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Bio-ecological characteristics of *Malus* genus species in the context of prospective directions in horticulture and landscape forestry

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Abstract. The study aimed to conduct a comparative assessment of representatives of the genus *Malus* based on morphological traits, biological characteristics, physiological mechanisms of resistance to fungal pathogens, ornