Another key problem of lending in the agro-industrial complex of Kazakhstan is the limited availability of long-term loans. As of 2024, most bank loans in the agricultural sector were for up to 3 years, which does not correspond to the life cycle of agribusiness. For comparison, in EU and US countries, the term of agricultural lending reaches 7-15 years, which enables farmers to plan development for the long term and evenly distribute the financial burden. The short-term lending model creates particularly severe challenges for industries with a long payback period, such as livestock and horticulture. This is because growing perennial crops (orchards, vineyards) requires 5-7 years before reaching full yield, and the payback period of large livestock complexes (dairy farms, feedlots) takes at least 7-10 years. However, in conditions of a shortage of long-term financing, agrarians are forced to either attract expensive short-term loans or limit themselves to their personal resources, which decelerates the development of the sector. The lack of long-term loans also adversely affects the modernisation and technical re-equipment of the agro-industrial complex. For instance, the cost of modern grain harvesting equipment can reach KZT 200-300 mn, which makes its purchase impossible without borrowed funds. Therewith, a short-term loan with a high interest rate (15-20% per annum) increases the financial burden and reduces the profitability of the business. In developed countries, such capital expenditures are financed through 10-15-year loans with a grace period, which allows agrarians to invest in technological upgrades without major financial risks.

Another problem is the limited choice of financing instruments. In Kazakhstan, long-term loans are mainly provided by state development institutions, such as Agrarian Credit Corporation and the "Fund for Financial Support of Agriculture", but their programmes are insufficient to cover all the needs of the industry. Commercial banks, oriented towards faster capital turnover, are reluctant to lend to agriculture on a long-term basis for fear of high default risks. It is also worth noting significant factors that can lead to instability in the agro-industrial complex of Kazakhstan, including wide fluctuations in the prices of agricultural products, especially grain crops. Thus, according to the Ministry of Agriculture of the Republic of Kazakhstan (n.d.) and Bureau of National Statistics (n.d.), the price of wheat in Kazakhstan in 2020-2024 showed dramatic changes: in 2020 a tonne of grain cost about KZT 80,000, in 2021 the price increased to KZT 110,000, and by 2023 it reached KZT 135,000. In 2024, wheat prices in Kazakhstan also showed significant fluctuations. In September 2024, Prodkorporatsiya set purchase prices for Grade 3 wheat within KZT 85,000-110,000 per tonne, depending on gluten values (Zhazetova, 2024). Such fluctuations were driven by a series of factors, the key ones being changes in global market demand, climatic conditions, and logistical constraints.

At the global level, grain demand is determined by production volumes in the largest exporters (USA, EU), as well as by the geopolitical situation and trade sanctions (Liu *et al.,* 2023). For instance, wheat prices rose sharply in 2022 due to global supply disruptions caused by crises in the Black Sea region. In Kazakhstan, price increases were exacerbated by drought, which led to yield reductions of 15-20% in some regions, as well as by rising logistics costs. Specifically, a shortage of grain wagons and limited capacity of Kazakhstan's railway infrastructure hampered exports, leading to domestic price volatility. Strong price fluctuations adversely affect the financial sustainability of farmers. During periods of soaring prices, farmers can make considerable profits, but when prices fall sharply due to market saturation or reduced export demand, many farms face cash gaps and an inability to repay loan obligations. This situation increases the risk of loan defaults, making agricultural producers less attractive borrowers for banks.

Another critical factor of instability is the fluctuation of the tenge exchange rate, which directly affects the cost of agricultural production. Kazakhstan's agro-industrial complex is heavily dependent on imported goods – seeds, fertilisers, agricultural machinery, spare parts, and fuels and lubricants. All these components are purchased for foreign currency, and with the devaluation of the tenge, the cost of agricultural production automatically increases. Thus, according to the reports of the National Bank of Kazakhstan (n.d.b), in 2022 the dollar exchange rate increased from KZT 431 at the beginning of the year to KZT 470 at the end of the year, which led to an increase in the cost of imported agricultural technologies by an average of 9%. Therewith, the cost of mineral fertilisers, such as urea and ammonium nitrate, increased by 15-20%, which greatly increased farmers' production costs (KazAzot announces prices..., 2023). Thus, while in 2021 the price of a tonne of ammonium nitrate was around KZT 140,000, in 2023 the price exceeded KZT 180,000. In 2024, the price of ammonium nitrate in Kazakhstan also continued its growth. According to the data, as of mid-2024, the wholesale price of ammonium nitrate in Almaty was between KZT 235,000 and KZT 255,000 per tonne. Thus, compared to 2023, there was a marked increase in the cost of this crucial fertiliser in 2024 (Ammonium nitrate b..., n.d.).

Exchange rate fluctuations are particularly hurtful for farmers who have loans in foreign currency. In Kazakhstan, some agricultural holdings and large farms borrow in dollars or euros because international financial institutions offer lower interest rates. However, with the sharp weakening of the tenge, servicing such loans becomes more challenging, increasing the debt burden and reducing business profitability. Furthermore, the devaluation of the tenge also affects the cost of diesel fuel, which is a key consumable in agriculture. Kazakhstan produces major volumes of petroleum products, but fuel prices depend on global conditions and domestic regulatory decisions. In 2023, the cost of diesel fuel increased from 230 KZT per litre to 295 KZT per litre, which increased farmers' costs for sowing and harvesting campaigns (Information and reference..., 2024). In 2024, the cost of diesel fuel in Kazakhstan continued to rise. From 17 May 2024, new retail price ceilings were set: for foreign citizens, diesel fuel (summer and off-season) cost 315 KZT per litre, while for Kazakh citizens with a driver's licence the price was 295 KZT per litre for up to 100 litres per day, which increased farmers' costs for sowing and harvesting campaigns.

The geopolitical situation in the world also significantly affects Kazakhstan's economy, and the agro-industrial complex is no exception. In 2020-2022, external factors such as sanctions restrictions, changes in trade routes and rising logistics costs put considerable pressure on Kazakhstan's agricultural exports. The changes were particularly strong from 2022 onwards, when international sanctions against Russia and related transit transport restrictions led to changes in export routes. Prior to 2022, a sizeable portion of Kazakhstan's grain and flour exports travelled through Russian ports on the Black and Baltic Seas. However, the imposed sanctions made transit through Russia more cumbersome and caused disruptions in transport chains (Consequences of Russia's..., 2024). As a result, Kazakh exporters had to switch to alternative routes, including the Trans-Caspian International Transport Route (TCITR), which runs through the Caspian Sea, Azerbaijan, and Turkey. While this route enabled diversification of exports, it proved to be significantly more expensive. For instance, while grain delivery through Russian ports cost on average USD 30-40 per tonne, logistics costs through the TCITR rose to USD 70-80 per tonne. This led to a decrease in the competitiveness of Kazakh products on world markets, as their production costs increased. Analogous problems arose in the export of agricultural products to Central Asian countries, which are historically key consumers of Kazakh flour, wheat and oil. Sanctions restrictions and transit problems led to delays in deliveries and increased transport costs, resulting in a 15-20% increase in the cost of grain delivery to Uzbekistan compared to 2021 (Uzbekistan again became..., 2023).

Another factor worsening the situation was overloaded railway infrastructure. The disruption of usual export routes increased the load on Kazakhstan's railways, especially on the Trans-Caspian corridor. This caused many agro-exporters to face a shortage of grain cars in 2022-2023, which led to contract cancellations and delays in deliveries. This forced companies to look for alternative means of delivery, including road transport, which is more expensive, which also adversely affected the profitability of exports as the added transport costs reduce producers' margins (Fernandes *et al.,* 2023).

China is a strategically significant market for Kazakhstan, but challenges emerged there as well. Kazakhstan's grain, oil, and meat shipments to China increased in 2023-2024, but stringent phytosanitary requirements and periodic border crossing restrictions posed extra obstacles. In 2022-2023, due to changes in China's quarantine policy (related to COVID-19 and other sanitary risks), repeated delays in cargo clearance occurred at the border, resulting in rail car downtime and greater logistics costs. Furthermore, the capacity of railway border crossings between Kazakhstan and China is limited, creating bottlenecks in the transport system. Thus, geopolitical instability, sanctions restrictions, changes in logistics routes, and other factors discussed earlier have become serious challenges for Kazakhstan's agribusiness, increasing risks for agro-producers and forcing them to adapt to the new economic reality. These conditions challenge agro-producers to react quickly to changes in the market situation, prices for agricultural products, as well as external economic factors, such as currency fluctuations and changes in logistics conditions. In this environment, ensuring the sustainability of financial flows in the sector and access to necessary credit resources becomes one of the key factors for maintaining the normal operation of the agro-industrial complex.

Based on the above-mentioned factors, a methodology was developed to assess and optimise the sustainability of lending to the agro-industrial complex of Kazakhstan under conditions of market instability, which considers various economic and external economic factors, which will enable effective adaptation of credit strategies to changing conditions (Fig. 1).

The assessment of the current state of lending and economic sustainability of the agro-industrial complex in conditions of instability requires a comprehensive approach, which includes in-depth analysis of a variety of factors affecting the availability and efficiency of credit resources. First of all, the importance of assessing the risks associated with price volatility should be noted, as the agribusiness sector is traditionally subject to sharp fluctuations in the prices of key agricultural products. Unpredictable weather conditions, changes in international politics, and fluctuations in demand for agricultural products can cause sharp price volatility, which increases the financial burden on agricultural producers and increases the risk of loan defaults. For example, the price of wheat in Kazakhstan in 2020 was around KZT 80,000 per tonne, but in 2023 it reached KZT 135,000, which was 68% greater (Bureau of National Statistics, n.d.). Such price hikes pose serious challenges for long-term financial planning, as seed, fertiliser, and fuel costs do not always change proportionately with income. Analogously, the cost of ammonium nitrate increased from KZT 140,000 to over KZT 235,000 per tonne between 2021 and 2024, while diesel fuel rose from KZT 230 to KZT 295 per litre over the same period, increasing the cost of agricultural production (KazAzot announces prices…, 2023; Information and reference…, 2024). Considering this, special mechanisms must be put in place to mitigate these risks, such as the use of futures contracts to hedge price risks. For example, farmers could enter into forward contracts for grain at a fixed price, which would enable them to fix their income level in advance and minimise the effects of market fluctuations. Furthermore, the development of state income insurance programmes and stabilisation funds will reduce the impact of sharp changes in market conditions. Together, these instruments can improve the financial sustainability of the agricultural sector, ensuring predictability of cash flows and reducing the probability of credit defaults.

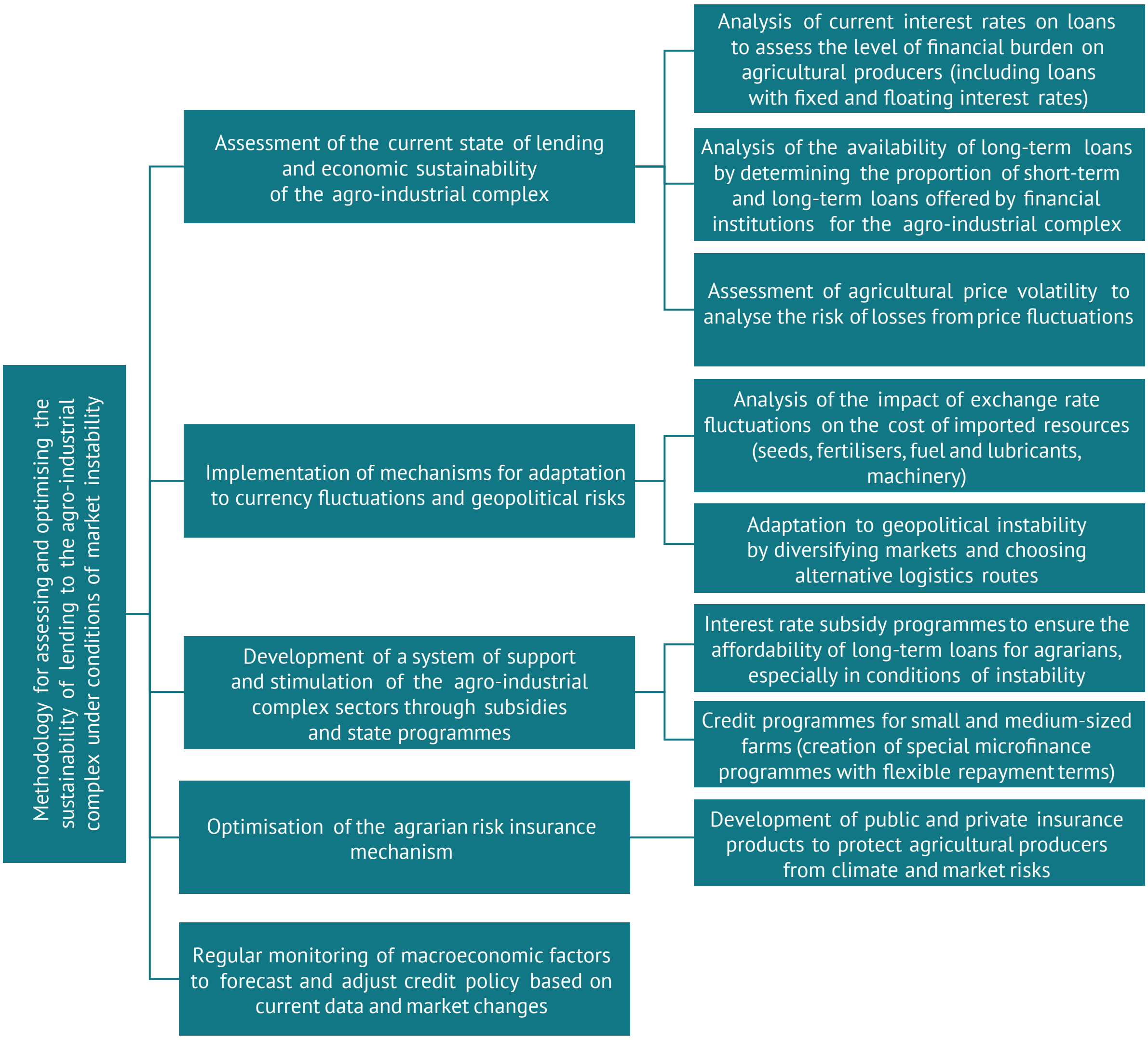

***Figure 1**. Developed methodology of assessment and optimisation of sustainability of lending to the agro-industrial complex of Kazakhstan under conditions of market instability*
***Source:** compiled by the authors*

For agricultural producers, the creation of stabilisation funds that would provide a financial safety cushion in case of sharp drops in product prices is also an essential tool. For example, the creation of a fund to compensate for losses from falling grain or meat prices could play a key role in supporting agribusiness in times of crisis. In 2022, when wheat prices in Kazakhstan fell by 15% year-on-year, a stabilisation fund could compensate for some of the agrarians' losses, preventing financial distress and loan defaults. Moreover, in conditions of currency volatility, attention should be paid to currency risks. For the agro-industrial complex of Kazakhstan, where a significant part of resources (seeds, fertilisers, machinery) is imported, exchange rate fluctuations play a key role in the formation of production costs. For example, in 2022, a 10% devaluation of the Kazakh tenge against the US dollar led to a 12% increase in the cost of fertilisers and an 8% increase in the cost of agricultural machinery, which greatly increased the prime cost of agricultural products (Bureau of National Statistics, n.d.).

Currency devaluation, as a rule, leads to an increase in the cost of imported goods and services, which increases the financial burden on agricultural producers and complicates debt servicing for them. In such a situation, one solution is to use currency hedging mechanisms, e.g., through currency futures contracts or currency risk insurance. For example, farmers could contract with banks for a fixed exchange rate for a fixed period, which would allow them to reduce uncertainty and plan costs more accurately. It is also possible to provide credit resources in a currency that is linked to Kazakhstan's key trading partners, such as the Russian rouble or the Chinese yuan. This will allow agro-producers to avoid increased costs in case of tenge devaluation. Assessing the sustainability of lending in the face of geopolitical instability is also a crucial aspect. In 2023-2024, amid sanctions and changes in the external political situation, Kazakhstan faced a drop in foreign trade with Europe and the US, which adversely affected the export-oriented agricultural sector. The projected adaptation of credit mechanisms should include the creation of conditions for diversification of foreign trade, for example, through the development of new trade routes and improved logistics. This would allow agro-producers to compensate for losses caused by external shocks and reduce dependence on a single source of income. Furthermore, improving internal infrastructure and developing alternative markets would greatly mitigate the effects of geopolitical instability on agricultural sustainability.

To achieve sustainable development of the agro-industrial complex, a prominent aspect is the development of an effective system of support and incentives for agricultural sectors through subsidies and government programmes. In conditions of economic instability, when market conditions can change rapidly, increasing the availability of credit resources and reducing the cost of lending become key factors for agrarians, contributing to the modernisation and development of agriculture. One notable method is the implementation of interest rate subsidy programmes. These programmes ensure the affordability of long-term loans for agro-producers, especially in an environment of increased inflation and economic uncertainty. In 2023, Kazakhstan allocated KZT 580 bn for concessional loans in the agro-industrial complex, which demonstrated positive changes in support for the agro-sector (Olzhas Bektenov on support..., 2024). This step has become a crucial tool in ensuring the sustainability of agribusinesses, especially for those interested in expanding production or introducing the latest technologies. A foreseeable future need includes the creation of specialised programmes focused on modernising agro-production and improving the financial performance of enterprises. This would not only improve financial conditions, but also stimulate investment in the latest technologies, productivity and competitiveness of the sector.

Credit programmes for small and medium-sized farms are an equally significant element in the AIC support system. Small farmers, as a rule, face great challenges in obtaining loans, as they cannot provide sufficient collateral to secure the loan. In such cases, support in the form of microfinance programmes with flexible repayment terms is particularly valuable. These programmes provide access to finance for farmers struggling to access conventional credit markets and improve their production capacity. An example of a successful programme is the interest rate subsidy in 2023, which provided smallholder farmers with access to finance, helping to increase their production capacity and improve their financial performance. The programme has provided loans worth over KZT 10 billion, allowing 3,500 small farms to increase production by 15-20% (Bureau of National Statistics, n.d.). In the future, it is worth developing these programmes to include not only small but also medium-sized farms to stimulate growth and development of the sector at all levels. A major step could also be to expand access to concessional loans for modernisation of equipment and introduction of innovative technologies, which would help to increase the competitiveness of the agricultural sector in international markets.

One of the key measures to optimise the sustainability of Kazakhstan's agricultural sector in conditions of instability is the development and introduction of an effective mechanism for insurance of agricultural risks. The development of comprehensive insurance products covering both climatic and market risks is critical for improving the sustainability of agribusiness and ensuring its financial stability. The primary method of optimising the insurance mechanism is to create public and private insurance products that would protect agricultural producers from risks associated with adverse weather conditions (droughts, floods, frosts, and other climatic anomalies) and market instability (fluctuations in product prices). An example of a successful government programme is "Agroinsurance", which was launched to support farmers in case of damage caused by adverse weather conditions (About 3.3 billion..., 2021). This programme provides subsidised insurance policies, making them affordable to most agricultural enterprises. In 2023, thousands of hectares of agricultural land were insured under the programme, demonstrating a positive effect in reducing agro-producer losses and increasing confidence in insurance (Voluntary insurance in..., n.d.). The forecast for further development of agrarian risk insurance assumes expansion of existing programmes considering changes in the external economic environment. It is essential that insurance products not only protect against natural catastrophes, but also consider risks associated with external economic instability, such as exchange rate fluctuations and changes in external demand for products. These changes can greatly affect the financial stability of agro-producers, and therefore the development of programmes that could compensate for such risks would contribute to improving the overall situation in the agro-industrial complex.

It should be emphasised that forecasting and adapting credit policies require constant monitoring of macroeconomic factors such as changes in interest rates, currency fluctuations, and fluctuations in agricultural prices. These factors significantly affect the financial sustainability of agrarians and may require a prompt response from financial institutions and the government. Regular monitoring of macroeconomic indicators allows for prompt adjustment of lending terms in response to changes in the external economic environment. Changes in interest rates on world markets or currency fluctuations may require a revision of lending rates in the national economy. In 2022 in Kazakhstan, the rise in the dollar led to higher prices for imported inputs and increased costs of agricultural production (Bureau of National Statistics, n.d.). Under such conditions, it is vital to adjust credit conditions in time to reduce the financial burden on agricultural producers.

Furthermore, monitoring the prices of agricultural products, including major export commodities such as wheat and barley, allows forecasting future fluctuations in the profitability of agrarians and, accordingly, adjusting credit policy. For example, in 2023-2024, rising wheat prices on the world market could reduce risks for Kazakhstan's agro-producers, but at the same time, price volatility also carries risks associated with possible price drops. This requires the introduction of flexible lending models that can adapt to the market situation. Looking ahead, it is essential to introduce digital platforms to monitor macroeconomic data in real time. Such platforms provide up-to-the-minute information on the current state of the economy, enabling financial institutions and agro-producers to better manage credit risks and adjust strategies in response to changes in the external and internal environment. The use of digital technologies for data collection and analysis can optimise credit strategies and increase predictability in volatile market conditions, which helps to reduce financial risks and improve the resilience of agribusinesses. Table 2 presents the assessment steps, parameters, methods, and tools for optimising the sustainability of agribusiness lending.

***Table 2**. Assessment stages, parameters, methods, and tools for optimising the sustainability of agribusiness lending*

Assessment stage	Assessment parameters	Methods and tools	Goal and outcomes
1. Analysis of macroeconomic conditions	GDP, inflation, exchange rates, interest rates	Analysis of economic reports, monitoring of statistics	Assessing economic stability and forecasting the effects of macroeconomic changes on the agribusiness sector
2. Agribusiness risk assessment	Price volatility, weather conditions, market fluctuations, currency risks	Statistical forecasting models, scenario analysis, futures contracts	Determination of the effect of external risks on profitability and ability to repay loans
3. Analysis of public policy and regulation	Government subsidies, support programmes, tax incentives, export restrictions	Analysis of political and economic regulations, consultations with government agencies	Assessment of the impact of government initiatives on the availability of funding and subsidies provided
4. Assessment of credit resources	Credit terms, interest rates, availability of long-term loans, guarantees	Analysis of bank offers, comparison of interest rates	Determination of credit availability for agrarians and assessment of conditions for obtaining financing
5. Assessment of financial sustainability of agricultural enterprises	Liquidity, solvency, profitability ratios	Financial analysis, analysis of company statements	Assessment of the ability of enterprises to perform their loan obligations promptly
6.	Insurance products, risk coverage, insurance subsidies	Analysis of existing insurance programmes, examination of international practices	Assessment of the effectiveness of insurance mechanisms to protect against price and climate risks
7. Assessment of market-based lending mechanisms	Financing conditions, access to long-term investments, flexibility of credit mechanisms	Modelling of market situations, comparison of credit offers	Optimisation of credit conditions, facilitation of access to flexible credit mechanisms for agribusinesses
8. Assessment of the impact of geopolitical and external factors	Trade restrictions, currency fluctuations, geopolitical situation	Foreign policy analysis, economic and political situation in partner countries	Assessment of the effects of external factors on the financial stability of the agribusiness sector

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

The table above serves as the basis for a detailed methodology for assessing and optimising the sustainability of lending to the agro-industrial complex, which will enable an accurate assessment of the effects of various internal and external factors on the financial situation in the agricultural sector and identification of strategies to improve its sustainability. Optimisation of the sustainability of agribusiness lending through the implementation of the proposed methodology contributes to the solution of a series of critical tasks for the development of agriculture in conditions of market instability. Creating conditions for obtaining long-term and affordable loans will reduce dependence on short-term borrowed capital, which, as a rule, is associated with high interest rates and major risks for agricultural producers. When agricultural producers are forced to turn to short-term loans, their financial sustainability becomes vulnerable, especially when the market situation or weather conditions change. The introduction of long-term lending mechanisms with optimum conditions will help to significantly reduce the burden on agribusiness, ensuring its stability and long-term sustainability.

The use of price risk hedging and insurance instruments will allow agro-producers to protect themselves from unexpected market fluctuations, which will increase the financial sustainability of the entire agribusiness. Agro-insurance programmes that cover losses from adverse weather conditions will help minimise losses associated with natural disasters such as droughts or floods, as well as fluctuations in the prices of key agricultural commodities. Diversifying risks and reducing dependence on external fluctuations helps to ensure that agribusinesses stay profitable and viable even in volatile environments. Furthermore, optimising the sustainability of lending in the agribusiness sector will greatly increase investment in the sector. Subsidising interest rates and creating incentive programmes for investment in the modernisation of agricultural production will help attract further capital investment. Investment in the latest technologies, agricultural machinery and infrastructure helps to increase the productivity and efficiency of agribusinesses. This is particularly significant in the context of global change when agriculture needs to adapt to emerging economic and climatic conditions. Support for investment programmes and financial accessibility will help to significantly increase the innovation potential of the agro-industrial complex and accelerate the process of its modernisation.

DISCUSSION

The findings of the present study provided a deeper understanding of the complexity and multifaceted nature of the problems faced by the agro-industrial complex of Kazakhstan in accessing credit resources. The identified problems indicated the presence of structural and systemic gaps that hinder the effective functioning of the financial system aimed at supporting agriculture. The observed challenges in ensuring the sustainability of lending, despite the existing state support programmes, highlighted the need for fundamental changes in approaches to financing the agricultural sector. These findings also pointed to weaknesses in the organisation of credit mechanisms, which may negatively affect the long-term financial stability and investment attractiveness of agricultural producers. Still, the analysis of the situation opened prospects for the development of more flexible and adapted models of financial support, which could increase the sustainability and independence of agrarians from external economic factors. K. Brockova *et al.* (2021) also highlighted the significance of adapting government programmes to changing market conditions, noting major advancement in the flexibility of approaches to support agrarians, but the drawback of this study was the limited consideration without accounting for the specifics of Kazakhstan's regions, which may affect the outcomes.

E.J. Kane (2021) examined approaches to agricultural subsidies and support, exploring useful methods to improve existing programmes, but at the same time, not paying due attention to the possible effects of international economic factors on the internal market, which limited its practical value for the specific situation of Kazakhstan. B.B. Balana and M.A. Oyeyemi (2022) focused on credit systems in developing countries using Nigeria as an example, emphasising the potential for transferability to other countries, but its findings were not fully applicable due to differences in economic structures and the level of development of the agricultural sector, which was a major limitation. Y. Xia *et al.* (2022) examined the potential of new financial instruments for the agribusiness sector, but did not explore in sufficient detail the risks associated with the instability of the global financial system, making the findings of the study somewhat incomplete. A. Ullah *et al.* (2020) highlighted the effects of socio-economic factors on farmers' access to credit and sources of finance in Pakistan, emphasising the significance of farm size as key determinants, but without considering regional differences in infrastructure and climatic conditions, which limits the generalisability of the findings. Thus, the findings of this study largely complemented and extended the findings of the above-mentioned works, providing a detailed picture of current credit problems in Kazakhstan, as well as offering concrete recommendations to improve the financial sustainability of the agro-industrial complex.

The problems identified in this study demonstrated the complexity of the financial environment where Kazakhstan's agro-industrial complex operates. Limited access to long-term loans constrains the investment activity of enterprises, reducing their opportunities for expansion and modernisation. High interest rates increase the debt burden on agrarians, which hampers their ability to effectively manage their finances and adapt to market fluctuations (Manatovna *et al.*, 2023). Volatility in agricultural commodity prices creates further risks for borrowers and lenders, complicating the forecasting o f financial flows. External factors, including exchange rate movements and geopolitical instability, significantly affect the availability of financial resources, making the credit system vulnerable to macroeconomic changes (Musca & Kara, 2023). These aspects emphasise the existence of structural problems in the industry's financing mechanisms, which require a detailed review and adaptation to the current economic conditions.

T. Havemann *et al.* (2022) noted the significance of diversification of financial instruments in lending to the agricultural sector, which allows expanding the range of available sources of financing and reduce dependence on bank loans, but the lack of detailed analysis of the effects of macroeconomic factors on the effectiveness of these instruments limited the results obtained. A.A. Yadgarov *et al.* (2023) noted the positive impact of risk insurance mechanisms on reducing the financial burden on agrarians, showing their potential in stabilising the incomes of agricultural producers, but the study did not address the impact of global economic trends, which limited its applicability in conditions of high market volatility. A.D. Kehinde and A.A. Ogundeji (2022) highlighted the role of agricultural cooperatives in improving access to credit resources, confirming their effectiveness in increasing farmers' financial sustainability, but the paper did not sufficiently address the obstacles associated with institutional constraints and the complexities of managing such associations.

A.R. Khanal and O. Omobitan (2020) highlighted the value of credit sources affecting the demand for credit among small farms and enterprises, emphasising the relevance of credit availability for agricultural improvement, but without considering the effect of macroeconomic factors, which limited the comprehensiveness of the findings. A.A. Chandio *et al.* (2021) examined the factors influencing credit demand among small farmers in Pakistan, identifying key aspects such as farm size, but the study was limited to analysing only at the farm level without considering the broader economic and social contexts. Thus, the present study offered a more comprehensive approach to analysing agribusiness credit problems in Kazakhstan, considering not only individual financial instruments, but also their interplay with market and institutional factors. Unlike the above-mentioned studies, the presented analysis covered a wide range of aspects affecting the availability of credit resources, which offered a more nuanced understanding of systemic constraints and possible areas for their elimination.

The comprehensive methodology for optimising the sustainability of agribusiness lending proposed in the study reflects the need for a systemic approach to solving existing financing problems. The development of interest rate subsidy mechanisms is an effective tool to reduce the debt burden, allowing farmers to obtain more affordable loans and minimise the effects of high interest rates on their financial performance. The creation of long-term credit programmes with flexible conditions meets the needs of farmers for stable and predictable sources of financing, which is especially significant in conditions of market volatility. The development of agricultural risk insurance systems strengthens the financial stability of the sector, reducing the vulnerability of producers to unforeseen economic and market shocks (Cheremisina & Tomashuk, 2023). Together, these measures allow facilitating access to credit resources and to create a more sustainable financial environment conducive to the long-term development of the sector. Therewith, the key aspect of successful implementation of the proposed methodology continues to be the necessity of complex interaction between state structures, financial institutions, and agrarian business, which requires further study and adaptation of lending instruments to the specifics of the agrarian sector of Kazakhstan.

C. Csosz *et al.* (2021) also stressed the significance of an integrated approach to ensuring the financial sustainability of the agro-industrial complex, highlighting the prominent role of state support programmes in the formation of affordable lending mechanisms, but focusing mainly on the analysis of existing instruments without a detailed consideration of their adaptation to the specifics of the agrarian sector of Kazakhstan. I. Tetteh *et al.* (2022) focused on the need for long-term lending to increase the investment activity of agricultural enterprises, suggesting the improvement of financing mechanisms considering the seasonality of agricultural production, however, without considering the potential macroeconomic risks associated with the expansion of credit programmes, which may affect their sustainability in conditions of market instability. M.A. Bhuiyan *et al.* (2022) analysed the impact of agrarian risk insurance on the sustainability of agricultural business, proving that effective insurance programmes can greatly reduce financial losses of agrarians, but without paying sufficient attention to the possible mechanisms of integration of insurance instruments into the existing credit system, which limited the practical application of the findings.

O.C. Okunlola and O.A. Ayetigbo (2024) examined the effects of agrarian finance on the sustainability of agricultural growth in Nigeria, revealing the positive influence of credit programmes on the growth and development of the sector, but without addressing regional differences in the availability of finance, which limited the generalisability of the findings. D. Kirechev (2021) examined improved access to finance for agricultural enterprises in Bulgaria as a factor in the sustainability of agricultural finance, showing that improved credit availability favours agricultural development, but without considering the impact of external economic factors, which limited the accuracy of the findings. In contrast to the mentioned studies, the present study proposed a comprehensive approach combining interest rate subsidies, the establishment of long-term credit programmes, and the development of insurance systems. This comprehensive view allowed considering the existing financial support mechanisms and adapting them to the concrete needs of the agro-industrial complex of Kazakhstan, which made the proposed methodology more flexible and applicable in a dynamic economic environment.

The measures proposed in the present study are aimed at creating a more stable and predictable financial environment for the agro-industrial complex, which is crucial in conditions of high dependence of the industry on external factors. Expansion of insurance programmes focused on compensation for losses from natural disasters and market fluctuations helps diversify risks and reduce the probability of financial shocks for agrarians. The development of specialised insurance products adapted to the specifics of agricultural production allows increasing the protection of enterprises, minimising their losses in case of unfavourable economic or climatic changes (Pushak *et al.*, 2021). The creation of an effective system for monitoring the economic situation plays a key role in ensuring prompt adjustment of credit policy, which increases the resilience of credit mechanisms to market fluctuations. The introduction of digital platforms for monitoring and managing credit risks opens new opportunities for automating analysis and forecasting processes, which reduces uncertainty and expedites decision-making in the financial sector. Together, these measures ensure a greater level of adaptability of financial institutions and allow creating a balanced system of support for the agricultural sector, considering the specifics of its functioning in a changing economic environment.

E. Nshakira-Rukundo *et al.* (2021) also emphasised the value of insurance mechanisms in reducing risks for agrarians, noting successful examples of their implementation in international practice, but the lack of detailed analysis of the effectiveness of such mechanisms in the conditions of other countries limited the applicability of the findings obtained. A.O. Scott *et al.* (2024) examined the impact of digital technologies on credit risk management, considering modern approaches to automated monitoring of borrowers, but without factoring in the specifics of the agro-industrial sector, which limited the applicability of the proposed solutions. H.R.B.C. Tanaka (2023) analysed the effects of macroeconomic instability on credit availability for agrarians, detailing the external factors, but without any proposals for adapting credit instruments to these conditions. F.O. Odhiambo and R. Upadhyaya (2021) focused on the design of flexible credit programmes for agricultural enterprises, considering different financing models, but without addressing the integration of insurance mechanisms, which reduced the comprehensiveness of the proposed approach. In contrast to the mentioned studies, the present study offered a more comprehensive approach, an integrated solution that factors in the specifics of the agro-industrial sector of Kazakhstan and is aimed at creating a balanced system that can effectively respond to changes in the external environment and risks.

Thus, the findings of all the reviewed studies emphasised the significance of an integrated approach to solving the problems faced by the agro-industrial complex in the context of lending and financial sustainability. Each of the studied areas contributes to strengthening the financial stability and adaptability of the agricultural sector. However, despite the existing achievements, there is still a need to further improve the mechanisms and adapt them to the specifics of Kazakh agriculture. Ultimately, only the integration of all these solutions into a single system, as well as consideration of external factors that can affect financial flows, will allow creating a sustainable and long-term basis for the development of the agro-industrial complex of Kazakhstan.

CONCLUSIONS

This study analysed the current problems of lending to Kazakhstan's agro-industrial complex and developed proposals to improve the sustainability of lending under conditions of market instability. The study found that despite the promising potential of the agro-industrial complex, the industry faces a series of major challenges, including high interest rates, limited availability of long-term loans, volatility in agricultural commodity prices, and the impact of external factors such as exchange rate changes and geopolitical instability. The study found that the primary challenge is the high financial burden on agro-producers caused by high interest rates and insufficient availability of long-term credit. For example, in 2024, the interest rate on long-term loans was 6% for concessional loans, and could be as high as 25-27% for commercial loans, well above the level needed to stimulate investment in agriculture. These factors substantially limit opportunities for long-term investment and modernisation of agro-production, which is critical for the sustainable development of the industry. Moreover, fluctuations in agricultural commodity prices (in 2020, a tonne of grain cost about KZT 80,000, and by 2023-2024 it reached KZT 135,000) and currency risks make agribusiness vulnerable to external economic shocks (in 2022, a 10% devaluation of the KZT led to a 12% increase in the cost of mineral fertilisers).

A prominent part of the study was the proposal of a comprehensive methodology aimed at optimising the sustainability of lending. It was stressed that the introduction of interest rate subsidy mechanisms (in 2023, KZT 580 billion was allocated for soft loans for agribusiness), the creation of long-term credit programmes with flexible terms, and the development of agricultural risk insurance systems can greatly reduce the financial burden on agricultural producers and increase their financial sustainability. It was also proposed to expand insurance programmes aimed at compensating losses from natural disasters and market fluctuations, which allows diversifying risks and protecting agribusiness from external instability. Furthermore, the study proposed to develop specialised public and private insurance products that will provide agrarians against climatic and market risks, as well as to create an effective system for monitoring the economic situation for prompt adjustment of credit policy. The introduction of digital platforms for monitoring and managing credit risks will increase the efficiency of decision-making and reduce market uncertainty. Thus, an integrated approach to solving the problems of lending in the agro-industrial complex and implementation of the proposed methodology will increase the availability of credit resources, reduce the financial burden on agrarians, improve the financial sustainability of agribusiness, and stimulate investment in the modernisation of agricultural production.

Notably, this study had a limitation in the form of its restriction to the territorial context of Kazakhstan, which limited the universality of conclusions for other countries. In the future, it would be advisable to conduct studies that would confirm the findings in real conditions and adapt the proposed measures to the specific features of the agro-industrial complex of other countries, as well as to investigate the effects of various economic factors on the financial sustainability of agrarians.

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CONFLICT OF INTEREST

None.

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Оптимізація кредитних стратегій в агропромисловому комплексі в умовах ринкової нестабільності

Діас Бабаш
Докторант
Жетісуський університет імені Ільяс Жансугурова
040009, вул. Жансугурова, 187А, м. Талдикорган, Республіка Казахстан
https://orcid.org/0009-0001-3425-0804
Даніяр Калдіяров
Доктор економічних наук, професор
Жетысуський університет імені Ільяс Жансугурова
040009, вул. Жансугурова, 187А, м. Талдикорган, Республіка Казахстан
https://orcid.org/0000-0002-0181-2962
Гульнар Тулешова
Кандидат економічних наук
Жетісуський університет імені Ільяс Жансугурова
040009, вул. Жансугурова, 187А, м. Талдикорган, Республіка Казахстан
https://orcid.org/0009-0001-4717-0969
Жанар Туралiна
Кандидат економічних наук
Міський науково-методичний центр нових технологій в освіті м. Алмати
050007, Ш. Калдаякова, 62, м. Алмати, Республіка Казахстан
https://orcid.org/0000-0003-2249-9124
Олеся Лемещенко
Магістр
Жетісуський університет імені Ільяс Жансугурова
040009, вул. Жансугурова, 187А, м. Талдикорган, Республіка Казахстан
https://orcid.org/0000-0002-8907-9768

Анотація. Метою цього дослідження був аналіз проблем кредитування агропромислового комплексу Казахстану та розробка методології його сталого фінансування. Дослідження базувалося на системному підході, що включає теоретичний аналіз економічних та фінансових факторів, порівняльний аналіз міжнародної практики, а також розробку методів субсидування, страхування та моніторингу для оптимізації сталості кредитування агропромислового комплексу. Результати дослідження показали, що забезпечення сталості кредитування агропромислового комплексу вимагає комплексного підходу, що включає інтеграцію механізмів державного регулювання, ринкових інструментів та методів управління ризиками. Аналіз існуючої практики фінансування агропромислового комплексу в Казахстані показав, що ключовими проблемами продовжують залишатися висока вартість позикових коштів (у 2024 році кредитна ставка становила 6 % для пільгових кредитів та сягала 25-27 % у випадку комерційних кредитів), обмежений доступ малих та середніх фермерських господарств до кредитних ресурсів, а також нерозвиненість механізмів страхування сільськогосподарських ризиків. У цьому контексті дослідження підтвердило ефективність таких інструментів, як субсидії на процентні ставки, державні кредитні гарантії та розширення програм пільгового кредитування сільськогосподарських виробників. Згідно з висновками, це дозволило дрібним фермерам отримати доступ до фінансування в розмірі 10 мільярдів тенге та збільшити виробничі потужності на 15-20 %. Крім того, дослідження показало, що в нестабільному макроекономічному середовищі регулярний моніторинг макроекономічних факторів та адаптація кредитної політики до змін на фінансових ринках є важливими, оскільки тонна зерна коштувала близько 80,000 тенге у 2020 році та може досягти 135,000 тенге до 2024 року. Використання цифрових платформ та аналітичних інструментів для оцінки ризиків та прогнозування ринкових тенденцій може значно підвищити ефективність управління кредитами в агробізнесі. Крім того, міжнародна практика у сфері фінансування сільського господарства, зокрема моделі кредитної підтримки, що використовуються в розвинених та перехідних економіках, може бути адаптована до умов Казахстану, враховуючи специфічні особливості його сільськогосподарського сектору та фінансової системи. Отримані результати стали основою для вдосконалення механізмів кредитування агропромислового комплексу, підвищення доступності фінансових ресурсів для сільськогосподарських виробників та мінімізації кредитних ризиків в умовах економічної нестабільності

Ключові слова: макроекономічні фактори; субсидії; страхування; сільськогосподарська продукція; коливання валютних курсів; фінансування; процентні ставки

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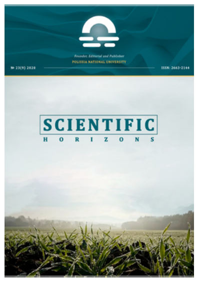

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Prospects of using international grants to develop organic farming in Ukraine

Nataliia Sharata[*]
Doctor of Pedagogical Sciences, Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-6306-6934

Olena Usykova
Doctor of Economic Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0001-6734-5757

Oleksandr Bilichenko
PhD in Economic Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-5241-3195

Hanna Poberezhets
PhD in Historical Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-9064-6731

Tetiana Kravchenko
PhD in Philological Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0001-5818-8307

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Abstract. The purpose of this study was to analyse the possibilities of attracting international grant funding to support and develop organic farming in Ukraine. The study proposed a classification of international grants according to various criteria, such as sources of funding and programme objectives. The study considered the grants provided by government agencies, international organisations, and private foundations, such as the European Union's programmes, including the Common Agricultural Policy,

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*Corresponding author

and Horizon Europe, as well as initiatives of the United States and the United Nations. Methodologically, the study included an analysis of secondary data, a survey of 100 farmers from Odesa, Mykolaiv, and Kherson regions of Ukraine, and 10 in-depth interviews with representatives of agricultural enterprises that received grants. The findings showed that international grants have significantly influenced the development of organic agriculture in Ukraine, especially in the southern regions. 60% of the farmers surveyed used international grant programmes, with 25% of them reporting reduced costs and increased production due to the funds received. However, despite the positive outcomes, farmers faced a series of challenges, including bureaucratic obstacles, lack of information, and difficulties related to the war. The study offered recommendations for improving the efficiency of international grants, including the establishment of advisory centres for farmers, increasing financial literacy, and supporting agricultural cooperatives that can streamline application processes and reduce preparation costs. The conclusions of the study pointed to the significance of a comprehensive approach to attracting and using international grants in the Ukrainian agricultural sector, with a focus on developing educational programmes, improving cooperation, and using digital tools to simplify the application process

Keywords: agricultural sector; innovative technologies; farmer cooperatives; financial support; European initiatives

INTRODUCTION

In the face of global challenges related to climate change, soil depletion, and growing demand for environmentally friendly products, organic farming is gaining in value. This type of agriculture helps to preserve natural resources, improve soil fertility, and produce safe food. Ukraine has a great capacity to develop organic agriculture and could become one of the leading suppliers of organic products to the global market. However, the effective development of this sector is hampered by a series of challenges, including insufficient funding, lack of proper infrastructure, and limited knowledge and skills of farmers. One of the most promising ways to overcome these challenges is to attract international grants, which can be a valuable source of financial support for organic producers. Grant funding allows not only covering the costs of certification and modernisation of production, but also promotes the introduction of innovative technologies, training programmes, and the creation of cooperative associations. A prominent advantage of such programmes is their focus on the long-term development of the industry and its competitiveness.

International organisations such as the European Union (EU), the United Nations Development Programme (UNDP), the World Bank, and others actively support environmental initiatives in Ukraine (Konovalyuk *et al.*, 2023). They provide funding to develop sustainable agriculture, which includes support for small and medium-sized farms, educational programmes, and the development of export potential for organic products. However, the process of obtaining grants is often associated with stringent requirements for projects, complexity of documentation, and the need for co-financing from recipients. Thus, the significance of the study lies in identifying the key opportunities for using international grants to stimulate the development of organic farming in Ukraine. The successful use of international grants will contribute not only to the economic growth of the agricultural sector, but also to the development of sustainable environmental approaches in Ukrainian agriculture.

The impact of international grants on the development of organic farming has been investigated by many researchers who explored various aspects of this issue. L.C. Stringer *et al.* (2020) analysed the financial mechanisms for supporting farms and concluded that international grants contributed not only to production growth but also to improving its quality. G. Pe'er *et al.* (2020) studied the effectiveness of grant funding in European countries and determined that the successful implementation of grant programmes requires clear coordination between the state, donors, and producers. L. Pronko *et al.* (2020) analysed the principal challenges faced by Ukrainian farmers in obtaining grant aid and stressed the need to simplify application procedures.

R. Sapbamrer and A. Thammachai (2021) placed an emphasis on the educational component, finding that international grants contributed to improving farmers' knowledge of organic production. The researchers stressed that grant-funded training programmes contributed to the introduction of the latest agricultural technologies and increased yields without harming the environment. J. McCormick (2023) investigated the role of international organisations in financing environmental initiatives and found that the most effective projects were those that involved a comprehensive approach, from training farmers to implementing technological solutions. A detailed analysis of the effects of grant funding on sustainable agriculture was conducted by V. Piñeiro *et al.* (2020), who found that international support has considerably reduced economic risks for smallholders. J.F. Parr *et al.* (2020) investigated the long-term effects of grant programmes and concluded that they contribute not only to short-term modernisation of production but also to the development of sustainable environmental practices.

F. Rexhaj *et al.* (2023) examined the cooperation between Ukrainian farmers and international donors. The researchers found that the most successful initiatives were those that involved cooperation between small producers, which enabled them to use financial aid more efficiently and strengthen their market position. A. Gamage *et al.* (2023) also concluded that combining grant funding with national organic farming development programmes increases resource efficiency and promotes greater farmer engagement in environmental initiatives. Overall, the research findings confirmed that international grants are a valuable tool for the development of organic farming, but their effective use depends on the availability of information, competent management, and favourable governmental conditions. Despite a considerable amount of research, the effectiveness of the use of international grants in various regions of Ukraine continues to be understudied, specifically in terms of their economic and environmental effects. Mechanisms for increasing the availability of grant funding for small farms and cooperatives also lack sufficient coverage. The issue of integrating grant programmes with the national policy of organic farming development continue to be significant.

The purpose of this study was to analyse the effectiveness of international grants in the development of organic farming in Ukraine to develop recommendations for optimising the use of grant funds. The objectives of this study were to analyse existing international grant programmes and their effects on the development of organic farming in Ukraine; to identify the key problems and constraints that prevent Ukrainian farmers from effectively attracting grant funding; and to develop recommendations for improving access to international grants and increasing the efficiency of their use.

MATERIALS AND METHODS

The study of the effectiveness of attracting international grants for the development of organic agriculture in the Southern region of Ukraine employed a comprehensive methodology that combined secondary data analysis and sociological methods of data collection. The primary sources of information included official documents of the EU (Common Agricultural Policy, n.d.; Horizon Europe, n.d.), and the United Nations (UN) (specifically, the Food and Agriculture Organization (FAO) (n.d.) and the United States Agency for International Development (USAID) (n.d.). Special attention was paid to the analysis of reports of Ukrainian authorities on the attraction and distribution of international aid in the agricultural sector, as well as statistics on the area of organic land, the number of certified operators, and the level of financing available to Ukrainian farmers (Organicinfo, n.d.).

The study focused on countries such as Germany, France, Sweden, Denmark, Spain, Italy, and Austria, as they have the most developed support systems for organic farming in Europe. The choice of these countries was based on several factors: leadership in financing the organic sector, developed farmer support policies, innovative approaches to organic production, high share of organic land, and successful experience in attracting international grants. The empirical stage of the study employed a sociological survey method to obtain quantitative and qualitative data on the level of involvement of farmers in the Southern region of Ukraine in international grant programmes. An online questionnaire survey was conducted among 100 farmers operating in three regions: Odesa, Mykolaiv, and Kherson. The sample was formed by random selection among the owners and managers of farms engaged in organic farming or in the organic certification process. Dichotomous questions (yes/no) and multiple choice were used. The questionnaire contained 25 questions divided into four thematic blocks: general information about the respondent (farm size, specialisation, organic certification, experience in agriculture); level of awareness of international grants (whether they are familiar with the concept of grant funding, sources of information, whether they have sought advice from relevant organisations); experience of participation in grant programmes (number of applications submitted, success in obtaining funding, which programmes were used, amount of funds received); the key challenges in attracting grant funds (what barriers were encountered in preparing the application, whether third-party help was needed, problems with project implementation after receiving funding). The authors adhered to the principles of the American Sociological Association's Code of Ethic (1997).

The quantitative research was complemented by 10 in-depth semi-structured interviews with representatives of farms that have successfully received international grants and implemented development projects. The respondents were selected using a purposive method: farmers who had received funding from organisations such as USAID, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), EBRD, and UNDP were selected. The interview was conducted online. The following aspects were discussed:

- motives for applying for a grant; the documentation preparation procedure (key challenges, need for external help, consulting services);
- timeframe for reviewing the application and receiving funding; practical use of grant funds (what the investment was for: equipment, staff training, marketing, production expansion, etc;)
- results obtained after the implementation of the grant project (impact on production volumes, product quality, profitability of the enterprise);
- further plans for participation in grant programmes.

Comparative analysis methods were employed to assess the effectiveness of various grant programmes, as well as factor analysis methods to identify the key factors that influence the success of obtaining and using international grants.

RESULTS

In the context of agricultural development, international grants play a key role in supporting sustainable and environmentally friendly agricultural practices. Organic farming, which is based on the principles of natural balance, the elimination of chemical fertilisers and pesticides, and the preservation of soil fertility, requires extensive financial investment. However, not all farmers, especially in developing countries, have access to the necessary resources to switch to organic production (Norton & Alwang, 2020). It is in this context that international grants are becoming a vital tool to stimulate the development of the organic sector, enabling farmers to finance modernisation of production, certification, training, and infrastructure development.

International grants for organic farming can be classified according to several criteria. One of the key approaches to their distribution is by funding source. They can be divided into grants from government agencies, international organisations, and private foundations. For example, the EU actively supports the development of organic agriculture through programmes such as Horizon Europe and the Common Agricultural Policy (CAP), which are aimed at the environmental modernisation of the agricultural sector. The UN and its agencies, including the FAO, are implementing global initiatives aimed at developing sustainable agriculture. Furthermore, numerous private foundations, such as the Rockefeller Foundation or the Bill and Melinda Gates Foundation, invest in projects that promote sustainable agriculture in different countries (Dhiman, 2020).

Another approach to classifying grants is based on their purpose. There are several major categories. Research and innovation grants are aimed at developing and implementing the latest organic production technologies, e.g., funding projects related to the development of biological fertilisers or the efficiency of permaculture systems. Grants for certification and standardisation allow farmers to cover the costs of obtaining certificates of compliance with organic standards, which is a crucial step in entering the international market. Grants for infrastructure and equipment finance the purchase of modern machinery, the construction of environmentally friendly farms and the creation of supply chains for organic products. Grants for education and training are aimed at educating farmers, agronomists, and agricultural specialists in organic farming methods. A separate group includes grants to support cooperatives and farmers' associations, which help small organic producers to form cooperatives to share resources and access markets (Custer & Akaeze, 2021).

Grants aimed at supporting small and medium-sized agribusinesses are especially significant for Ukraine, as this sector faces the greatest financial challenges in the transition to organic production. The use of international grants allows not only to expand the organic market, but also to contribute to the overall improvement of the environmental situation, biodiversity conservation, and the quality of life of the population (Jovanović & Zubović, 2019). The EU is one of the world leaders in the development of organic farming, and the effective use of grant funding plays a great role in this. EU countries are actively implementing policies aimed at supporting farmers switching to organic production and funding numerous initiatives that promote sustainable agriculture. One of the key grant programmes in the EU is CAP, which is funded jointly by the European Commission and national governments. This policy includes subsidies for farmers who practice organic production, as well as special grant initiatives to help farmers adapt to new requirements. For example, Germany has a state programme to support organic farming, which compensates farmers for part of the costs of certification and environmental modernisation of their farms (Hamm *et al.,* 2017).

Apart from the CAP, EU countries actively use the Horizon Europe programme, which finances research and implementation of innovative organic farming methods. For instance, in France, this programme is implementing projects to develop biological plant protection methods that reduce the use of pesticides (Robert *et al.,* 2020). In Spain and Italy, a considerable portion of grant funding is directed to the development of agroecological practices, including crop rotation, biofertilisers, and integrated farming systems (Iocola *et al.,* 2023). Particular attention is paid to the organic sector in the Nordic countries, specifically Sweden and Denmark. Denmark, for example, has one of the most developed support systems for organic agriculture in the world. Grants provided by the government and European funds are aimed not only at direct financial support for farmers, but also at expanding the market for organic products, raising consumer awareness, and developing cooperative sales systems. A positive example is also set by Austria, where more than 25% of agricultural land is used for organic production, which is the highest in Europe (Connor, 2022). Thanks to a competent support policy, including transition subsidies, compensation for certification costs, and grants for the modernisation of organic farms, Austrian farmers have managed to create an effective export-oriented model of organic production.

Thus, the experience of EU countries shows that successful implementation of grant programmes to support organic farming requires a comprehensive approach. It includes financial aid to farmers, promotion of scientific research, and creation of favourable conditions for certification and marketing of products. Ukraine can use this experience to develop its mechanisms for integrating international grants into national agricultural policy and stimulating the transition to organic agriculture. In Ukraine, the state policy on attracting international grants to agriculture is in active development and improvement. As organic farming is becoming increasingly in demand both on domestic and foreign markets, the Ukrainian government is developing strategies and programmes aimed at supporting sustainable agriculture, including through attracting international funding. One of the key initiatives is the National Economic Strategy 2030 (n.d.), which stipulates the development of environmentally friendly production and an increase in the share of organic products in the overall structure of the agricultural sector. This strategy focuses on attracting international grants to support small and medium-sized farms, as well as developing the export potential of organic products.

Ukraine is actively cooperating with the EU under the Association Agreement, which facilitates access of Ukrainian farmers to European grant programmes such as Horizon Europe and EU4Business (Ukraine. Membership status, n.d.). These initiatives enable Ukrainian farmers to take part in research projects, improve their production processes, and integrate into European supply chains. The role of the United States Agency for International Development's (n.d.) Agriculture and Rural Development Support Programme, which provides grants and technical advice to Ukrainian farmers to introduce modern agricultural technologies and increase the productivity of organic production, should be noted separately. With USAID's support, a series of successful projects have been implemented that have helped to increase the competitiveness of Ukrainian organic products on international markets. Another major initiative is the cooperation with the United Nations Development Programme (n.d.), which, through projects such as Strengthening Business Associations of Small and Medium Enterprises, helps Ukrainian organic producers to create cooperatives, unite to share resources, and ensure access to international markets.

However, despite Ukraine's active involvement in international programmes, there are also significant challenges. These include bureaucratic obstacles in the grant application process, lack of awareness among farmers of available funding opportunities, and limited access to information in rural areas. Solving these problems requires not only simplification of administrative procedures, but also active outreach by governmental and non-governmental organisations. Attempts are also being made at the state level to create favourable conditions for attracting international grants by adopting legislative initiatives. An analysis of the grant programmes available to Ukrainian farmers shows that there are ample opportunities to attract international funding for agriculture, particularly for the development of organic farming. These programmes are implemented by both foreign governments and international organisations, funds, and banks. They are all aimed at supporting farmers in the transition to sustainable, environmentally friendly farming practices, the introduction of innovative technologies, and increasing the productivity and export potential of organic products.

Ukrainian farmers have access to a variety of grant programmes aimed at supporting organic farming. These programmes are funded by international organisations such as the EU, EBRD, and the US government through the US Agency for International Development. The EU4Business programme, initiated by the EU, aims to support small and medium-sized businesses in Ukraine, including the agricultural sector. It provides financial and technical advice to businesses seeking to improve their competitiveness and meet EU standards. According to the EU4Business official website, as of 2022, 42 projects have been implemented in Ukraine, supporting more than 25,000 SMEs (EU4Business, n.d.). A joint initiative of the EU and the EBRD, the EU4Business-EBRD Credit Line, enables Ukrainian enterprises to obtain financing for equipment modernisation and the implementation of European standards. The programme offers three financing approaches: for simple equipment upgrades up to EUR 300,000, for investments up to EUR 3 million, and a simplified approach for food safety. Furthermore, compensation of up to 15% of the investment amount is provided upon successful project implementation (Eu4Business-EBRD Credit Line, n.d.).

The United States Agency for International Development (USAID) is implementing the Agriculture and Rural Development Support Programme in Ukraine, which aims to support agricultural producers, including organic farms. The programme provides grants for the introduction of modern technologies, increasing production efficiency and access to international markets. According to information published in El País, during the three years of the war, Ukraine received over EUR 34 billion in US aid, much of which was channelled through USAID to support the agricultural sector (Segura, 2025). These programmes provide Ukrainian farmers with opportunities to develop organic farming, improve product quality, and integrate into European and global markets. The use of available grant resources contributes to the sustainable development of Ukrainian agriculture and the strengthening of its economy. Figure 1 presents the indicators of organic production in Ukraine.

Analysis of organic production indicators in Ukraine showed its active development until 2021 and a sharp decline in 2022-2023 caused by the war. The area of land with organic status was growing until 2020, reaching 410.6 thsd ha, but in 2023 it fell to a critical 71.7 thsd ha. The total area of agricultural land decreased almost fivefold compared to 2021 due to the occupation, mining, and destruction of farms. The number of organic operators has also changed: it grew until 2019, but began to decline in 2020-2021, and in 2023 it fell to 152 operators, which is four times less than in 2019. These trends demonstrated that organic farming suffered a serious setback, and its recovery requires international financial support, government incentive programmes, and adaptation of farmers to the new reality. Figure 2 presents the organic map of Ukraine.

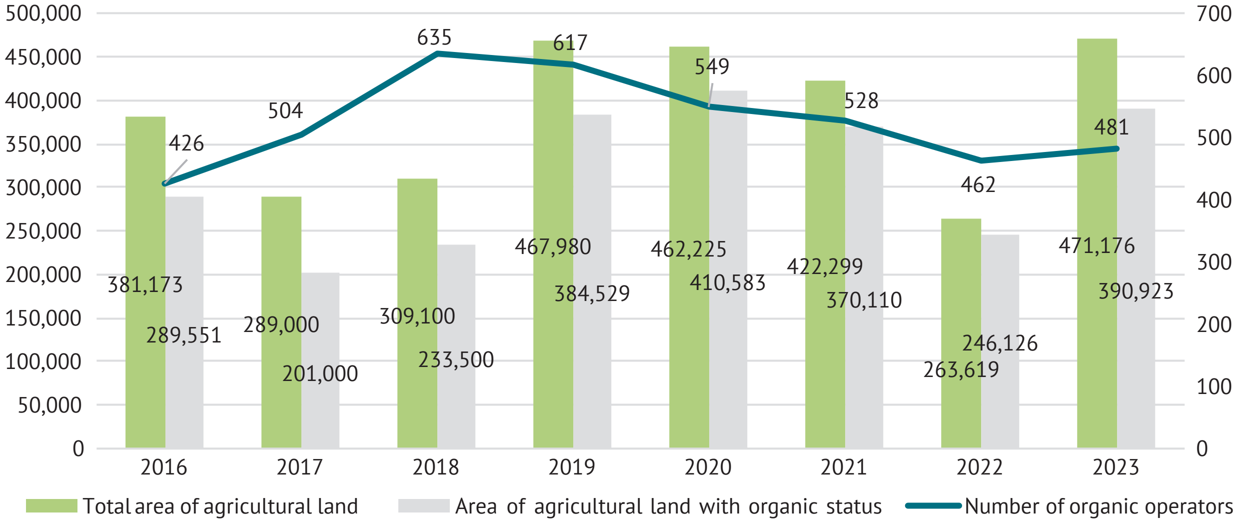

***Figure 1**. Indicators of organic production in Ukraine in 2016-2023*
***Source:** compiled by the authors of this study based on Organicinfo (n.d.)*

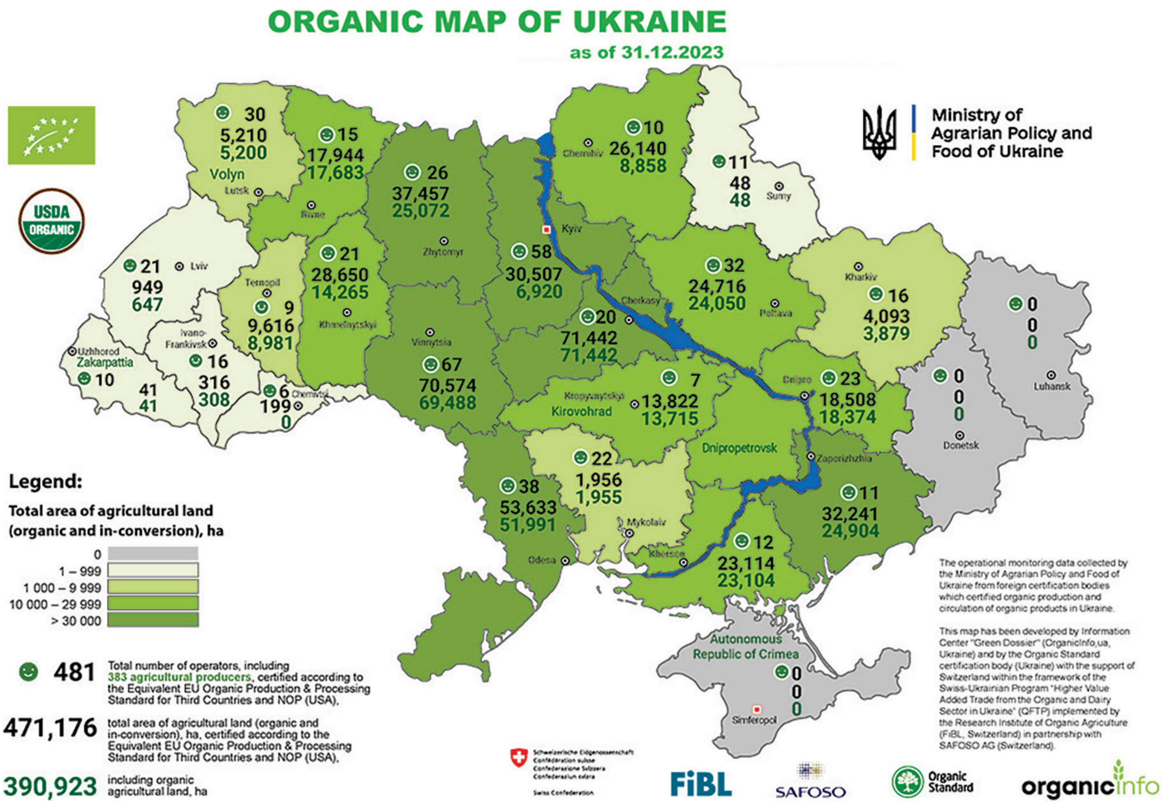

***Figure 2**. Organic map of Ukraine as of 2023*
***Source:** compiled by the authors of this study based on Organicinfo (n.d.)*

The total area of certified organic agricultural land in Ukraine is 471.2 thsd ha, of which 390.9 thsd ha have organic status. There are 481 certified producers in the country that operate under standards equivalent to the EU organic legislation and NOP (USA). The distribution of organic land by region shows the dominance of the central, western, and southern regions. The largest areas of organic land are recorded in Cherkasy (71.4 thsd ha), Odesa (52 thsd ha) and Vinnytsia (69.5 thsd ha) regions. Zhytomyr (25.1 thsd ha), Poltava (24.1 thsd ha) and

Zaporizhzhia (24.9 thsd ha) regions also demonstrate significant indicators. At the same time, the situation in the eastern regions continues to be challenging. Donetsk and Luhansk regions and Crimea have no registered organic land. Kharkiv region has only 3.9 ha of organic land, which is significantly less than the leaders in this area.

The growth of organic land in Ukraine is driven by increasing demand for organic products, stronger government support, and international cooperation. The development of this sector is actively supported by the Ministry of Agrarian Policy and Food of Ukraine, as well as international partners such as FiBL, SAFOSO and the Swiss Cooperation Office (Results of 2024…, 2024). Despite the positive trends, organic farming faces challenges, including military action, the need for financial support for producers, certification, and expanding markets. Of particular interest is the export of organic products to the EU and the US, which could help attract investment in the sector. International grants play a key role in the development of organic farming in the southern region of Ukraine, contributing to the modernisation of farms, product certification, and market expansion. To evaluate the effectiveness of their use, a study was conducted, which included an analysis of secondary data, a survey of 100 farmers from Odesa, Mykolaiv, and Kherson regions, as well as 10 in-depth interviews with representatives of the companies that received grants.

The survey results showed that 60% of the farmers surveyed had experience of receiving international grants, which indicated a relatively strong level of involvement of agricultural producers in financing programmes. At the same time, 40% of respondents had never applied for grants, of which 15% explained this by a lack of information about such options, 10% explained it by the complexity of the application process and the need to collect a voluminous package of documents, while another 8% reported that their farms did not meet the requirements of donor organisations. Among those who received grant funding, 25% of respondents reported a considerable reduction in production costs and a simultaneous increase in production volumes. This was achieved through the modernisation of equipment, the introduction of modern agricultural technologies, and the purchase of high-quality sowing material and fertilisers. Another 18% of farmers noted an improvement in product quality, as the grant funds enabled them to introduce certified organic production methods. However, 12% of respondents faced obstacles in implementing grant projects, with the most prevalent being delays in receiving funds, difficulty in reporting to donors, and mismatching of expected outcomes with initial forecasts. Some farmers noted that due to the demanding reporting requirements, they were forced to hire more staff or engage external consultants to prepare documents. In terms of the overall assessment of the effectiveness of grant funding, 47% of farmers described it as a key tool for developing their farms, which enabled them not only to obtain the necessary resources but also to establish links with international partners and learn how to work according to modern business models. At the same time, 30% of respondents believed that the availability of such programmes was still limited due to complex requirements and competition among participants.

In-depth interviews with representatives of agricultural enterprises confirmed the significant positive effect of grants. One of the most influential programmes was USAID's "Support for Agricultural and Rural Development", which financed the modernisation of farms. For instance, Eco-Pivden farm (Odesa region) received a USD 50,000 grant to purchase new machinery and certified seeds, which enabled it to increase its organic land area by 16% and enter the European market. Another key programme was EU4Business, which supports the certification of organic products according to European standards. Thanks to this initiative, 25 farms in Odesa and Mykolaiv regions managed to obtain the necessary certificates to export their products. Specifically, Bio-Fresh used the grant funds to certify and improve its logistics infrastructure, which helped reduce transportation costs. A separate area of grant support was the financing of processing plants. Under the EBRD programme, Eco-Resource (Kherson region) received a EUR 30,000 grant to upgrade its organic vegetable processing equipment. This helped to increase production by 20% and expand export opportunities to Poland and Romania. The Vidrodzhennia farm (Mykolaiv region) received USD 40,000 to upgrade machinery, which reduced equipment rental costs by 15% and increased yields by 10%. Another successful use of grant funds was demonstrated by Omega Farm (Odesa region), which used financial support to expand its organic land area. This allowed the farm to boost its productivity and establish regular deliveries to European markets, which increased its exports by 20%.

Despite the positive outcomes, farmers face a series of challenges. Bureaucratic obstacles continue to be the primary barrier to receiving grant aid. 25% of the surveyed farmers reported problems when applying for grants, particularly due to the requirement to provide a vast number of documents and confirmations. Another problem was the impact of the war. 20% of farmers from Odesa and Kherson regions reported severe hardships caused by the hostilities. Logistical problems, disruption of transport routes, and security threats led to increased transportation costs and reduced access to markets. Furthermore, about 35% of respondents reported a lack of awareness of grant opportunities, which limited their participation in funding programmes. Many farmers did not have access to relevant advisory centres that could help them with application and compliance.

In summary, international grants significantly contribute to the development of organic farming in the

Southern region of Ukraine, enabling farmers to modernise their farms, increase the competitiveness of their products, and enter international markets. However, to further improve the effectiveness of grant programmes, it is necessary to simplify application procedures, improve information for farmers, and develop special support programmes for farmers in the areas affected by the conflict. One of the key tools that enable small farmers to overcome the obstacles they face in accessing international grant funding is farmers' cooperatives and producer associations. Cooperatives enable farmers to pool resources, share grant funding opportunities, reduce costs, and mitigate risks. In the context of limited financial resources for individual farmers, the association allows for a much larger scale of production, which makes such projects more attractive to international donors and funds (Candemir *et al.,* 2021).

The submission of collective grant applications is one of the major advantages of cooperatives, as it allows farmers' associations to demonstrate greater potential for the efficient use of financial resources. Cooperatives can combine multiple activities and diverse agricultural enterprises, which creates more diversified projects (Luo *et al.,* 2022). This increases the chances of obtaining funding, as donors tend to focus on large, complex projects that can generate large-scale results and have greater potential for development. A striking example of such a cooperative project is the Association of Organic Producers "Organic Ukraine" (n.d.), which takes an active part in international funding programmes, receiving grants to improve organic production in Ukraine. With the funds it receives, the association organises training for its members and promotes certification of organic products, which is a prerequisite for entering international markets. The farms that are members of the organisation managed to get certified according to international standards, which enabled them not only to expand production but also to enter new markets. This became possible through a cooperative approach, which ensured efficient use of grant funds for training, certification, and development.

Cooperation can also have a major positive impact on reducing farmers' costs for advisory services and administrative expenses. Working together in a cooperative allows for the pooling of financial resources to hire experts to prepare grant applications and other necessary documents (Sharata *et al.,* 2023). This can greatly reduce the costs for each individual member of the cooperative, as they can use professional services at a much lower price than in the case of individual cooperation with consultants. Collaborative activities also lead to better outcomes in terms of export opportunities, increased market competitiveness, improved marketing and product branding, which ultimately increases the chances of obtaining funding from international donor organisations. Considering all these factors, cooperation is not only a crucial element for the effective use of grants, but also a strategic tool for the sustainable development of organic agriculture in Ukraine.

International grant programmes can become a valuable tool to support Ukrainian organic producers in times of war and economic instability (Sirenko *et al.,* 2024). Practical recommendations on how to improve the efficiency of attracting and using international grants is a crucial aspect for the development of organic farming in Ukraine, particularly in the Southern region. One of the primary barriers faced by farmers is the lack of skills in preparing grant applications. To increase the efficiency of using international funding, it is essential to invest in training and establish advisory centres for farmers. Regular trainings, seminars, and webinars with agribusiness experts can improve farmers' knowledge of the requirements for grant applications and the requirements of international organisations. It is especially significant to train farmers on how to properly prepare documents, considering the specific features of each programme, which will minimise the number of rejections. Establishing partnerships with consultants and specialists with experience in obtaining international grants can help reduce the cost of preparing applications.

As previously mentioned, farmers' cooperatives are one of the crucial tools for attracting funding. The association of farmers not only increases the chances of receiving grants but also optimises the costs of preparing and submitting applications. By pooling resources, several small farms can submit a collective application, which increases the probability of success and reduces individual costs. Additionally, cooperatives can receive grants for standardisation and certification of organic products, which opens new markets for producers. Joint projects to expand market opportunities and invest in agricultural infrastructure are also significant. To be successful in obtaining international grants, it is necessary to have a well-structured application strategy. Optimising the project preparation process includes clearly defining the purpose, objectives, and results, as well as implementing practical measures to achieve these results. It is vital to consider the specific requirements of donors, which often set strict standards for compliance with sustainable development goals. Farmers should create a clear business plan that demonstrates profitability and self-financing beyond the grant period. Specifically, the potential environmental and social impacts of the grant project should also be considered.

In the modern environment, large international organisations often use online platforms to submit grant applications. It is essential to provide access to digital tools that enable agricultural producers to apply for grants without physical limitations, saving time and resources. Platforms such as the EU Funding and Tenders Portal allow Ukrainian farmers to stay up-to-date on current grant opportunities in real time. Furthermore, the use of analytical tools to monitor grant opportunities and access to finance allows agricultural producers to react promptly to changes in international donor policies and funding programmes. The availability of experienced partners for project implementation is a significant aspect, as international donors often require applicants to have experience in implementing such projects. Partnerships with international organisations, institutes, research institutions, and other businesses allow submitting competitive applications, particularly due to additional knowledge and experience. It is also vital to create partnerships with foreign companies and universities to train farmers and develop innovative approaches to organic production.

Active engagement in international forums, exhibitions, seminars, and conferences is also necessary, where farmers can establish connections with international donors and organisations that fund organic farming projects. Through personal contacts, farmers can receive further support and advice that will help them take part in competitions for grant funds more effectively. It is key to improve financial literacy among farmers, as international grants often require clear financial pla nning and reporting. Agricultural producers should understand how to properly spend grant funds, how to keep accounting and reporting to avoid mistakes in the use of grant funds and not to lose the opportunity to receive funding in the future. Effective attraction and use of international grants require a comprehensive approach that includes training farmers, establishing cooperatives, optimising project preparation, actively using digital platforms, and engaging experienced partners to implement grant programmes. With proper support and development of these instruments, Ukraine can greatly improve its position on the organic market and attract more international financing for agriculture.

DISCUSSION

Analysis of international grants for organic farming revealed both major potential and challenges faced by countries seeking to attract such funding. International financial support plays a key role in the development of organic farming, and various international organisations, including government agencies, private foundations, and multinational institutions, are increasingly promoting sustainable agricultural development. For Ukraine, the integration of international grants into the national agricultural policy could be a crucial step for the recovery of the organic sector, especially after the military actions. E. Kiryluk-Dryjska *et al.* (2020) noted that grants, as the primary source of funding for organic farmers, are most effective for large enterprises that can organise large-scale projects. According to the researchers, most small farmers lack sufficient experience to apply for grants effectively. W. Łuczka *et al.* (2021) emphasised that despite the considerable potential of international grants, their accessibility to small farmers continues to be limited due to underestimated administrative requirements and complexity of procedures. These findings are generally in line with present findings on the challenges faced by small farmers due to complex application procedures. However, the present study additionally emphasised the role of farmer cooperatives, which can act as intermediaries in the grant process.

One of the principal conclusions was the diversity of international grants available for organic farming, which could be classified by funding source, purpose, and geographical focus. Government agencies and international organisations such as the EU are actively funding organic farming projects worldwide (Nakonechna & Samsonova, 2021). In the EU, initiatives such as the Common Agricultural Policy and Horizon Europe have been extremely effective in supporting organic farmers, providing not only direct subsidies but also promoting research, infrastructure, and market access. These programmes are a reliable model for integrating international funding into national agricultural policies. J. Wesseler (2022) found that financial support for organic farming in many countries is provided through national and international programmes. The researcher also addressed programmes that actively support innovation and research in the agricultural sector and argued that organic farmers often have access to financial instruments aimed at modernisation and adaptation to climate change, but the lack of effective support for small farmers' development reduces the overall impact of these programmes. This highlighted the difference from the present findings, which focused more on social aspects and access to grants for small farmers, while J. Wesseler focused on technological and innovation aspects.

The experience of Ukraine highlighted both the potential and the challenges faced by Ukrainian farmers in accessing international grants. Despite the strong demand for organic products on both domestic and foreign markets, Ukrainian farmers face numerous challenges, including bureaucratic barriers, limited access to information, and the effects of the war (Tanchyk *et al.*, 2024). The war had a devastating impact on agricultural infrastructure, leading to a drastic reduction in the area of organic land and the number of certified organic operators (Mamenko *et al.*, 2024). This decline underscores the need for continued international support to restore and develop organic farming in Ukraine. The study also found that while international grant programmes have positively influenced some Ukrainian farmers, particularly for equipment upgrades and certification, access to these funds was still unequal. Simplifying administrative procedures and raising awareness of available grants among farmers are critical steps to increase their participation and improve the efficiency of their use of funding.

The hostilities have made the transition to sustainable development much more challenging, but a circular economy can contribute to a faster economic recovery through the efficient use of resources and reduced dependence on imported raw materials (Dovgal *et al.,* 2024). I. Prokopa *et al.* (2024) analysed the effects of war and political crises on organic farming in Ukraine. The researchers noted that under conditions of political instability, the amount of grant funds available to organic farmers decreases, as international donors often shift funding to more stable regions. The present findings in this case also coincided with the researchers' findings, as it was also noted that war and political challenges greatly affect the ability of farmers to attract grants. X. Fernández-i-Marín *et al.* (2024) also investigated the impact of bureaucratic barriers on the efficiency of international grants in developed countries. The researchers noted that bureaucratic difficulties, such as complex application processes, lack of transparent procedures, and complexity of reporting, greatly reduce the efficiency of grant use even in large farms. These findings were in line with the present findings on the need to simplify administrative procedures and provide another argument in favour of improving the support system. However, the present study focused more on social aspects, such as the lack of awareness of farmers about available grants.

A valuable finding of the present study was the role of farmer cooperatives in overcoming these obstacles. Cooperatives enable small farmers to pool resources, share costs, and jointly apply for international grants (Oliynyk *et al.*, 2020). Through their combined efforts, cooperatives can submit larger, more diverse projects that are more attractive to international donors. Experience shows the potential of cooperation to maximise the use of grant funds. R. Ajates (2020) studied the role of farmers' cooperatives in countries as a mechanism to improve access to international grants. According to the researcher's findings, the association of farmers in cooperatives significantly increases the probability of receiving funding, as large projects submitted by cooperatives look more promising to donor organisations. S. Kalogiannidis (2020) emphasised the significance of not only financial but also advisory support for cooperatives, which helps them to apply for grants more effectively. This is directly in line with the current findings, which also highlighted those cooperatives can be a powerful tool for small farmers to access international grants, enabling them to consolidate resources and reduce administrative barriers.

N. Thakur *et al.* (2022) investigated the role of globalisation and climate change in the development of organic farming. The researchers argued that organic farmers who use sustainable farming methods become less vulnerable to the adverse effects of climate change, such as droughts and crop failures. G.T. Patle *et al.* (2020) also noted that international grants to support climate change adaptation are an important tool, but that they were still limited and need to be expanded. Although the current findings did not focus on climate change-related issues, the researchers provided valuable perspectives for future research that could focus on how climate change affects organic farming, and which grant programmes could be effective in supporting farmers in these circumstances.

Specialised advisory services that help farmers navigate the grant application process play a major role in supporting them (Nifatova & Danko, 2024). As noted in the study, there is an urgent need to establish training centres and workshops to improve grant writing skills. These services can help farmers to adapt their projects to donor requirements and minimise the risk of funding rejection. Partnerships with international organisations and research institutions can also provide Ukrainian farmers with the necessary technical support to make their projects more competitive on the international level. G. Prain *et al.* (2020) analysed the effects of advisory and educational programmes on farmers' success in attracting international grants. The researchers noted that farmers who had received specialised training or support from advisory centres had a greater chance of successfully obtaining grants compared to those who applied independently. These findings are in line with present findings on the significance of supporting small farmers in obtaining funding. The lack of awareness and skills in preparing grant applications was also highlighted as a major barrier for farmers.

Overall, while international grants are a valuable tool for the development of organic farming, their effectiveness depends on addressing key issues. The experience of Ukraine highlighted the necessity of simplifying application processes, improving awareness and access to information for farmers. The successful integration of international finance into national policy and practice will be a crucial component of Ukraine's long-term strategy for agricultural development and economic recovery.

CONCLUSIONS

The study analysed international grant programmes aimed at supporting organic agriculture. It was found that international grants can be classified according to several criteria, including the source of funding and their purpose. The major donors are government agencies, international organisations, and private foundations. Programmes such as Horizon Europe and CAP EU, UN initiatives, and foundations such as the Rockefeller Foundation and the Bill & Melinda Gates Foundation play a great role in the development of organic farming. The analysis helped to identify the key areas of grant use. Grants for research and innovation support the development of innovative technologies in organic production. Funding for certification and standardisation helps producers obtain the necessary documents to enter international markets. Grants for infrastructure and equipment are aimed at modernising farms, while support for education and training helps to improve farmers' skills. Support for cooperatives was also considered, which allows small producers to use resources more efficiently.

EU experience showed that a comprehensive approach to grant support ensures the sustainable development of the organic sector. Successful examples include financing the transition period for organic farmers, supporting research initiatives and promoting environmental practices. Specifically, Denmark and Austria achieved prominent levels of organic farming development through a combination of government support and grant funding. In Ukraine, the policy of attracting international grants is at the stage of active development. Thanks to cooperation with the EU, USAID, and the UN, Ukrainian farmers have access to programmes that finance farm modernisation, product certification, and training. However, there are considerable challenges, including bureaucratic barriers, lack of awareness of funding opportunities among farmers, and limited access to information. The empirical part of the study confirmed the effectiveness of grant support in the Southern region of Ukraine. The study showed that 60% of farmers had experience of receiving grants, of which 25% reported reduced costs and increased production, and 18% reported improved product quality. At the same time, 40% of respondents had never applied for grants, including 15% due to lack of information, 10% due to complexity of the application process, and 8% due to ineligibility. While 47% of farmers considered grant funding to be a key development tool, 12% had faced challenges such as delays in funds and complex reporting. Nevertheless, grant programmes contributed to market expansion and increased the efficiency of agricultural enterprises.

To further improve the effectiveness of international grants in Ukraine, it is necessary to simplify application procedures, increase information support for farmers, develop cooperatives, and create educational programmes to improve grant application skills. Considering international practices will help integrate Ukraine into the global organic farming system and increase the competitiveness of its products on international markets. A limitation of this study was its focus on a sample of farms in a few regions, which may not fully reflect the situation in other regions. Further research could cover a wider geography, as well as analyse the long-term effects of grant funding on the sustainability of agricultural enterprises.

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CONFLICT OF INTEREST

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Перспективи використання міжнародних грантів для розвитку органічного землеробства в Україні

Наталія Шарата
Доктор педагогічних наук, професор
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-6306-6934
Олена Усикова
Доктор економічних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-6734-5757
Олександр Біліченко
Кандидат економічних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-5241-3195
Ганна Побережець
Кандидат історичних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-9064-6731
Тетяна Кравченко
Кандидат філологічних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-5818-8307

Анотація. Робота була направлена на аналіз можливостей залучення міжнародного грантового фінансування для підтримки та розвитку органічного землеробства в Україні. В рамках роботи запропоновано класифікацію міжнародних грантів за різними критеріями, такими як джерела фінансування та цілі програм. Розглянуто гранти, що надаються державними органами, міжнародними організаціями та приватними фондами, такі як програми Європейського Союзу, включаючи Загальну сільськогосподарську політику та Horizon Europe, а також ініціативи США та Організації Об'єднаних Націй. Методологічно дослідження включало аналіз вторинних даних, опитування 100 фермерів з Одеської, Миколаївської та Херсонської областей України та 10 глибинних інтерв'ю з представниками сільськогосподарських підприємств, які отримали гранти. Результати свідчать, що міжнародні гранти мають значний вплив на розвиток органічного сільського господарства в Україні, особливо у південних регіонах. 60 % опитаних фермерів використали міжнародні грантові програми, при цьому 25 % з них відзначили скорочення витрат та збільшення обсягів виробництва завдяки отриманим коштам. Однак, незважаючи на позитивні результати, фермери стикаються з низкою проблем, включаючи бюрократичні перешкоди, брак інформації та труднощі, пов'язані з війною. У роботі запропоновано рекомендації щодо покращення ефективності використання міжнародних грантів, включаючи створення консультативних центрів для фермерів, підвищення фінансової грамотності та підтримку сільськогосподарських кооперативів, які можуть оптимізувати процеси подання заявок та зменшити витрати на підготовку. Висновок роботи вказує на важливість комплексного підходу до залучення та використання міжнародних грантів в аграрному секторі України, з акцентом на розвиток освітніх програм, покращення кооперації та використання цифрових інструментів для спрощення процесу подання заявок

Ключові слова: агросектор; інноваційні технології; кооперації фермерів; фінансова підтримка; європейські ініціативи

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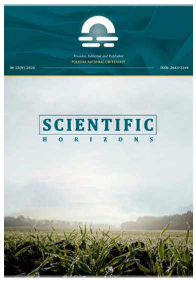

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Decision-making models in information management systems of agro-industrial enterprises

Gulzhaukhar Abdigul
Senior Researcher
S. Seifullin Kazakh Agro Technical Research University
010000, 62 Zhenis Ave., Astana, Republic of Kazakhstan
https://orcid.org/0009-0006-3000-5496

Gulnara Assanova
PhD in Economics, Associate Professor
S. Seifullin Kazakh Agro Technical Research University
010000, 62 Zhenis Ave., Astana, Republic of Kazakhstan
https://orcid.org/0009-0002-0910-4677

Damira Iskakova
PhD
Scientific and Production Enterprise "Innovator" LLP
010000, 2/1 Zheltoksan Str., Astana, Republic of Kazakhstan
https://orcid.org/0009-0008-3124-9542

Rysty Sabirova
PhD in Economics, Associate Professor
Kh. Dosmukhamedov Atyrau University
060011, 1 Studenchesky Ave., Atyrau, Republic of Kazakhstan
https://orcid.org/0009-0005-4410-1588

Aida Balkibayeva*
PhD in Economics, Associate Professor
Academy of Physical Education and Mass Sports
010000, 2.2B Mangilik El Ave., Astana, Republic of Kazakhstan
https://orcid.org/0000-0002-2710-8930

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Abstract. The relevance of the stated subject is determined by the wide spread of information intelligent systems (IIS) in various spheres of modern science, technology and industry, and the need to develop and implement effective algorithms for decision-making based on IIS technologies in the agricultural sector of the economy of the Republic of Kazakhstan. The main objective of the study was to propose a model of managerial decision-making in the agrarian sector of Kazakhstan. The methodological

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**Corresponding author*

approach here was based on the combination of methods of a comprehensive study of the key principles of decision-making in information management systems and an analytical study of the current prospects for the practical application of artificial intelligence technologies in the processes of enterprise management in the agro-industrial complex. Methods of analytical comparison and synthesis of data gathered during the study were also used. The findings obtained determine the main tasks of decision-making methods in the information networks of management of enterprises in the agricultural sector of the Republic of Kazakhstan, considering the current issues in this area and practical options for their resolution. The study revealed that, between 2000 and 2024, the average yield of all crops increased by 153%, with significant improvements observed in oilseeds, sunflower seeds, and potatoes. The study also observed a substantial increase in the use of information and communication technologies in Kazakhstan, with a nearly 3.5-fold rise in related expenditures. Furthermore, the research highlights the potential for automation in the agricultural sector, particularly in enhancing resource utilisation and boosting productivity. The practical significance of the findings lies in their implementation in the activities of enterprises in the agricultural sector to create effective management systems, leveraging artificial intelligence technologies. These developments will support the further modernisation of the sector, contributing to its economic sustainability and alignment with global trends in digital transformation

Keywords: artificial intelligence; information intelligent systems; agrarian sector; agriculture; management solutions; innovative technologies

INTRODUCTION

Ensuring the most effective development of the enterprise is an important task for managers of enterprises in modern conditions. This is primarily caused by the fact that this component is one of the main ones to ensure competitive advantages in the domestic and foreign markets. In Kazakhstan, agro-industrial enterprises are currently facing an increased need to optimise production processes to address the difficulties that are observed in the agricultural sector. In this regard, it remains relevant to research existing decision-making principles improvement ways. Problematics of the stated subject lies in the wide use of modern information technologies in various areas of social life, but also with the need to develop and practical implementation of artificial intelligence systems in the management of processes that take place in the activities of an agrarian enterprise. This study examines both theoretical and practical aspects of the use of modern information systems in management decision-making used by the enterprises of the agro-industrial complex of the Republic of Kazakhstan.

The environmental accounting and auditing model was considered in the framework of the research by B. Korabayev *et al.* (2024). They noted that the environmental accounting and auditing model formed in the state can have a significant impact on the financial results of industrial enterprises, and not only help the enterprise to effectively justify its costs and taxes but also receive certain benefits from the government related to the stimulation of environmental protection activities. However, this system should be designed to satisfy the needs of both the state, in terms of openness and reliability of the data obtained, and agrobusiness. A. Sumets (2020) considered a methodological approach to the evaluation of the management system of manufacturing enterprises. He pointed the peculiarities of the essence of the company's activity management within the framework of modern economic literature, describing the main elements of this system considering the specifics of its sphere of activity. Furthermore, an emphasis was made on what parameters to consider in the process of enterprise management, and what to strive for to achieve company maximum efficiency. Nevertheless, the scholar provided little empirical data (reports of enterprises, etc.) to show the calculation of such indicators in practice. In addition, the emphasis placed on the peculiarities of individual spheres of activity was rather superficial.

R. Gabdualiyeva *et al.* (2024) emphasised the digitalisation of the agricultural sector in Kazakhstan. The scientists noted that under current conditions farmers face quite a lot of obstacles, which digitalisation can partly help to solve. They also recommend optimising sowing and harvesting times, improving pest control methods, better irrigation and fertilisation of crops. However, scholars did not sufficiently consider the formation of management models, which are also an important part of both the digitalisation process and the improvement of the state of enterprises in the agricultural sector. G. Lukhmanova *et al.* (2019) also highlighted the innovative development of the agro-industrial complex of the Republic of Kazakhstan in modern conditions. They concluded that the country needs targeted modernisation of all components of the digitalisation complex in the country and suggested strengthening protectionism to ensure the development of innovation in the country in the long term. The peculiarities of strategic planning in agricultural production were studied by B. Myrzaliyev *et al.* (2023). They acknowledged that in the current conditions, the agricultural sector plays a huge role in the welfare of the Republic of Kazakhstan, in this regard, the development of long-term development strategies in this area is relevant. Based on the peculiarities of the agricultural sector in Kazakhstan, scientists have developed certain advice on long-term planning.

The purpose of this study was to propose the model of decision-making in the agrarian sector of Kazakhstan.

MATERIALS AND METHODS

The study assessed selected statistical data that can indirectly characterise the quality of governance in the country, for which economic and statistical research methods, namely descriptive statistics, i.e. the direct collection and organisation of quantitative data, were used. Information from the official website of the organisation The World Bank (2024) on the ratio of expenditures on the development of innovative technologies to gross domestic product (GDP) was used for this purpose. The logic behind this indicator is that the more funds (compared to the level of GDP) are used for the development of the latest technologies, the more effective will be the management of information systems in the country. Innovative developments play the most important role in this context.

Data from the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (2024a; 2024b; 2025) on the level of investment in agriculture in general, as well as the level of yields of individual crops, were also assessed. The importance of assessing the level of investment in agriculture is that the more funds are allocated for the development of this sphere, the more effective the management of internal processes in it should be. This can also be partially evidenced by crop yields (this study assessed cereals (including rice) and legumes, oilseeds, sunflower seeds, potatoes, open field vegetables, melons, and sugar beet). Thus, although yields are influenced by many factors, especially cultivation methods, the management of the enterprise also plays an important role in this context. Therefore, an assessment of this indicator may indicate an improvement in such processes within the company. The factors – external socio-economic conditions, internal financial and innovative capacities, and technology advancements – constituted the foundation for evaluating governance efficacy in the agriculture sector. The analysis was supplemented by schematic representations of management decision-making spheres, which contributed to the qualitative organisation of agricultural activities.

An expert survey was conducted to assess the qualitative factors influencing managerial decisions. The survey involved experts rating various factors on a scale from 0 to 10, with higher scores indicating a stronger positive influence on decision-making. This survey provided valuable data for computing weighted average assessments, which were incorporated into the decision-making models. The qualitative factors assessed by the experts were integrated with quantitative evaluations of key indicators, providing a comprehensive approach to decision analysis. Informed consent was obtained from all individuals included in this study. All procedures performed in the study were in accordance with the ethical standards of the institutional research committee and with the Helsinki Declaration (1964) and its later amendments.

The system analysis of decision-making principles allowed the formation of a unified system of analysing the relationship between the problems of activity of agricultural enterprises and possible practical solutions. The study utilised formulas for normalisation and weighted averaging of expert evaluations for qualitative decision-making. These mathematical models allowed for a more structured and objective analysis of decision options, improving the accuracy and effectiveness of management strategies. An analytical study of the real prospects of introducing artificial intelligence technologies in the management of agro-industrial enterprises of Kazakhstan made it possible to identify the problems facing information intelligent systems. The study was conducted in the conditions of Kazakhstan, taking into account the peculiarities of the country's economic development, especially in the agricultural sector. This particular model was used in the work, since it allows to improve the ability to use information systems to form more effective conclusions of management decisions. It also improves resource utilisation, productivity, workplace safety and supply chain efficiency.

The modelling method was also used within the framework of the research. It was used to build a system in the area of managerial decision-making when using information intelligent systems in the agro-industrial complex. The depiction of this model was made using the graphical method. Systematisation was used to evaluate the analysed factors within a single system where they interact with each other. The generalisation method was used to simplify the process of data analysis in the study. The descriptive method was used to characterise the individual data in the paper, assessing their main characteristics. The historical method was used to evaluate past quantitative data of changes in the parameters characterising the quality of management at enterprises. The comparison was used to assess the dynamics of individual countries (in the context of expenditures on research and development) to understand what the situation in Kazakhstan is. The abstract-logical method was used to make assumptions about what the actual model of information management at agrarian enterprises should be.

RESULTS

There are a number of issues in the development of the agro-industrial complex of the Republic of Kazakhstan that require immediate resolution in the context of a modern market economy (Smagulova *et al.*, 2022; Tkacheva *et al.*, 2024). Such issues include insufficient material and technical support, weak control over the available natural, labour, and material resources along with their irrational use, and insufficient cooperation of small non-commodity enterprises into larger, commodity ones. Other concerns involve unsatisfactory processing of raw materials in agriculture and inadequate control over this process, an excessive number of intermediaries in the supply chain of agricultural products to the end consumer, and limited implementation of advanced scientific, technical, and software developments in agricultural production. Additionally, the economic mechanisms for attracting investment funds and state support measures to the agro-industrial complex remain underdeveloped.

One of the most effective and timely options for solving these current problems is the introduction of information intelligent systems for managing processes within these enterprises. The tasks assigned to such systems, currently being implemented in the agro-industrial complex of Kazakhstan, can be roughly divided into two main areas: monitoring the management processes of enterprises in this sector and making decisions to optimise the management process at any stage. The use of intelligent information management systems in agricultural enterprises is primarily driven by the need to transform the very structure of agricultural activities. This transformation includes an increase in the volume of agricultural production, coupled with improved organisation of management activities. When appropriate automated management systems and optimal information management tools are chosen, labour productivity at an agricultural enterprise can increase significantly compared to manual management. Another key aspect is the qualitative improvement of agricultural production safety and the enhancement of working conditions within agricultural enterprises.

The introduction of automated systems for managing the activities of an agricultural enterprise is especially effective when it comes to harmful agricultural production associated with the use of pesticides, pesticides, various chemical fertilisers, along with waste products of cattle or poultry farms. The automation of the agricultural sector also offers the prospect of significantly reducing occupational morbidity and injury in the agricultural sector, and of cutting the cost of rehabilitation and workplace health and safety measures. To date, one of the most significant problems in the development of enterprises in the agricultural sector of the economy of the Republic of Kazakhstan is the mismatch between the level of management and the technologies used by enterprises to meet the requirements of a modern market economy. One of the key requirements for economic management technology in the agribusiness sector under market conditions is the development of effective tools for this purpose, which include methods, algorithms, models, and information bases (Binu & Rajakumar, 2021; Srivastav *et al.*, 2022). Figure 1 provides a schematic representation of the main areas of management decision-making when implementing intelligent management information systems in an agricultural enterprise.

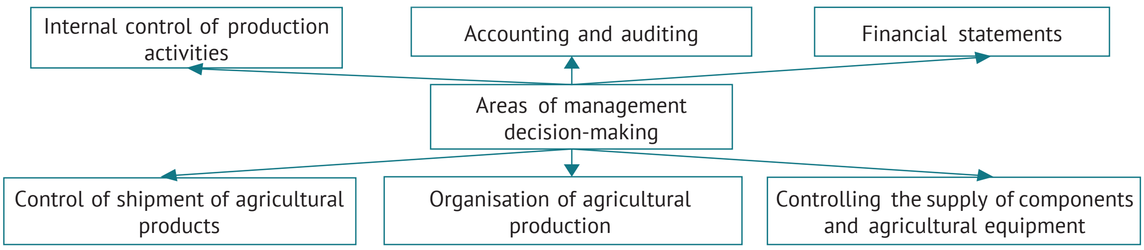

Figure 1. *Areas of management decision-making when using information intelligent systems in the agricultural sector*
Source: *compiled by the authors*

Decision-making models in agribusiness management information systems are divided into two main classes. The first class focuses on planning and ensuring the production activities of agricultural enterprises. This includes accounting for the supply of components and agricultural equipment, organising agricultural production processes, controlling the quality of finished products, and managing their shipment to the final consumer. The second class pertains to planning and ensuring the financial activities of agricultural enterprises. It covers the organisation and control of financial reporting, as well as accounting and auditing.

The closest to solving the problems of organising agricultural activities and production should be considered mathematical methods for processing data on economic parameters, through which the degree of informativeness of the presented parameters and the level of impact of extreme factors are determined (Caixeta *et al.*, 2022; Kumar *et al.*, 2022). However, these decision-making techniques, which are implemented separately and with no apparent correlation, do not fully equip the agribusiness sector with the capacity to manage successfully in a market environment (Huang *et al.*, 2021; Deebak & Al-Turjman, 2022). The final quantitative characteristics based on the results of the analysis of identified indicators do not always contain objective information or reflect the direction of entropy fluctuations of individual indicators or the entire farm correctly. A schematic diagram of intelligent information management and processing system is shown in Figure 2.

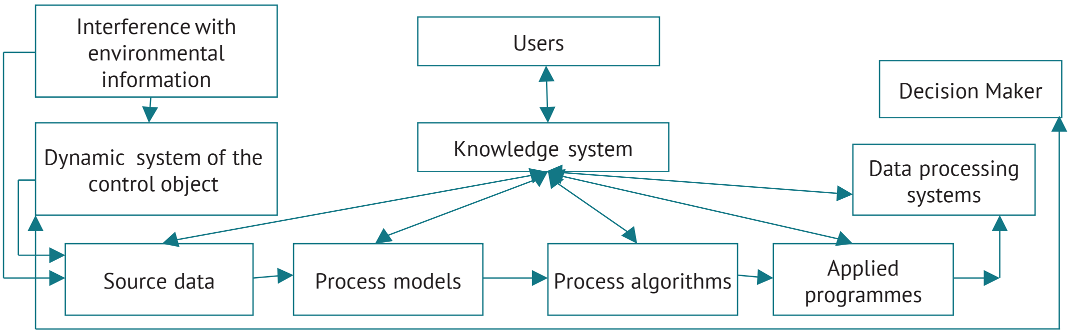

***Figure 2**. Information intelligent control and data processing system*
***Note:** LPD is linear, programme distribution*
***Source:** compiled by the authors*

The data presented in Figure 2 suggest that the accurate formulation of the task of comprehensive application of mathematical methods of decision-making in information management systems involves a sufficient number of algorithms and data processing systems, and software packages for the implementation of the task. The situation is complicated by the fact that until recently, information technologies for managing the activities of agricultural enterprises in Kazakhstan were almost completely absent, due to the lack of an objective demand regarding their use, given the near absence of competition between enterprises in the agricultural sector. Agricultural production worldwide and in Kazakhstan in particular is considered to be among the low investment-attractive economic sectors. The total volume of investment in Kazakhstan was set at KZT 18 trillion (The volume of investments..., 2024). Attracting investment into this economic sector requires the formation of attractive investment projects. Leasing and investment credit can be sources of investment funds for agriculture (Abbad, 2021; Tkacheva, *et al.*, 2024).

Any managerial decision-making should be based on the analysis of certain factors, both quantitative and qualitative. Quantitative decisions rely on statistical data, while qualitative decisions are based on expert opinions. Additionally, key factors can be identified for each decision, and these factors may vary. However, certain benchmarks should be given priority. The external environment includes socio-economic, technological, market situation, and climatic factors. The internal environment encompasses the financial and economic features of the enterprise, the level of innovation development, competitive advantages, and the level of strategic management.

Nevertheless, as already mentioned, these are only guidelines that can be relied upon in forming the factors on the basis of which conclusions will be formed, whereas in reality they may be quite different and only indirectly related to those proposed above. As already mentioned, factors can be both quantitative and qualitative, and their analysis will differ significantly depending on the type. To commence, the peculiarities of analysing qualitative factors must be taken into account. It should be assumed that the number of factors X1, X2, ... Xn has been determined; regarding their influence on the management decision, a survey of experts was conducted, in which they could rate each of the factors on a scale from 0 to 10. If the factor has a positive influence on the factor, you high score indicates a stronger interaction, compared to others; if the factor has a negative influence, the high score indicates a lower influence on this factor. Thus, authors obtain the sum of m expert evaluations for each of n factors. The weighted average assessment of experts can be calculated by finding the arithmetic mean, namely by using the formula (1):

$$X_n = \frac{(E_1+E_2+E_3...E_m)}{m}, \tag{1}$$

where X_n – value of the factor with index n; E_1, E_2, E_3, E_m – corresponding estimates of the factor's influence on the managerial decision; m – number of experts that take part in the survey.

It is also worth noting that if one wishes to give a greater role to the evaluation of individual experts, a slightly different model can be proposed. Within its framework, it can be proposed to use weighted assessments for each expert's decision. The main thing is that in the end the sum of indices for each expert's assessment should equal 100%. In the case of quantitative assessments, it is worth applying approaches to normalise the data, bringing it to a uniform value. This paper proposes an approach in which the most favourable value of a quantitative indicator is determined at the level of 10 and the least favourable at the level of 0. An example of such an indicator is Net Present Value (NPV) when implementing a project in an enterprise. Thus, to determine the value of the indicator Xn it is worth making the following calculation (2-4):

$$X_n = \frac{K_m - K_{min}}{\left(\frac{(K_{min}+K_{max})}{(X_{max}-X_{max})}\right)} + X_{min}, \tag{2}$$

$$X_{min} = \frac{G}{(n+1)}, \tag{3}$$

$$X_{max} = G - \frac{G}{(n+1)}, \tag{4}$$

where X_n – value of factor with index n; k_m – quantitative value of factor m; k_{min} – quantitative score of factor with minimum value; k_{max} – quantitative score of factor with maximum value; G – maximum possible score that can be obtained within the framework of this evaluation (within the framework of this paper it is at the level of 10); X_{min} – score for the indicator with minimum value; X_{max} – score for the indicator with maximum value.

Thus, a normalisation can be carried out which will produce a uniformly distributed series of scores from 0 to 10. As a consequence of estimating in this way, the following matrix of scores can be obtained, as shown below (5):

$$\begin{matrix} X_{11} & X_{12} & \cdots & X_{1m} \\ X_{21} & X_{22} & \cdots & X_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ X_{n1} & X_{n2} & \cdots & X_{mn}, \end{matrix} \tag{5}$$

where X_{mn} – values of n factors with m options for solving the management problem.

In this case, each of the options for solving the management problem is actually a vector, as it is shown below (6, 7):

$$\begin{bmatrix} X_{11} \\ X_{21} \\ \cdots \\ X_{n1} \end{bmatrix} \begin{bmatrix} X_{12} \\ X_{22} \\ \cdots \\ X_{n2} \end{bmatrix} \begin{bmatrix} \cdots \\ \cdots \\ \cdots \\ \cdots \end{bmatrix} \begin{bmatrix} X_{1m} \\ X_{2m} \\ \cdots \\ X_{mn} \end{bmatrix}, \tag{6}$$

where L_m – length of vector m; X_m – value of factor with initial n for the variant of solution of management problem m.

$$L_m = \sqrt{(X_1^2 + X_2^2 + \cdots + X_n^2)}, \tag{7}$$

where L_m – length of vector m; X_m – value of factor with initial n for the variant of solution of management problem m.

Thus, at the end, n vectors with different lengths can be defined: the longer the vector is, the more effective the solution to a problem is considered to be. It is worth paying attention to the fact that in this case it is also possible to determine weight coefficients for each of the factors when analysing management problems, but it is worth paying attention to the fact that the sum of coefficients should be equal to 1. In addition, this leads to the possibility of additional errors due to the existence of the human factor. This can be graphically depicted as follows (assuming that only three factors are considered). As can be seen from Figure 3, it is not always obvious which of the options for solving a management problem is more favourable; the assessment is even more difficult when there are actually many more options.

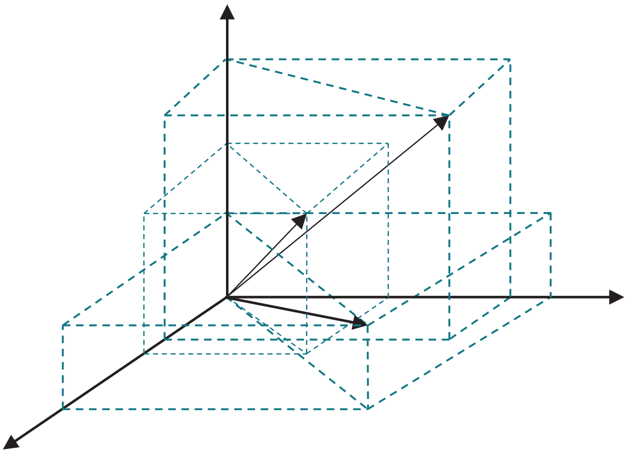

***Figure 3**. Example of vectors image in space*
***Source:** compiled by the authors*

Managerial decisions should be evaluated based on the model proposed above (with randomly assigned values, provided as an example). It is to be assumed that there are 4 factors that were evaluated using assessments from 5 experts, and there are 4 factors that can be evaluated quantitatively for each option of managerial decisions. There are 3 such decisions. For each of the factors in the context of each managerial decision the impact of experts was assessed. During the assessment the following results were obtained (Table 1).

***Table 1**. Example of assessment of qualitative factors of influence on the management problem in the context of management decisions*

Management decision 1						
Indicator	**Expert 1**	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Average**
Factor 1	9	8	8	3	10	7.6
Factor 2	7	7	3	1	9	5.4
Factor 3	10	8	6	2	8	6.8
Factor 4	4	4	7	1	8	4.8
Management decision 2						
Indicator	**Expert 1**	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Average**
Factor 1	0	10	4	4	1	3.8

Table 1. Continued

Indicator	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Average
Management decision 2						
Factor 2	5	4	9	1	9	5.6
Factor 3	3	0	2	8	1	2.8
Factor 4	9	6	7	7	7	7.2
Management decision 3						
Indicator	**Expert 1**	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Average**
Factor 1	4	6	2	1	1	2.8
Factor 2	4	3	3	2	9	4.2
Factor 3	0	5	4	6	5	4
Factor 4	8	2	9	8	4	6.2

Source: *compiled by the authors*

According to Table 1, due to the different estimates of the influence of factors for different management problems, it is possible to obtain indicators that differ significantly between the different management solutions. Authors will also conduct an impact assessment for the quantitative factors as well, as shown in Table 2.

Thus, authors get 3 vectors with 8 values, for each of which it is worth calculating the length (Table 3).

Table 2*. The obtained results of the influence of quantitative factors within the framework of individual management decisions*

Indicator	Management decision 1	Management decision 2	Management decision 3
Estimation of in-kind indicators			
Factor 5	175	590	855
Factor 6	491	263	811
Factor 7	822	471	262
Factor 8	532	602	375
Evaluation of indicators in terms of scores			
Indicator	**Management decision 1**	**Management decision 2**	**Management decision 3**
Factor 5	2.5	5.55	7.5
Factor 6	4.58	2.5	7.5
Factor 7	7.5	4.37	2.5
Factor 8	5.96	7.5	2.5

Source: *compiled by the authors*

Table 3*. Final results of calculating the effectiveness of management decisions*

Indicator	Management decision 1	Management decision 2	Management decision 3
Factor 1	7.6	3.8	2.8
Factor 2	5.4	5.6	4.2
Factor 3	6.8	2.8	4
Factor 4	4.8	7.2	6.2
Factor 5	2.5	5.55	7.5
Factor 6	4.58	2.5	7.5
Factor 7	7.5	4.37	2.5
Factor 8	5.96	7.5	2.5
L	16.59	14.76	14.32

Source: *compiled by the authors*

As can be seen from Table 3, within the selected data the most effective is the use of management decision 1. Thus, the proposed methodology allows to determine which of the methods is more effective for enterprises, and therefore the hypothesis can be considered confirmed. The application of decision-making techniques in information intelligent systems for managing agro-industrial enterprises is aimed at solving several key tasks (Galanakis, 2021; Yessilbayeva *et al*., 2025). These include developing effective mechanisms to enhance the competitiveness of agricultural enterprises in a real market economy and identifying key trends in the development of integration processes within the agricultural sector. Additionally, it involves outlining the main priorities for agricultural sector development in the context of national food security and identifying prospects for strategies to increase the competitiveness of agricultural enterprises.

Further objectives include conducting an objective analysis of existing agricultural production management methods using forecasting techniques and analysing business processes within individual enterprises in the sector. Another critical task is developing an effective system for managerial decision-making at all levels and in all areas of an agricultural enterprise to ensure an appropriate level of management. Lastly, the creation of an information-analytical system using mathematical models is essential for making accurate forecasts of financial, economic, and production indicators in agricultural production.

Prospects of the practical introduction of artificial intelligence technologies in the processes of enterprise management of the agrarian sector of the economy in Kazakhstan are largely determined by both real problems of this industry, and options for their practical resolution, in the context of the realities of economic development of the country. The practical effectiveness of any management decision-making models used by agricultural enterprises in Kazakhstan can be supported by real improvements in their functioning, manifested in an increase in agricultural production, improved labour safety of employees of enterprises, and their stable functioning regardless of changes in the current economic situation and various negative external factors.

In reality, managerial decision-making is closely linked to the development of innovations. This is related to the fact that companies actively involved in innovation discover new opportunities to improve business processes and create new products. In addition, decision-making processes include analysing technological trends, risk management, and supporting an innovative culture, stimulating creativity and initiative among employees. Integration of innovation into the business model includes assessing the impact on current processes and possible changes in strategy. Thus, innovation and decision-making complement each other, creating the basis for sustainable development and competitiveness of the company. In this regard, by assessing the level of innovation spending in a country, it is possible to partly infer the extent to which the effectiveness of decision-making in the country is increasing (Fig. 4).

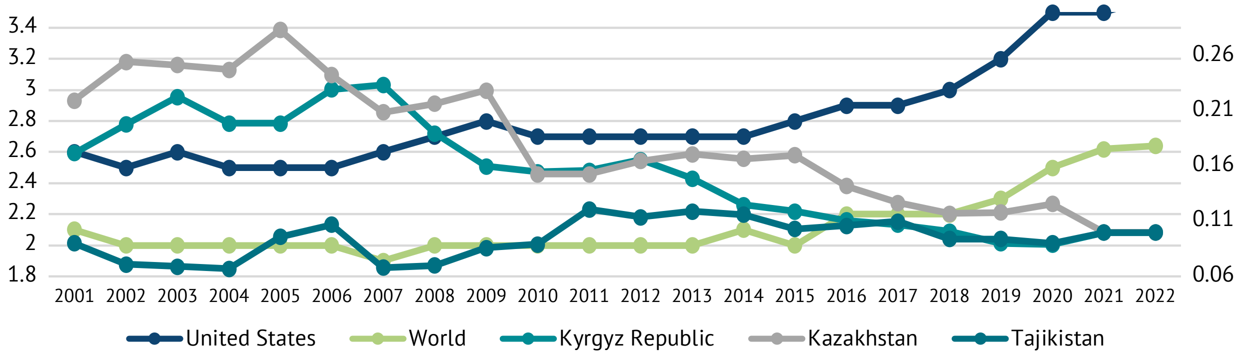

Figure 4. *Research and development expenditure in selected countries from 2001 to 2022, %*
Source: *compiled by the authors based on The World Bank (2024)*

As can be seen in Figure 4, the level of innovation expenditure in Kazakhstan relative to GDP is gradually decreasing. The value in the country in 2001 was 0.22%, while in 2022 it was 0.1%, which is on par with Kyrgyzstan and Tajikistan. Compared to the world average, such values remain quite low. Although the country defines innovation as one of the most important strategic goals in its development, the data show that the ratio of costs to the latest technologies is only getting lower, which may be a bad factor, indicating, among other things, the insufficient pace of development of decision-making methods. Such dynamics are primarily caused by the rapid GDP growth rate in the country as a whole, which outstrips the growth of innovation costs. Nevertheless, it can be argued that the public authorities pay insufficient attention to the development of innovations in the country. The change in Tajikistan, on the other hand, is uniform. For developed countries, in particular the United States of America, the dynamics are upward, as is the global average, which is different from Kazakhstan's trends. Another component that can influence the effectiveness of management in agriculture is the level of investment (Fig. 5).

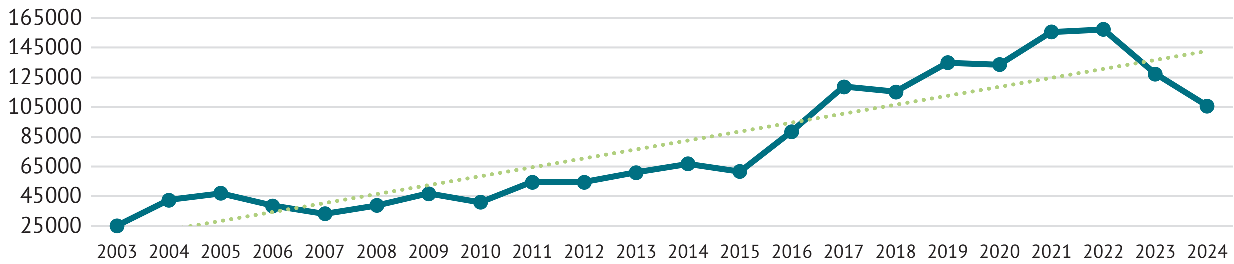

***Figure 5**. Level of investments in agriculture adjusted for inflation (in 2003 prices) in the period from 2003 to 2024, million tenge*

***Source:** compiled by the authors based on Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (2024a)*

As can be seen from Figure 5, the level of investment in agriculture in Kazakhstan has been experiencing fluctuations in recent years. After a period of steady growth until 2022, there is now a noticeable decrease in investments in 2023 and 2024, indicating a decline rather than gradual improvement in this sector. Another indicator worth considering is the yield level (which characterises productivity) (Table 4).

***Table 4**. Yield level of individual crops in Kazakhstan in the period from 2000 to 2024, quintals/ha*

Year	Cereals (including rice) and legumes (in weight after cultivation)	Oilseeds	Sunflower seeds (in weight after processing)	Potatoes	Outdoor vegetables	Gourds	Sugar beet (in weight after processing)
2000	9.4	3.9	4	106	153	119	154
2001	12.2	5.7	6	133	166	127	173
2002	11.5	6.3	5.9	139	172	135	207
2003	10.8	7.1	6.8	139	177	144.5	210.4
2004	8.8	6.2	5.9	134	186	153.2	197.4
2005	10	7	6.3	150	196	159.3	209.2
2006	11.7	6.6	5.9	153.6	201	167.1	240.8
2007	13.3	7.2	5.9	155.8	211	171.7	248.9
2008	10.1	5.5	4.1	143.7	204	158.9	204.3
2009	12.6	6.5	5.7	160	218.7	161.1	182.9
2010	8	5	4.4	143	214.4	177	174.3
2011	16.9	6.7	4.6	167.2	222.9	186.1	188.2
2012	8.6	6.1	5.9	165.9	234	206.8	168.2
2013	11.6	8	7	181.5	238.7	212.4	267.7
2014	11.7	7.8	6.7	184.3	243	217.1	240.6
2015	12.7	8.1	7.6	185.5	245.8	221	232.5
2016	13.5	9.6	9.3	190.4	250	221.4	285.5
2017	13.4	9.7	10.2	194.2	253.7	224.2	274.4
2018	13.5	9.7	10	197.9	257.3	224.2	305.3
2019	12.3	9.3	10.3	203.4	260.5	234.6	324.5
2020	12.8	9.5	11.3	206.7	265.9	238.8	323.2
2021	10.4	8.3	11	207.4	268	252.7	275.5
2022	13.8	9.1	12	205.4	271.3	255.6	341.4
2023	10.3	8.8	11	220.1	271.9	260.3	379.0
2024	15.2	12.2	14.6	219.1	284.2	253.2	507.3
Change, quintals/ha	5.8	8.3	10.6	113.1	131.2	134.2	343.3
Change, %	62	213	265	107	86	113	223

***Source:** compiled by the authors based on Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (2025)*

As can be seen from Table 4, yields of all crops in Kazakhstan have increased, with an average yield increase of 153% between 2000 and 2024. This may partly indicate that the overall management efficiency of the industry is increasing. The scale of use of information and communication technologies can be assessed using individual statistical data provided in Table 5.

***Table 5**. Selected data characterising the use of information and communication technologies in Kazakhstan in the period from 2008 to 2023*

Years	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Share of organisations using computers, %	76.6	69.8	62.7	65.2	66.9	66.2	58.1	66.3
Share of organisations with access to the Internet, %	55.5	54.2	52.9	55.4	58.4	60.7	52.4	61.2
Share of organisations with Internet resources, %	7.4	7.6	24.8	20.4	5.8	26.2	19.3	20.5
Share of organisations receiving orders for goods and services via the Internet, %	14.1	13	13	4.7	4.5	6.7	7.1	11.5
Share of organisations ordering goods and services via the Internet, %	14.9	15	15.7	3.6	3.9	5.9	7.7	15.3
Total costs for information and communication technologies, billion tenge	78.2	126.6	147.5	214.2	309.8	220.8	237.1	375.6
Total costs for information and communication technologies, taking into account inflation, billion tenge	71.4	108.7	117.3	158.5	216.2	146.9	146.7	204.7
Years	**2016**	**2017**	**2018**	**2019***	**2020***	**2021***	**2022***	**2023**
Share of organisations using computers, %	73.7	70.7	77.7	83	83.9	80.2	75.9	81.4
Share of organisations with access to the Internet, %	69.4	67.7	75.1	80.4	81.6	78.2	79.1	79.1
Share of organisations with Internet resources, %	18.5	21.7	22.3	18.9	17.9	17.6	25.6	26.5
Share of organisations receiving orders for goods and services via the Internet, %	4.4	1.5	1.6	5.4	7.4	8.5	9.3	10.6
Share of organisations ordering goods and services via the Internet, %	6.6	6.1	4.9	8.2	7.9	10.1	11	12.9
Total costs for information and communication technologies, billion tenge	269.5	349.9	305.2	337.7	388.9	443.1	589.9	918.3
Total costs for information and communication technologies, taking into account inflation, billion tenge	135.6	164.2	135.9	142.6	153	160.7	177.7	263

***Note:** * – for the first five indicators, the values were calculated until 2019 without taking into account government institutions, and from 2019 – together with them*
***Source:** compiled by the authors based on Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (2024b)*

As can be seen from Table 5, different parameters have shown varying trends over time. According to the available data, the number of organisations using computers increased by 7.7 percentage points, while the number of organisations using the Internet to receive or place orders for goods or services rose by 5.5 and 4.9 percentage points, respectively. On the other hand, the share of organisations with Internet resources has remained relatively stable with a slight increase of 6.1 percentage points, while the portion of organisations with access to the Internet saw a significant rise of 14.6 percentage points. Additionally, the total costs for information technology have increased approximately 3.5 times. These changes indicate that the use of information and communication technologies in the country is steadily increasing. However, despite these positive trends, the level of Internet usage for business activities remains relatively modest. The upward trend in information technology spending among enterprises is a promising sign. All this suggests the potential for further positive development in this sector in the future. Although there is no specific data on the implementation of digital technologies in the agricultural sector, it is reasonable to assume that their share is still limited.

DISCUSSION

Taking into account the information analysed above regarding the formation of management information systems in agriculture, authors can offer separate recommendations aimed at shaping public policy in this area. So, it is worth increasing the share of budget expenditures on investing in infrastructure, which provides agriculture with the necessary tools and technologies. Also important is work on the legislative framework, which should be carried out towards the introduction of stricter rules and oversight mechanisms to ensure the sustainable and efficient use of natural, labour and material resources in the agricultural sector. In general, any government programs that could encourage enterprises to form and improve the quality of internal management systems are also an important component of the development of this area. The introduction of such components into the country's public policy is a fundamental principle for ensuring high-quality implementation of information systems in agricultural enterprises.

In general, the model proposed in the work can solve a fairly large number of difficulties in the country. It explains the relationship between identified problems and potential mechanisms for solving them through strategic measures, in particular the implementation of information systems. This is primarily due to the fact that the economic sector of Kazakhstan itself is faced with systemic inefficiency, which includes insufficient material and technical support, weak resource management and limited cooperation between enterprises (Manatovna *et al.*, 2023). This inefficiency results in low productivity, resulting in a mismatch between the sector's development and the demands of a modern market economy. The model shown in the work allows you to create a structure for the formation of management decisions, use innovative technologies, programs and algorithms to form them, which makes the process faster and more accurate. Thus, its use makes it possible to increase the level of efficiency of applied management decisions, and therefore improve the quality of the company's functioning as a whole.

X. Pantazi *et al.* (2019), who investigated the application of intelligent analysis systems in agricultural activities, concluded that the artificial intelligence and data fusion techniques currently used in the agricultural industry for production control and crop monitoring have shown to be highly effective. The authors point out that neural networks and sensors with an artificial intelligence architecture make it possible to qualitatively identify trends in climatic conditions that negatively affect crop prospects. The need to apply the devices described competently to achieve the desired result is also stressed. The findings of the researchers can be accepted in the context of this study with the caveat that they should only be considered true if the equipment listed by the authors is adequately controlled.

At the same time, M. Khan *et al.* (2022), reviewing the prospects for the practical use of machine learning technologies in agriculture, argue that artificial intelligence technologies can only improve agricultural production and increase its economic efficiency only if they are used competently. Accordingly, since artificial intelligence methods are used to increase yields through optimal planting, fertilisation, irrigation, and harvesting, they are only part of a complex picture that should also consider economic investments and their optimised returns. The performance of machine learning models improves over time as various mathematical and statistical models are tested (Karaiev *et al.*, 2021). The conclusions in the context of the findings of this study seem questionable, due to the difficulty of controlling the level of return on investment invested in the development of agriculture in a particular region when it is not properly used.

P. Sharma *et al.* (2022), investigating the problematic aspects of bioinformatics in agriculture, came to a joint conclusion that echoes the findings of the researchers described above. The authors point out that the introduction of innovative processes in the agricultural sector will only be effective if they are properly implemented. They also draw attention to the fact that the application of artificial intelligence technologies in crop quality improvement management requires a high degree of competence from all parts of the chain involved, from the system designers to the direct performers of the tasks assigned. These findings show no clear contradiction with the results of this investigation, supporting and further extending it. R. Poonia *et al.* (2022), studying some problematic aspects of the use of artificial intelligence systems in agriculture, concluded that the success of such systems is largely related to the efficient use of information stored in databases of computer systems. Researchers note that managing artificial intelligence software databases requires the use of a special software learning algorithm to ensure high efficiency in solving the tasks at hand. Sustainable agriculture data determine the prospects for the sector and the possibilities for quality solutions to the challenges faced by agricultural enterprises at any stage of their existence (Yzakanov *et al.*, 2024). The conclusions can be challenged on the grounds that any algorithm requires an appropriate level of use, which implies quality training for the service personnel.

On the other hand, the subject raised is being further developed by G. Kaur *et al.* (2020) in a collaborative study on the application of artificial intelligence to the Internet of Things solutions. Researchers point out that to achieve a sustainable result, the introduction of artificial intelligence technologies in any sphere of everyday life requires a special algorithm that accounts for all features of the behaviour of an information intelligent system in a constantly changing external environment. According to a group of scientists, agriculture is an unstable environment with constantly changing external conditions, so the introduction of artificial intelligence systems in this environment involves constant monitoring of the nature of changes occurring at different stages of the system's functioning. These conclusions are fully in line with the author's findings. The results are consistent with those obtained in this study, presented in the case of the mathematical model for managerial decision-making.

The study by S. Kim and G. Deka (2021) examined the application of hardware accelerator systems and artificial intelligence in machine learning, assessing the prospects for their implementation in various branches of science and technology. The authors conclude that the development of deep neural networks and machine learning have opened vast prospects for many industries and economies. Special attention is paid to the fact that the transition of agriculture to the application of artificial intelligence technology is possible only if the infrastructure of agricultural enterprises is sufficiently prepared for the implementation of new innovations (Zelisko *et al.*, 2024). Otherwise, it will not be possible to achieve high performance in the management of agricultural enterprises and increase the volume of agricultural output. These conclusions are fully in line with the author's findings. The results are consistent with those of this study, while also revealing new aspects of the problem under investigation.

Notably, the study by P. Srivastava and G. Tsakiris (2020) devoted to the consideration of challenges in the application of artificial intelligence systems in the management of water resources of agricultural enterprises, concluded that the effectiveness of their practical application depends to a large extent on the training of the personnel of these enterprises. Artificial intelligence can now effectively manage the water supply to irrigate fields or garden plots, whereas volume control and water delivery can be fully automated (Shahini *et al.*, 2023). The ultimate impact of such a system is determined by operator training, controlling the sequence in which commands are executed and the nature of changes to the underlying data. In the context of assessing the role of the information system operator (user), the findings mirror those of this investigation.

N. Nilsson (1998), in a study of the development prospects and practical applications of artificial intelligence systems, concluded that the further spread of artificial intelligence information systems in various areas of daily life opens great opportunities to solve a range of tasks that were previously unattainable. The author emphasises that the application of information management systems for agricultural enterprises enables effective control over all areas of agricultural activity, including animal husbandry, the planting of crops or the cultivation of fruit and berries. According to the scientist, this can be achieved through the use of large amounts of data containing information about all aspects of the activities of agricultural enterprises at all its stages. The conclusions drawn do not clearly contradict the findings of this study, aligning with them in substantial terms. Zh. Abuova *et al.* (2023) studied the possibilities of creating a favourable environment for outsourcing relationships in the agro-industrial complex of Kazakhstan. Scientists noted that there are critical problems facing agricultural organisations in Kazakhstan due to inadequate market infrastructure and lack of support systems. In this regard, they believe that the use of outsourcing can help solve these difficulties. The use of outsourcing is often also associated with the implementation of information and management systems, since it requires more active and efficient management of processes in such enterprises (Potryvaieva & Palieiev, 2023). In this regard, this work generally supports the idea of this study that increased implementation of management systems is an important component of agricultural development in Kazakhstan.

R. Dulambayeva *et al.* (2023) in turn analysed the relationship between innovation and the development of the agro-industrial complex in Kazakhstan. They noted that there is a significant positive impact from the introduction of new technologies on the agricultural sector. They considered agricultural credit one of the most effective methods for creating more active innovative development. In addition, they noted the role of stimulating agricultural enterprises to develop in this direction. They emphasised government support for such enterprises as one of the proposed ways to achieve this. This study also suggested that this could be a qualitative method for both increasing the efficiency of companies in Kazakhstan and ensuring a higher overall level of digital technology adoption in the country.

CONCLUSIONS

The challenges of managing enterprises in the agrarian sector can be successfully solved through the introduction of information intelligent systems into their management practices. Systems of this kind ensure the efficiency of management of all processes occurring throughout the activities of enterprises of the agrarian sector, through the practical application of management decision-making models for all common scenarios occurring in the activities of a single agrarian enterprise. The integration of such systems has significantly improved the efficiency of management practices in the agricultural sector of Kazakhstan, particularly by automating decision-making processes, optimising resource utilisation, and enhancing productivity. For example, between 2000 and 2024, the average yield of all crops increased by 153%, which highlights the positive impact of management automation.

Decision-making models in the management systems of enterprises of the agro-industrial complex of the Republic of Kazakhstan are created using the capabilities of the available mathematical apparatus. At the same time, it is necessary to consider such factors as business options within a particular management model, the acceptable variants of events and decisions, and the amount of the input data, which determine the nature of the optimal options to resolve the situation in the management of the agricultural enterprise, along with the utility function, the relationship between decisions and the results, uncertainty of the external environment parameters. Consideration of the above factors in their systemic variation allows the creation of effective decision-making models in control systems. The study assessed certain indicators that may indirectly indicate an increase in the efficiency of governance in the agricultural sector. Additionally, the data indicated that the overall trends in the dynamics of management efficiency remain positive, with a noticeable increase in agricultural production and improved labour productivity, driven in part by the implementation of automated management systems.

The tasks solved by implementing these models into the information management systems of agricultural enterprises are performed sequentially, as the data processing speed increases. The efficiency of an agricultural enterprise and the timeliness of practical solutions to problems arising in the process of its economic activity depend on the quality of its solution. Furthermore, automated decision-making systems have minimised the impact of human error, leading to more accurate and faster management decisions, which directly improves operational efficiency. The study demonstrated that the use of automated information management systems can enhance the operational efficiency of agricultural enterprises in the country. Notwithstanding the favourable trends, Kazakhstan's agricultural investment has varied, exhibiting a significant reduction in 2023 and 2024. The overall expenditures for information and communication technology in Kazakhstan have increased by nearly 3.5 times, signifying a favourable trend towards digital transformation. In 2022, Kazakhstan's innovation expenditure constituted under 0.1% of GDP, a figure that is comparatively low against global standards and underscores the inadequate momentum of innovation within the agricultural sector.

The state can facilitate this process by formulating its own policy in this domain. This approach can foster more favourable conditions for the integration of intelligent information systems in agriculture, enhance investment appeal by promoting innovation, and establish targeted initiatives to improve digital literacy among agricultural enterprises. The state might also support digital transformation expenditures for small and medium-sized firms and enhance infrastructure, particularly in regional areas. These initiatives should considerably expedite the implementation of information systems in agricultural operations.

Further examination of enhancement chances for decision-making models in management information systems has significant prospects for the advancement of enterprise management systems within Kazakhstan's agricultural sector. The practical efficacy of these technologies will manifest as heightened agricultural output, augmented worker safety, and bolstered economic stability within the agriculture sector. These developments will enhance the profitability of these firms and contribute to the general prosperity of Kazakhstan's agro-industrial complex.

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CONFLICT OF INTEREST

None.

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Моделі прийняття рішень в інформаційних системах управління агропромисловими підприємствами

Гульжаухар Абдігул
Старший науковий співробітник
Казахський агротехнічний дослідницький університет імені С. Сейфулліна
010011, просп. Женіса, 62, м. Астана, Республіка Казахстан
https://orcid.org/0009-0006-3000-5496
Гульнара Асанова
Кандидат економічних наук, доцент
Казахський агротехнічний дослідницький університет імені С. Сейфулліна
010011, просп. Женіса, 62, м. Астана, Республіка Казахстан
https://orcid.org/0009-0002-0910-4677
Даміра Іскакова
Доктор філософії
ТОВ «Науково-виробниче підприємство «Інноватор»
010000, вул. Желтоксан, 2/1, м. Астана, Республіка Казахстан
https://orcid.org/0009-0008-3124-9542
Ристи Сабірова
Кандидат економічних наук, доцент
Атирауський університет імені Х. Досмухамедова
060011, просп. Студентський, 1, м. Атирау, Республіка Казахстан
https://orcid.org/0009-0005-4410-1588
Аїда Балкібаєва
Кандидат економічних наук, доцент
Академія фізичної культури та масового спорту
010000, просп. Мангілік Ел, 2.2В, м. Астана, Республіка Казахстан
https://orcid.org/0000-0002-2710-8930

Анотація. Актуальність заявленої теми визначається широким поширенням інформаційно-інтелектуальних систем (ІІС) у різних сферах сучасної науки, техніки та промисловості, а також необхідністю розробки та впровадження ефективних алгоритмів прийняття рішень на основі технологій ІІС в аграрному секторі економіки Республіки Казахстан. Основною метою дослідження було запропонувати модель прийняття управлінських рішень в аграрному секторі Казахстану. Методологічний підхід ґрунтувався на поєднанні методів комплексного дослідження основних принципів прийняття рішень в інформаційних управлінських системах та аналітичного дослідження перспектив практичного застосування технологій штучного інтелекту в процесах управління підприємствами агропромислового комплексу. Також використовувалися методи аналітичного порівняння та синтезу даних, зібраних під час дослідження. Отримані результати визначали основні завдання методів прийняття рішень в інформаційних мережах управління підприємствами аграрного сектору Республіки Казахстан з урахуванням сучасних проблем цієї сфери та практичних варіантів їх вирішення. У дослідженні було виявлено, що в період з 2000 по 2024 рік середній урожай усіх культур зріс на 153%, при цьому спостерігалися значні поліпшення у вирощуванні олійних культур, соняшнику та картоплі. Також було зафіксовано значне збільшення використання інформаційно-комунікаційних технологій у Казахстані, з майже 3,5-кратним зростанням витрат на ці технології. Крім того, дослідження підкреслило потенціал для автоматизації аграрного сектору, зокрема для покращення використання ресурсів та підвищення продуктивності. Практична значущість результатів полягає у їх впровадженні в діяльність підприємств аграрного сектору для створення ефективних управлінських систем з використанням технологій штучного інтелекту. Ці розробки сприятимуть подальшій модернізації сектора, підвищенню його економічної сталості та узгодженості з глобальними тенденціями цифрової трансформації

Ключові слова: штучний інтелект; інформаційні інтелектуальні системи; аграрний сектор; сільське господарство; управлінські рішення; інноваційні технології

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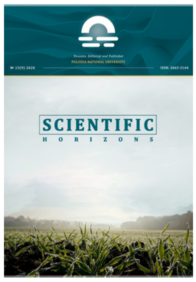

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The role of local communities in the restoration of agricultural infrastructure after destruction

Alona Kliuchnyk*
Doctor of Economic Sciences, Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0001-6012-6666

Nataliia Shyshpanova
PhD in Economic Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0001-8347-5682

Liudmyla Prohoniuk
PhD in Law, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0003-0376-5079

Nataliia Galunets
Senior Lecturer
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0001-7709-9238

Anzhela Husenko
Senior Lecturer
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-3989-2400

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Abstract. The research aimed to evaluate the efficacy of financial, organisational, and managerial strategies for the rehabilitation of agricultural infrastructure in Ukraine from 2022 to 2024. The analysis examined the socio-economic prerequisites for the agricultural sector's development before the onset of conflicts, along with their effects on the devastation of production facilities, land resources, and the logistics infrastructure. The study determined that the hostilities destroyed 4,800 agricultural

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*Corresponding author

infrastructure facilities, damaged 3.2 million hectares of land, destroyed 12,500 km of roads, and reduced employment in the agricultural sector by 15%. By the end of 2024, the company managed to restore 2,750 facilities (57%), return 1.8 million hectares of land to cultivation and repair 7,300 km of roads. The financing gap in 2022 was more than USD 3.8 billion, rendering it impossible to modernise production facilities in a timely manner. Private investment, which dropped to USD 600 million in 2022, began to grow only in 2023-2024, reaching 950 million USD. In the same period, crowdfunding totalled more than USD 33 million, of which the largest share was used to modernise irrigation systems (USD 9.1 million in 2024). At the same time, the cooperative sector rehabilitated 65 farms in 2024, providing more than USD 21 million in economic contribution. Volunteer initiatives have also shown growth, supporting small farmers and the restoration of critical infrastructure. Demographic shifts from rural regions, particularly the exodus of approximately 120,000 individuals in 2022, have substantially diminished the agricultural sector's workforce capacity. The findings demonstrated that comprehensive reconstruction of agricultural infrastructure necessitates the acquisition of supplementary financial capital, optimal utilisation of public-private partnership frameworks, and implementation of initiatives to facilitate workforce repatriation. This investigation provides a foundational structure for enhancing investment strategies within the agricultural domain and optimising collaborative efforts among local communities, governmental entities, and international funding organisations

Keywords: agriculture; investment projects; financial support; cooperative initiatives; international assistance; recovery processes; communities

INTRODUCTION

The research's significance was established by the considerable devastation of agricultural infrastructure due to wars, which disrupted production processes, diminished crop acreage, decreased employment levels, and restricted market access. In such circumstances, the definition of the role of local communities in the recovery process remained relevant due to the mobilisation of resources, coordination of recovery efforts and maintenance of socio-economic stability in rural areas. The study covered the issues of involving local communities in the process of restoring agricultural infrastructure, mechanisms of their interaction with government agencies, international partners, and the private sector, as well as the effectiveness of the initiatives implemented. The main challenges were a lack of financial resources, a shortage of qualified personnel, the destruction of transport infrastructure, and the need to introduce modern technologies into production processes. The analysis of these aspects identified the key factors that influenced the pace of recovery and outlined the prospects for stabilising the agricultural sector through the intensification of local initiatives and improved financing mechanisms.

The theoretical framework of the study was based on the concepts of decentralisation of governance, mechanisms of local self-government development and theories of sustainable agricultural development. The approaches used were those related to the role of communities in the processes of economic recovery, structural changes in the agricultural sector and the impact of military conflicts on agricultural production. The financing of reconstruction processes, including public-private partnership mechanisms, attracting international assistance and the role of cooperative associations in the restoration of agricultural production were emphasised. The analysis of scientific sources demonstrated that the issue of restoring agricultural infrastructure after the destruction was addressed from various aspects, including state support, international financing, involvement of local communities, innovative approaches to agricultural development, and the role of the cooperative movement. O.A. Samoshkina (2024) highlighted state programmes to compensate for the losses of agricultural producers, which contributed to the modernisation of the agricultural sector, but the effectiveness of these measures in the context of unstable funding remained insufficiently covered. Similarly, the study by T. Gagalyuk (2024) analysed international grant programmes but did not consider the long-term economic effects of these initiatives and their sustainability in the post-crisis period.

O. Kravchenko *et al.* (2023) considered international institutional support but did not analyse the impact of regional economic conditions on the effectiveness of such programmes. I. Zapatrina (2022) studied the mechanism of public-private partnerships but did not provide a detailed assessment of the legal aspects and risks associated with attracting private capital to restore agricultural infrastructure. The analysis by L. Bovsh *et al.* (2024) addressed the cross-sectoral adaptation of farms but did not incorporate the structural challenges associated with labour outflows and migration processes. T. Zaiats *et al.* (2024) emphasised the role of non-governmental organisations in strengthening the adaptive capacity of territorial communities but did not cover the issue of integrating such organisations into state programmes to support the agricultural sector. M. Kohut (2024) analysed the relationship between foreign direct investment and national economic competitiveness; however, the study neglects to address the distinctive characteristics of the investment environment within the agricultural sector and fails to account for the associated potential risks. The study by D. Riznyk (2023) analysed the investment strategy of post-war reconstruction but did not consider in detail the mechanisms for attracting financing for small and medium-sized farms.

V. Bobyl and D. Rezhko (2024) confirmed the importance of local government cooperation with central authorities in the recovery of the agricultural sector but did not address the issue of the efficiency of resource allocation at the regional level. The study by M. Kropyvko and M. Kropyvko (2022) substantiated the need to introduce modern agricultural technologies but did not provide a comprehensive assessment of the financial costs of such measures. I. Solodovnykova (2024) covered the mechanisms of agricultural insurance but did not consider the impact of security risks on the effectiveness of insurance programmes. Despite the wide range of issues analysed, there were still key aspects that required further study. Initially, an absence of a thorough examination of the enduring socio-economic repercussions of agricultural infrastructure restoration, encompassing the effects of rebuilding production facilities and transportation networks on employment, income, and demographic trends in the impacted regions, was observed. Research on the mechanisms for integrating local communities into the implementation of state and international support programmes, which affected the efficiency of financial resources and coordination between levels of government, was insufficient. There were also gaps in the study of the role of volunteer initiatives, crowdfunding, and the cooperative movement in agricultural recovery.

To achieve this goal, the main areas of participation of local communities in the restoration of agricultural infrastructure, including organisational aspects and decision-making mechanisms at the regional level, were investigated. The economic impact of community participation in the restoration of the agricultural sector was assessed, in particular through the involvement of international support programmes, private investment and public funding. The effectiveness of the applied coordination mechanisms between local communities, government agencies and international partners to optimise the recovery process was analysed.

MATERIALS AND METHODS

The timeframe encompassed 2020-2024, detailing the evolution of the agricultural sector before the full-scale invasion, the dynamics of its reconstruction during the war, evaluating the efficacy of the financial and organisational resources employed, and identifying the principal challenges encountered in the reconstruction process. Data from the State Statistics Service of Ukraine (n.d.), the Ministry of Agrarian Policy and Food of Ukraine (n.d.), the Ministry of Finance of Ukraine (n.d.), as well as reports by the World Bank Group (2022), the United Nations Development Programme (UNDP) (2024), the Food and Agriculture Organisation of the United Nations (FAO) (2023), the United States Agency for International Development (USAID) (n.d.), and the European Bank for Reconstruction and Development (EBRD) (n.d.) were used to collect information. The financial and economic indicators were assessed, reflecting the scale of destruction, the pace of reconstruction of infrastructure facilities, the level of investment attraction, and changes in the structure of employment in the agricultural sector.

The analysis also covered the role of local communities in the reconstruction process, including their involvement in coordinating recovery efforts, raising additional financial resources, and introducing new organisational mechanisms. An assessment of the effectiveness of crowdfunding initiatives, the cooperative movement and volunteer programmes as methods of agricultural production support was conducted. The information was systematised through a comparative analysis of available sources, which identified patterns in financing, organisational management models and the impact of government and international programmes on the reconstruction of agricultural infrastructure. Statistical analysis methods were used to assess the extent of the destruction and the effectiveness of reconstruction measures. The dynamics of the destruction and restoration of agricultural facilities, investment activity, changes in employment, and the volume of international financial assistance were analysed. The systematisation of statistical indicators identified the key factors that influenced the pace of reconstruction and the effectiveness of financing recovery measures.

A comparative study was employed to evaluate the efficacy of rebuilding financing mechanisms, encompassing public-private partnerships, international grant programs, private investment, and volunteer activities. An analysis of the experience of countries such as Bosnia and Herzegovina, Colombia, Iraq, Rwanda and Afghanistan, which have undergone similar processes of rebuilding the agricultural sector after crises, identified the most effective practices in managing recovery measures. The content analysis method was used to study reports of international organisations, research results, statistical surveys and analytical materials related to the post-crisis recovery of the agricultural sector (World Bank Group, 2022; Food and Agriculture…, 2023; United Nations Development Programme, 2024). An analysis of the positions of international experts, the findings of research centres, and publications in professional sources has identified key challenges that affect the effectiveness of agricultural policy in the context of hostilities, as well as generalised practices used in other countries to restore agricultural infrastructure (United States Agency for International Development, n.d.; European Bank for Reconstruction and Development, n.d.).

The results were interpreted through a thorough examination of quantitative and qualitative indicators that illustrated the dynamics of agricultural infrastructure repair and the involvement of local populations in this process. The sample included communities from the most affected regions of Ukraine (Kharkiv, Donetsk, Luhansk, Zaporizhzhia, Kherson and Mykolaiv oblasts), as well as areas that served as transit or hosts for internally displaced persons (in particular, Vinnytsia, Lviv, Ivano-Frankivsk, Ternopil, and Kyiv oblasts). The main selection criteria were: agricultural specialisation of the community's economy, the extent of damage to agricultural infrastructure, the level of involvement in post-crisis financing programmes, activity in partnership with state and international institutions, and the dynamics of internal migration. This approach was used to compile a representative assessment of reconstruction management models, identify regional differences in financial mobilisation, and determine the degree of community involvement in the process of agricultural production recovery.

RESULTS

The comprehensive Russian invasion of Ukraine has precipitated a profound crisis across all economic sectors, notably the agricultural sector, which has historically been pivotal in the composition of national production and exports. Large-scale destruction of infrastructure, reduced production volumes, logistical constraints and financial risks have led to a significant decline in economic activity in agriculture. Disruptions in supply chains, destruction of production facilities, and a significant outflow of people from the affected regions have hampered the sector's recovery. At the same time, the agricultural sector continued to be a priority area for government policy and international assistance, as its stable functioning was critical to ensuring national food security and maintaining macroeconomic stability. According to the survey, Ukrainian respondents demonstrated the highest level of community and societal resilience among the countries affected by the conflict, which is an important factor in restoring not only social but also economic stability (Berxolli *et al.,* 2023; Kimhi *et al.,* 2024).

Despite significant suffering and adversity, hope and positive coping mechanisms, such as a sense of well-being, have emerged as crucial factors in fostering resilience within the agricultural sector, thus contributing to the stability of production processes and food security in the nation. There are examples of countries that lost a significant part of their agricultural production potential as a result of armed conflicts or large-scale internal crises but managed to restore the sector within a few years using adaptive management models, international assistance, and the development of local institutions. These examples are of practical importance for Ukraine in the context of finding effective mechanisms for post-crisis recovery of the agricultural sector. To systematise key practices, the experience of five countries from different regions of the world that have implemented programmes for the reconstruction of agricultural infrastructure in the post-conflict period was analysed: Iraq, Afghanistan, Colombia, Bosnia and Herzegovina, and Rwanda. In each case, different models of coordination, resource mobilisation and institution building were applied, which identified the most effective approaches to stabilising the agricultural sector. Data for Ukraine is also included for comparative purposes. Table 1 summarises the extent of the damage, sources of funding, coordination mechanisms and level of recovery achieved.

***Table 1**. Comparative indicators of agricultural sector recovery in selected countries after the crisis*

Country	The period of crisis	Share of destroyed agricultural facilities (%)	Amount of investment in recovery (billion USD)	Key sources of funding	Key institutional arrangements	Recovery rate after 3 years (%)
Iraq	2003-2006	60	3.7	World Bank Group, USAID	Ministries + international partners	52
Afghanistan	2002-2005	45	2.8	FAO, UNDP, international non-governmental organisations (NGOs)	Provincial councils and technical assistance	41
Columbia	2016-2019	35	1.9	World Bank Group, EU, private sector	National Recovery Agency	64
Bosnia and Herzegovina	1995-1998	70	2.3	United Nations (UN), EBRD, public funds	Recovery Coordination Council	58

Table 1. Continued

Country	The period of crisis	Share of destroyed agricultural facilities (%)	Amount of investment in recovery (billion USD)	Key sources of funding	Key institutional arrangements	Recovery rate after 3 years (%)
Rwanda	1994-1997	80	1.5	FAO, USAID, voluntary donations	Rural cooperatives + municipalities	49
Ukraine	2022-2024	57	4.6	The state budget, FAO grants, crowdfunding	Local communities + public-private partnerships	57

Note: *for Ukraine, the values are indicated as of the conclusion of 2024, acknowledging that the crisis persists and the restoration of agricultural infrastructure post-conflict remains unfinished; the recovery level is fluid and may fluctuate based on the evolution of the security landscape, the accessibility of financial resources, and the efficacy of the execution of pertinent programs*
Source: *World Bank Group (2022), United Nations Development Programme (2024), Food and Agriculture Organisation of the United Nations (2023), United States Agency for International Development (n.d.), European Bank for Reconstruction and Development (n.d.)*

The analysis of Table 1 demonstrated that Colombia and Bosnia and Herzegovina achieved the greatest results, with the percentage of rehabilitated facilities exceeding 58%. A unifying factor in these countries was the presence of specialised institutions that coordinated the reconstruction process, with clear responsibilities for planning, implementing and monitoring agricultural programmes. The models of combining external assistance with domestic investment were also effective, reducing dependence on donor funding. In the cases of Iraq and Rwanda, the effectiveness of the reconstruction processes was limited by overdependence on international aid, fragmented governance and low institutional capacity of local authorities. In Rwanda, attempts to mobilise local cooperatives failed due to a lack of resources and personnel. At the same time, Iraq, despite the high level of funding, failed to ensure sufficient transparency in the use of funds, which affected the pace of reconstruction.

Ukrainian experience has demonstrated a relatively high recovery rate of 57% due to a combination of decentralised governance, grant mobilisation and the development of the cooperative sector. The most effective methods were crowdfunding, public-private partnerships, and community involvement in decision-making. Ukrainian practice has confirmed the effectiveness of mixed models that ensure adaptation to war conditions and a gradual transition to strategic development, considering international standards for the restoration of agricultural infrastructure. Local communities played a crucial role in the restoration of agricultural infrastructure following the catastrophe, overseeing land resources, assisting farms, and assuring the consistent operation of agricultural output. The strengthened powers of local governments as a result of decentralisation contributed to more effective coordination of the recovery process, adapting local development strategies to economic conditions and attracting additional funding from government and international sources.

Restoration of agricultural infrastructure required significant financial and technical resources, which were partially covered by government programmes and international assistance. In this process, local communities provided for the reconstruction of elevators, storage facilities, irrigation systems and livestock farms, which restored production activities (Klyuchnik *et al*., 2020). Interaction between the communities and agricultural enterprises identified priority areas for reconstruction according to the degree of damage and availability of material and technical resources. The rehabilitation of transportation and logistics infrastructure proved essential for ensuring the agricultural sector's operational stability. This reconstruction facilitated the efficient movement of agricultural inputs and outputs, thereby maintaining the sector's productivity and economic viability. The destruction of bridges, roads and railway junctions hampered the transport of agricultural products, resulting in higher logistics costs and reduced access to markets. Local communities have taken steps to repair roads, organise alternative transport routes and coordinate transport between agricultural producers and logistics operators. Table 2 provides statistics describing the extent of the damage and progress in restoring agricultural infrastructure during 2022-2024, including the number of restored agricultural infrastructure, transport routes, and changes in employment in the agricultural sector.

***Table 2**. Consequences of hostilities: Statistical indicators of the destruction and restoration of agricultural infrastructure (2022-2024)*

Analysis factor	Statistical indicator (units of measurement)
Number of destroyed agricultural infrastructure facilities	4.800
Number of restored agricultural infrastructure facilities	2.750
Total area of damaged agricultural land (thousand ha)	3.200
Restored area of agricultural land (thousand ha)	1.800
Length of destroyed roads (km)	12.500
Rehabilitated road infrastructure (km)	7.300
Change in the level of employment in the agricultural sector (%)	-15%

***Source:** State Statistics Service of Ukraine (n.d.), Ministry of Agrarian Policy and Food of Ukraine (n.d.), Ministry of Finance of Ukraine (n.d.)*

Table 2 demonstrates the extent of damage to agricultural infrastructure and its impact on agriculture. More than 4,800 agricultural infrastructure facilities were destroyed, of which only 2,750 had been restored by the end of 2024. Despite the attraction of government and international funding, the reconstruction process remained challenging due to a significant shortage of resources and high financial costs. In addition to the production infrastructure, agricultural land was severely damaged. The total area of the affected land was 3.2 million hectares, of which only 1.8 million hectares were returned to agricultural use. This demonstrated the need to continue soil restoration measures, modernise agricultural technologies and introduce innovative farming methods. The destruction of more than 12,500 km of roads significantly hampered logistics operations and agricultural exports. The rehabilitation of 7,300 km of roads partially improved transport connectivity, but further measures were needed to ensure stable logistics between agricultural regions and processing plants.

The consequences of the destruction also affected employment in the agricultural sector. During the analysed period, employment fell by 15%, which was due not only to the destruction of production facilities but also to the outflow of skilled labour. This necessitated the development of employment incentive programmes, vocational training, and the involvement of young professionals in agricultural production. The armed conflict's detrimental consequences extended beyond diminished production capabilities, imposing substantial damage on infrastructure networks, particularly within the contested regions of Kharkiv, Donetsk, Luhansk, Kyiv, Mykolaiv, and Zaporizhzhia, where economic assessments indicate infrastructural devastation amounting to hundreds of billions of dollars in monetary losses. According to the study, the assessment of infrastructure damage based on real data showed the extent of the destruction and highlighted the need to develop effective reconstruction strategies, both during the war and after it ended (Dunayev *et al*., 2024).

In addition to physical reconstruction, measures were taken to support social and economic initiatives that helped stabilise employment in rural areas. A significant number of agricultural workers lost employment due to the damage to production infrastructure, which led to lower incomes and forced migration. In response to these challenges, non-governmental organisations and local authorities implemented programmes to create temporary jobs in construction, logistics and agricultural processing, which partially offset the unemployment rate in the affected regions. The collaboration between local communities and foreign organisations, including FAO, USAID, and EBRD, was a crucial element in the rehabilitation of Ukraine's agricultural sector. However, as noted in the study, cities are key to the reconstruction process, not only in the post-conflict phase (Szpak *et al*., 2023). Support through bilateral channels, such as the twin city system and international and national networks of cities, has helped to attract additional resources for the reconstruction of not only the agricultural sector but also other important infrastructure elements. The implementation of these initiatives enhanced reconstruction efficacy by facilitating agricultural modernisation and technological innovation adoption. They provided crucial support for the transformation of farming practices, enabling the integration of advanced methodologies that improved productive capacity during the rebuilding phase.

The effectiveness of local communities in rehabilitating agricultural infrastructure is not limited to organisational capacity and coordination with government agencies and the private sector. An important aspect is also the involvement of academic institutions in this process, which was emphasised by I. Sikorska and T. Gerasymchuk (2023). The joint efforts of universities and communities can significantly strengthen resilience and sustainable development in times of war and the process of reconstruction. The use of intellectual resources, research capacities and community engagement initiatives by universities can address multifaceted issues, from infrastructure restoration to social cohesion. Such cooperation between educational institutions, government, non-governmental organisations and local communities creates opportunities for integrated and sustainable solutions that are essential for the recovery of the agricultural sector and food security in Ukraine. Private investment was one of the key financial instruments of recovery. Businesses channelled capital into reconstructing processing plants, expanding logistics capacities, and developing market infrastructure. Figure 1 demonstrates the changes in the volume of investments and the main areas of financing supported by private investors during this period.

***Figure 1**. Dynamics of private sector investment in agricultural infrastructure*
***Source:** State Statistics Service of Ukraine (n.d.), Ministry of Agrarian Policy and Food of Ukraine (n.d.), Ministry of Finance of Ukraine (n.d.)*

The data presented in Figure 1 demonstrated the dynamics of private investment in agricultural infrastructure in 2020-2024, reflecting both general economic trends and the effects of hostilities on the agricultural sector. During 2020-2021, investment experienced consistent growth, propelled by the upgrading of livestock farms, the installation of lifts, and the advancement of logistics hubs. However, in 2022, the volume of investments dropped significantly to USD 600 million, driven by infrastructure damage, reduced solvency of agricultural producers and general economic instability. In 2023, the agricultural sector commenced a gradual recovery phase characterised by heightened private capital inflows. Investments primarily targeted the acquisition of agricultural machinery, rehabilitation of transport infrastructure, and modernisation of processing facilities. These strategic allocations facilitated the effective restoration of agricultural production capabilities and contributed to the stabilisation of agricultural markets. The influx of private capital catalysed the sector's revitalisation, establishing foundational elements for sustainable growth following the preceding period of constraint.

The cooperative movement was significant in the recovery of the agricultural sector, especially in times of economic instability. International support programmes, including funding from the FAO and USAID, enabled some cooperatives to expand their activities, modernise their technical base and improve the efficiency of production processes. The dynamics of cooperative creation and financing fluctuated depending on the socio-economic situation, the level of international support, and the availability of financial resources. Figure 2 demonstrates the number of newly established cooperatives, as well as those that received funding from international grants.

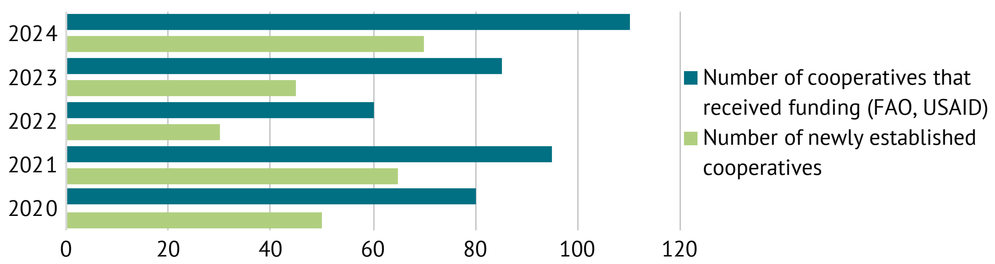

***Figure 2**. Number of cooperatives established and supported through international programmes*
***Source:** Food and Agriculture Organisation (2023), United States Agency for International Development (n.d.)*

Figure 2 demonstrates the growing role of the cooperative movement, especially in the periods following the crisis. In 2020-2021, there was an increase in the number of newly established cooperatives and an increase in international funding, which contributed to their development. However, in 2022, due to widespread infrastructure damage and economic instability, the pace of cooperative creation slowed significantly – only 30 new organisations were registered, compared to 65 in 2021. Commencing in 2023, the cooperative movement initiated a progressive recovery, marked by a rise in the establishment of new organisations and an augmentation of international financial assistance. This reflected an improvement in the overall economic situation, which was partly driven by increased assistance from international donors. According to a study by C. Schmidt (2024), donor interests largely influenced the amount and nature of assistance provided, with wealthier countries and those with ties to Russia being more inclined to support Ukraine.

The management of financial resources by local communities was accompanied by several challenges, including limited access to credit programmes, complex bureaucratic procedures and the need for transparent allocation of funds. Despite these difficulties, a combination of public, international and private funding provided the necessary resources to restore agricultural infrastructure, which helped stabilise the economic situation in rural areas. Rebuilding agricultural infrastructure required not only government support and international assistance but also the active participation of local communities. Communities have initiated numerous recovery programmes, raising funds through volunteer movements, crowdfunding campaigns, cooperative mechanisms and partnership projects. Their collaborative endeavours rehabilitated a substantial expanse of agricultural land, modernised supply lines, and enhanced conditions for the continued advancement of the agricultural industry.

Volunteer initiatives were central in the restoration of agricultural infrastructure, especially in the regions that suffered significant damage. The active participation of non-governmental organisations, agricultural producers and international partners contributed to the implementation of measures aimed at providing farmers with the necessary resources, demining and clearing agricultural land, repairing agricultural facilities and restoring critical irrigation systems. The dynamics of volunteer initiatives fluctuated depending on the scale of the destruction, the availability of financial resources and the level of support from the government and international organisations. Figure 3 demonstrates the number of volunteer initiatives in 2020-2024 and the main areas of their activities.

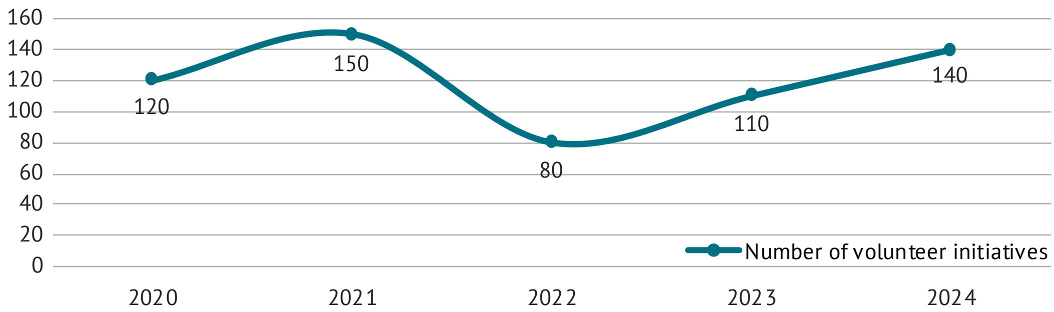

Figure 3. *Number of volunteer initiatives aimed at restoring the agricultural sector*
Source: *State Statistics Service of Ukraine (n.d.), Ministry of Agrarian Policy and Food of Ukraine (n.d.), Ministry of Finance of Ukraine (n.d.)*

The dynamics of volunteer initiatives demonstrated the remarkable agility of civil society organisations in addressing challenges precipitated by the crisis. During the initial phase, there was a notable proliferation of such activities; however, this momentum subsequently diminished as organisations confronted multiple constraints including restricted financial resource accessibility, heightened security vulnerabilities, and logistical complexities that impeded operational efficacy. However, as the situation gradually stabilised and additional international support was provided, volunteer activity intensified, demonstrating its important role in the agricultural sector's recovery. The change in the focus of volunteer initiatives responded to the needs of the agricultural sector at different stages of recovery. Initially, the focus was on supporting small farmers to restore basic production processes. Later, as coordination between communities, government agencies, and international partners improved, resources were channelled to larger projects of strategic importance for the restoration of agricultural infrastructure. This demonstrated a gradual increase in the organisational capacity of volunteer movements and their integration into long-term agricultural development programmes.

The significance of supplementary financial resources for the advancement of the agricultural industry, via crowdfunding, is paramount amid economic concerns (Khalatur *et al*., 2024). Crowdfunding can be used to raise funds directly from the population, private businesses, and international donors, which provides a flexible financial mechanism and facilitates a quick response to critical needs of the agricultural sector. This is especially relevant for the reconstruction of production facilities, modernisation of technologies and support for small farms. The dynamics of raising financial resources through crowdfunding platforms demonstrate changes in the priorities for allocating funds and the adaptation of communities to new economic and social conditions, which is an important element for the restoration of agricultural infrastructure and ensuring the sustainable development. Table 3 shows the total amount of funding received by communities through crowdfunding campaigns, as well as the main areas of its use in 2020-2024.

***Table 3**. Total amount of crowdfunding raised by communities to rebuild infrastructure*

Year	Crowdfunding volume (million USD)	Primary areas of crowdfunding
2020	5.2	Repair and restoration of agricultural buildings
2021	7.8	Procurement of agricultural machinery
2022	4.5	Farm support
2023	6.9	Construction of warehouses
2024	9.1	Modernisation of irrigation systems

***Source:** State Statistics Service of Ukraine (n.d.), Ministry of Agrarian Policy and Food of Ukraine (n.d.), Ministry of Finance of Ukraine (n.d.)*

The economic landscape and communal engagement levels exerted substantial influence on crowdfunding dynamics. Fluctuations in broader financial conditions corresponded with shifts in crowdfunding effectiveness, while the degree of social cohesion within communities similarly affected funding outcomes. Changes in the amount of funds raised indicated a periodic decline in the activity of crowdfunding initiatives, which could be caused by economic difficulties, reduced donor solvency, or competition for financial resources from other sectors. Despite these factors, public initiatives remained an important mechanism for mobilising finance to support the agricultural sector. The structure of the use of the funds raised varied according to the actual needs of the communities and the availability of other sources of funding. In the initial stages, crowdfunding campaigns focused on solving urgent problems, such as the basic reconstruction of agricultural facilities. The significance of initiatives focused on long-term infrastructure development and the implementation of contemporary technologies increased. This indicated a shift in strategic methodologies for the distribution of financial resources, which aligned with the adaptation of the agricultural sector to post-war recovery conditions.

The revival of the cooperative movement was significant in the development of the local economy, providing agricultural producers with access to financial resources, new technologies and markets. Thanks to government support and international programmes aimed at stimulating cooperation, a significant number of agricultural associations were able to resume their activities and expand their production. Cooperatives contributed to increasing the competitiveness of farms, optimising production costs and strengthening the resilience of the agricultural sector to crisis. Table 4 demonstrates the number of re-established cooperatives in 2020-2024, their economic contribution, and the main areas of activity supported by the state and international organisations.

***Table 4**. Number of restored cooperative farms in Ukraine*

Year	Number of restored cooperatives	Estimated economic contribution (million USD)
2020	40	12.5
2021	55	17.8
2022	35	11.3
2023	50	16.2
2024	65	21.5

***Source:** Ministry of Agrarian Policy and Food of Ukraine (n.d.), Food and Agriculture Organisation (2023), European Bank for Reconstruction and Development (n.d.)*

In addition to resuming traditional activities, cooperatives actively implemented new development strategies. A primary strategy involved consolidating producers to collectively acquire equipment and resources, thereby diminishing production costs and enhancing capital efficiency. Initiatives in organic farming were particularly developed, correlating with the trend towards greening agricultural production and the introduction of higher product quality standards. The significant contribution of the cooperative sector to the local economy confirmed its important role in building a sustainable agricultural system. Cooperative associations provided small and medium-sized agricultural producers with access to financial resources, the latest technologies and more favourable business conditions. This contributed to increased farm profitability and the overall development of regional economies, which in turn strengthened the resilience of the agricultural sector to crises.

The process of restoring agricultural infrastructure was accompanied by significant financial difficulties, which complicated the implementation of restoration projects. As noted by V. Jakupec (2024), the financial assistance provided by the Western Alliance is an important aspect of this process, but it still does not meet all the Ukrainian needs. The author emphasises that although international assistance is being provided, the lack of sufficient funding, exhaustion of previous resources and shortages of funds remain significant obstacles to recovery. In addition, international economic confidence in Ukraine, which was one of the most economically vulnerable and corrupt countries in Europe before the war, makes it difficult to attract the necessary financial resources for reconstruction. Therefore, international support and cooperation remain essential for effective infrastructure reconstruction. The financial deficit remained one of the key factors hindering the agricultural recovery process. Despite government support and international investment, the amount of funds needed far exceeded the available resources. The lack of funding affected the pace of reconstruction of production facilities, renewal of agricultural machinery, and modernisation of logistics systems. The assessment of the financing gap determined the scale of the problem and outlined the main factors that impeded the effective recovery of the industry. Figure 4 illustrates the fluctuations in the financing deficit from 2020 to 2024, together with the primary economic causes that contributed to the deficiency of financial resources (Ministry of Finance of Ukraine, Kyiv School of Economics (KSE)).

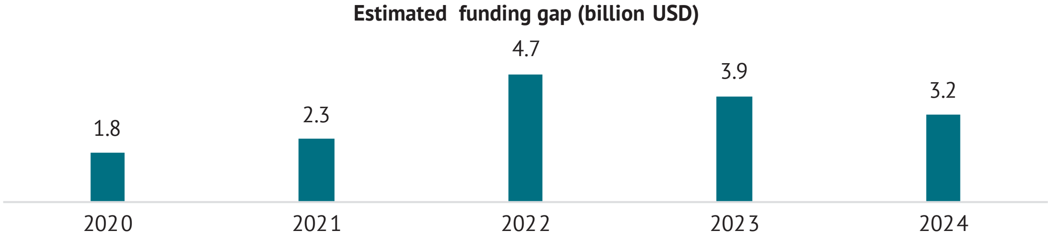

Figure 4. *Changes in the financing gap in 2020-2024*
Source: *Ministry of Agrarian Policy and Food of Ukraine (n.d.), World Bank Group (2022)*

The dynamics of the fiscal deficit exhibited notable volatility, reflecting the influence of endogenous and exogenous variables. During periods of crisis aggravation, the gap between financing needs and available resources grew, driven by a reduction in government support, economic instability, and increased spending on infrastructure reconstruction. Although international financial assistance partially compensated for the shortfall in resources, private investment remained limited due to high risks in agricultural production. The change in the nature of the financial deficit denoted a shift from the immediate restoration of agricultural infrastructure to addressing more complex challenges related to the long-term development of agricultural production. The main problems included not only the restoration of damaged production facilities, but also the need to modernise them, adapt the agricultural sector to climate change, and introduce modern technologies that would increase productivity and resource efficiency.

The destruction of the agricultural infrastructure had not only economic but also significant social consequences, leading to an outflow of rural population from the affected regions. The loss of jobs in the agricultural sector, the destruction of housing infrastructure and limited access to basic services forced some people to migrate to other regions in search of more stable living conditions. In some regions, this process has reached critical proportions, significantly changed the demographic situation and complicated the further recovery of agricultural production. Table 5 demonstrated the dynamics of migration processes due to the destruction of agricultural infrastructure, as well as the main factors that influenced the movement of the rural population.

Table 5. *The number of rural residents who left the regions due to the destruction of agricultural infrastructure*

Year	Population that left the regions (thousand people)	The main reasons for migration
2020	25	Job losses in the agricultural sector
2021	40	Deteriorating agricultural conditions
2022	120	Destruction of residential and industrial infrastructure
2023	95	Limited access to financial resources
2024	80	Lack of social infrastructure and medical services

Note: *the data covers the most affected regions of Ukraine, including Kharkiv, Donetsk, Luhansk, Zaporizhzhia, Kherson and Mykolaiv, where the fighting and destruction of agricultural infrastructure have caused a massive outflow of rural population. The highest level of migration was recorded in 2022, when a significant part of the population moved to safer regions, in particular Vinnytsia, Lviv, Ivano-Frankivsk and Ternopil regions. The main reasons for leaving were the destruction of production facilities, reduced employment in the agricultural sector, limited access to financial resources and a lack of social infrastructure*
Source: *State Statistics Service of Ukraine (n.d.), World Bank Group (2022), United States Agency for International Development (n.d.)*

The data demonstrated a change in internal migration trends, which depended on the extent of damage to agricultural infrastructure and the level of government support for the affected regions. During periods of crisis exacerbation, a large part of the rural population was forced to leave their homes because they could not continue their agricultural activities. At the same time, migration processes were not uniform: the largest outflows occurred during periods of active hostilities, after which there was a gradual slowdown in the rate of departure. The decline in the rural population created additional challenges for regional development. The loss of labour resources had a negative impact on the pace of agricultural infrastructure recovery, as the return of IDPs depended on the speed of reconstruction of housing and production facilities, access to social services, and employment opportunities in the agricultural sector. This underscores the necessity for a holistic strategy to assist rural regions, encompassing measures to promote population repatriation and secure sustainable prospects for agricultural economic development. In this context, M. González-Leonardo *et al.* (2024) highlighted the importance of considering potential refugee settlement areas, as migration and displacement can significantly affect local populations and resources. In particular, the study shows that in Ukraine there is a high concentration of refugees in urban areas with previous diasporas, which can put additional pressure on infrastructure and the labour market in host regions, including rural areas where partial refugee settlements are taking place. These aspects are relevant in the proper allocation of resources and humanitarian assistance.

The recovery of the agricultural sector after the large-scale destruction required significant investments in technical and human resources. A lack of modern equipment, a shortage of skilled labour and the need to modernise production facilities hampered the recovery process. Providing the industry with adequate resources was crucial to the recovery of agricultural production, increasing its productivity and competitiveness. An assessment of the needs for technical equipment and the involvement of specialists helped to identify key priorities for recovery measures aimed at stabilising the agricultural sector. Table 6 demonstrated the change in the needs for financing technical support and labour in 2020-2024, as well as the main areas of recovery in the industry.

Table 6*. Assessment of technical and human resource needs for sector recovery*

Year	Need for technical support (billion USD)	Demand for qualified personnel (thousand people)	Key areas of restoration
2020	1.2	20	Procurement of agricultural machinery
2021	1.5	25	Repair and construction of irrigation systems
2022	3.8	50	Restoring the infrastructure of agricultural enterprises
2023	3.2	45	Education and training of specialists in the field of agricultural technology
2024	2.9	40	The mechanisation of small farms

Source: *State Statistics Service of Ukraine (n.d.), Ministry of Finance of Ukraine (n.d.), World Bank Group (2022)*

The data demonstrated an increased need for technical support and skilled personnel during the period of active destruction of agricultural infrastructure. The fiscal exigencies reached their apex in 2022, during which time a substantial proportion of manufacturing infrastructure sustained damage or destruction, necessitating immediate capital allocation for equipment restoration and agricultural machinery replacement. This period represented an unprecedented convergence of infrastructural deterioration and consequent financial strain, as organisations were compelled to divert significant resources toward rehabilitating their operational capabilities. In the same period, the need for skilled personnel increased, which was a consequence of mass migration and a shortage of specialists in agricultural production.

The gradual decline in financial needs in 2023-2024 reflected the stabilisation of the situation and the effectiveness of investment attraction measures. At the same time, recovery priorities have changed: while the initial focus was on technical re-equipment and infrastructure rebuilding, in subsequent years, significant attention was paid to the development of agricultural education, retraining, and the introduction of modern agricultural technologies. According to M. Nehrey and R. Finger (2024), the Ukrainian government has implemented several measures, such as deregulation, lower input prices, and improved logistics, which have contributed to the adaptation of the sector to the new conditions and accelerated its recovery. However, as demonstrated by A.M. Countryman *et al.* (2024), the economic impact of the war, including disruptions in agricultural exports, has had a significant impact on the global market, which has complicated economic stability and food supplies worldwide. Given these global challenges, it was necessary to introduce a comprehensive approach to the recovery of the agricultural sector, combining not only logistical support but also the training of qualified personnel to ensure the sustainable development of agricultural production.

The results of the study demonstrated that the Russian full-scale invasion of Ukraine caused a deep crisis in the agricultural sector, which manifested itself in large-scale destruction of infrastructure, disruption of production processes and reduced access to markets. Significant destruction of the transport network and logistics centres became the main barriers to ensuring the stability of the food chain. The agricultural land situation, which had suffered significant damage as a result of the hostilities, mining and soil degradation, required special attention. Restoring agricultural production became a critical task for the state and international partners, as it directly affected the food security of not only Ukraine but also other countries that depend on Ukrainian exports (Zakharchenko *et al.*, 2020). The rebuilding of agricultural infrastructure occurred in an environment of limited financial resources and a shortage of skilled labour, which made it difficult to quickly restore production capacity. Despite the active involvement of international donors and government support, the recovery remained uneven, as the security situation and investment risks constrained active private capital. The cooperative movement, volunteer initiatives, and local communities played a key role in mobilising resources to meet the basic needs of the agricultural sector. At the same time, the recovery process required not only financing but also technological upgrades and adaptation to new economic realities, which required long-term strategic approaches.

The alterations in job dynamics and migration trends resulting from the war significantly influenced the subsequent evolution of the agricultural industry. The loss of labour resources and the outflow of skilled professionals created additional challenges for the sector's recovery, as the return of the population directly depended on the pace of rebuilding housing and social infrastructure. In the context of post-war recovery, a comprehensive approach to agricultural production became crucial, which included not only the physical restoration of damaged facilities but also the promotion of innovation, the creation of new jobs and the integration of the agricultural sector into global economic processes.

DISCUSSION

A critical analysis of the results showed that despite significant efforts to restore the agricultural sector, the amount of financial resources and investments attracted was not sufficient to ensure comprehensive modernisation. Statistics on the restoration of infrastructure and land show that although almost 57% of infrastructure losses were compensated by the end of 2024, the pace of recovery remained uneven. In some regions, there remained a high concentration of damage, requiring the identification of priority areas for financing and the implementation of governance changes, including improving mechanisms for attracting international assistance and developing effective strategies for attracting private capital. The findings of this analysis can be used for further research and development of targeted measures to strengthen the economic resilience of the agricultural sector.

The study also demonstrated that in 2022, the financing gap in the agricultural sector exceeded USD 3.8 billion, which significantly limited the ability to modernise production facilities, as high risk and lack of sufficient private capital made it difficult to implement recovery measures. This deficit hindered the integration of new technologies and the restoration of damaged infrastructure, which had a particularly negative impact on production efficiency in the agricultural sector. L. Lipper *et al.* (2021) highlighted the importance of blended finance, which includes both public and private investment, as well as support from multilateral development banks. This approach ensured access to affordable investment mechanisms, facilitating both private capital and international funds. This ensures the necessary adaptation of agricultural systems to climate change, which is important for sustainable development. A comparison of the study's results with international statistics indicated that the utilisation of blended finance significantly enhanced the sustainability of agricultural production. The availability of an adequate level of resources and adaptive measures has become a key factor in ensuring the successful transformation of the industry, particularly in the face of a changing climate and an unstable economic situation (Zuo *et al.*, 2024).

Other results are consistent with the findings of A. Elechi (2021), confirmed the significant constraints on public resources and the urgent need to attract private capital for the recovery of the agricultural sector, which was complicated by imperfect financial infrastructure and high investment risks. The study of the role of public-private partnerships (PPPs) demonstrated that this mechanism can significantly improve the resilience of the economy during the recovery period, as well as accelerate the implementation of large infrastructure projects, which is important for the stability. A comparison of research results has confirmed that the use of PPPs not only helps to compensate for the shortage of public funding but also helps to attract additional investments needed for infrastructure reconstruction. As a result of this process, the effectiveness of management and regulatory instruments is increasing, ensuring transparency of financial transactions and facilitating access to resources.

According to M. Malik *et al.* (2023), the creation of favourable legal and financial mechanisms, such as tax incentives and grant programmes, is necessary to ensure stable food production in times of crisis. A comparison of the results with other regions shows that support for entrepreneurship, including through tax optimisation and state aid, has fostered agribusiness initiatives at the regional level, helping to preserve local production and support employment in rural areas. Successful examples of similar mechanisms in other countries confirm the effectiveness of such measures in supporting the agricultural sector in times of economic and political instability, ensuring not only the restoration of production capacity but also the long-term sustainability of the sector in the post-war period. The problem of ensuring reliable supply chains in the context of military conflicts is critical for the agricultural sector, as noted by T.G. Bas (2025). The destabilisation of logistics channels increases the risk of food insecurity, which in turn can lead to a food crisis both domestically and abroad if export supplies are disrupted. To stabilise the sector, it is necessary to apply balanced approaches that combine global and local supply mechanisms. The creation of efficient logistics networks tailored to regional specifics will reduce dependence on monopolistic supply chains and ensure a more flexible and adaptive system that can respond quickly to changing conditions (Cherniavskyi, 2025). Comparisons with other countries that have faced similar challenges during military conflicts or global crises confirm the importance of developing local supply chains to ensure food security at the national level.

According to O. Shpykuliak *et al.* (2024), small agricultural entrepreneurship is key to maintaining food security and preserving jobs in rural areas. Statistics show that small farms have demonstrated high adaptability even in the face of limited access to financial resources, which confirms their ability to survive and continue production despite economic difficulties. This underscores the importance of small business development for the stabilisation of the agricultural sector, as these farms are the backbone of the rural economy and can adapt quickly to changing conditions. Small-scale agricultural enterprises serve a dual function of enhancing local food security while simultaneously generating employment opportunities – a critical factor for maintaining social cohesion in conflict-affected regions (Berdar *et al.*, 2024). The cultivation of agricultural entrepreneurship at the small-scale level potentially constitutes a foundation for an economic framework characterised by resilience, capable of withstanding systemic shocks and facilitating sustainable agricultural development throughout the post-conflict reconstruction phase.

The active participation of local communities in the rehabilitation of agricultural infrastructure has also proved to be important, as noted by F. Treffers (2023). The introduction of participatory planning methods, in which local communities are actively involved in setting recovery priorities, ensures a more efficient allocation of limited resources and targeting of the most important projects for local conditions. This approach contributes not only to the rational use of finances but also to the transparency of management processes. In addition, participatory planning methods contribute to strengthening social cohesion, as they involve the broad involvement of non-government organisations, farmers and local businesses. This ensures sustainable development, as communities are empowered to set in-house recovery priorities, which contributes to a more efficient and rapid recovery of agricultural infrastructure adapted to local needs and realities.

The increased economic instability and the negative impact on natural capital emphasise the need to develop comprehensive approaches to economic recovery, as outlined by O. Hrynevych *et al.* (2024). A comparison of data on the destruction and reduction of production potential confirmed the importance of the agricultural sector as a driving force for the country›s economy. At the same time, the crisis in the agricultural sector underscores the need to integrate social and environmental policies into the recovery strategy, which will ensure simultaneously addressing the issues of economic stabilisation and environmental conservation. Implementation of such strategies, which incorporate both economic and environmental aspects, is critical to ensure sustainable development and increase resilience to future crises. Only a comprehensive approach that integrates economic, social and environmental interests can ensure effective rehabilitation of agricultural infrastructure and maintain social stability in rural areas (Poltorak *et al.*, 2024).

E. Sheludko and M. Zavgorodnia (2022) identified the need to strengthen knowledge-intensive industries, which is crucial for the recovery of the agricultural sector and ensuring its technological development. Comparative analysis with other sectors revealed that revitalising industrial potential fosters job creation and stabilises agricultural output by facilitating technical advancements and enhancing production capabilities. The development of knowledge-intensive industries, such as agro-technologies, increases productivity and resource efficiency in the agricultural sector, which is a prerequisite for adapting to modern challenges, including climate change (Dankevych *et al.*, 2024). Restoring industrial capacity, including through investments in modern technologies and infrastructure, should be one of the key areas of recovery, as it not only stimulates economic development but also ensures the long-term stability of agricultural production, which is essential for food security. The importance of developing detailed local recovery programmes was also confirmed by M. Savytskyi *et al.* (2024), emphasising the need for close coordination with local authorities to effectively restore rural areas and ensure their resilience to future crises. Only through effective cooperation with local communities can not only rapid recovery be achieved but also strengthen social and economic stability in rural areas. Coordination with local authorities ensures a more precise and responsive response to the needs of specific areas, ensuring resilience to possible future economic or environmental challenges (Zibtsev *et al.*, 2024). Such local programmes should incorporate all aspects of recovery, from infrastructure projects to social and economic initiatives, which increases the effectiveness of agricultural recovery.

The analysis of the survey results showed that despite significant efforts to restore the agricultural sector, financial resources and investments were insufficient for comprehensive modernisation. The uneven pace of recovery, high concentration of damage in certain regions, and limited public resources point to the need to attract private capital and improve financing mechanisms. The high level of risks and the unstable economic situation make it difficult to attract private investment, and it is, therefore, important to improve regulatory mechanisms to ensure transparency and reduce risks for investors. The development of small farms, the active participation of local communities in the recovery, and the use of public-private partnerships have proven to be important factors in stabilising the agricultural sector. This approach not only helps to increase access to financial resources but also stimulates social activity, ensuring the sustainable development of the regions. Comparison with international studies has confirmed the universality of approaches aimed at innovation, coordination and adaptation to new economic realities, which is essential for the successful recovery of the agricultural sector in the post-conflict period.

CONCLUSIONS

The study assessed the impact of the Russian full-scale invasion on the Ukrainian agricultural sector, highlighting the role of local communities in the recovery process. The research novelty is determined by a comprehensive analysis of the mechanisms of financing the reconstruction of agricultural infrastructure, changes in investment dynamics, the role of the cooperative movement, the impact of migration processes and the prospects for modernising agricultural production. The use of data from government agencies, international organisations and the private sector determined the effectiveness of reconstruction measures and identified the main factors that determined the resilience to crisis phenomena. The analysis of the damage to agricultural infrastructure showed a significant reduction in production capacity and transport capabilities, which made it difficult for the agricultural sector to function. It was found that 2,750 of the 4,800 destroyed agricultural infrastructure facilities were restored, and 1.8 million hectares of damaged agricultural land were restored. The main challenges remained rising logistical costs, limited access to markets and a 15% reduction in employment in the agricultural sector. The survey results confirmed that local communities were key in the recovery process by coordinating repairs, allocating financial resources and attracting international assistance.

An analysis of the dynamics of financing showed significant fluctuations in the structure of investments. In 2022, private investment declined to USD 600 million, driven by rising security risks and economic instability. Starting in 2023, there was a gradual recovery in investment in infrastructure and production facilities. It was found that the international programmes of FAO and USAID contributed to the expansion of agricultural cooperatives and provided them with financial support. A comparative analysis of the experience of Iraq, Afghanistan, Colombia, Bosnia and Herzegovina, and Rwanda showed the effectiveness of mixed models of financing and institutional coordination that can be adapted in the Ukrainian context to accelerate the recovery. Analysis of migration processes demonstrated that the destruction of agricultural infrastructure has led to a significant outflow of the rural population, especially in 2022, when the number of displaced persons from rural areas reached 120,000. This has complicated the process of restoring agricultural production and necessitated the development of programmes for professional retraining, employment promotion, and the return of workers to the sector. The study's findings proposed multiple measures to expedite the revival of the agricultural sector. It is advisable to expand state and international programmes to support local communities in restoring agricultural infrastructure, which involves creating financial incentives to attract private investors. The development of public-private partnerships could help accelerate the reconstruction of logistics networks, modernise processing enterprises, and increase the competitiveness. In addition, there is a need to expand programmes to improve skills and return labour to the affected regions through professional retraining, tax incentives and loan programmes for small and medium-sized farms.

Further research is warranted to evaluate the longitudinal socio-economic implications of agricultural infrastructure restoration, with particular emphasis on the influence of technological innovation on sectoral productivity metrics. An additional avenue of scholarly inquiry concerns the efficacy analysis of cooperative organisational frameworks in post-conflict economic rehabilitation, which may yield valuable insights regarding optimal developmental strategies for small and medium agricultural enterprises. Moreover, a comparative examination of international precedents in agricultural reconstruction during periods of systemic disruption is recommended, as the subsequent adaptation of evidence-based methodologies to the Ukrainian context could potentially enhance the sector's capacity to withstand future perturbations.

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CONFLICT OF INTEREST

None.

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Роль місцевих громад у відновленні аграрної інфраструктури після руйнувань

Альона Ключник
Доктор економічних наук, професор
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-6012-6666
Наталія Шишпанова
Кандидат економічних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-8347-5682
Людмила Прогонюк
Кандидат юридичних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0003-0376-5079
Наталія Галунець
Старший викладач
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-7709-9238
Анжела Гусенко
Старший викладач
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-3989-2400

Анотація. Дослідження мало на меті оцінити ефективність фінансових, організаційних та управлінських механізмів відновлення аграрної інфраструктури в Україні у період 2022-2024 років. Аналіз охопив соціально-економічні передумови розвитку аграрного сектору до активної фази бойових дій, а також їхній вплив на руйнування виробничих потужностей, земельних ресурсів і логістичної системи. Було встановлено, що внаслідок бойових дій зруйновано 4,800 об'єктів аграрної інфраструктури, пошкоджено 3,2 млн га угідь, зруйновано 12,500 км автошляхів, а рівень зайнятості в аграрному секторі скоротився на 15 %. До кінця 2024 року вдалося відновити 2,750 об'єктів (57 %), повернути до обробітку 1,8 млн га земель та відремонтувати 7,300 км доріг. Обсяг дефіциту фінансування у 2022 році становив понад 3,8 млрд доларів США, що унеможливлювало своєчасну модернізацію виробничих потужностей. Приватні інвестиції, які знизилися у 2022 році до 600 млн доларів, почали зростати лише у 2023-2024 роках, досягнувши 950 млн доларів. У цей самий період краудфандингове фінансування становило понад 33 млн доларів, з яких найбільша частка спрямовувалася на модернізацію систем зрошення (9,1 млн доларів у 2024 році). Водночас кооперативний сектор відновив 65 господарств у 2024 році, забезпечивши понад 21 млн доларів економічного внеску. Волонтерські ініціативи також продемонстрували зростання, підтримуючи дрібні фермерські господарства та відновлення критичної інфраструктури. Попри це, міграція понад 120 тис. осіб із сільських регіонів, особливо у 2022 році, суттєво зменшила трудовий потенціал аграрного сектору. Отримані результати підтвердили, що для повноцінної реконструкції аграрної інфраструктури необхідно залучити додаткові фінансові ресурси, ефективно використовувати механізми державно-приватного партнерства та стимулювати повернення трудових ресурсів. Практичне значення роботи полягає у формуванні основи для вдосконалення інвестиційної політики в аграрному секторі та підвищення ефективності координації між місцевими громадами, державними інституціями та міжнародними донорами

Ключові слова: сільське господарство; інвестиційні проекти; фінансова підтримка; кооперативні ініціативи; міжнародна допомога; процеси відновлення; громади

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Видавництво: Поліський національний університет
10008, б-р Старий, 7, м. Житомир, Україна
Тел. (0412) 22-04-17
E-mail: info@sciencehorizon.com.ua
https://sciencehorizon.com.ua

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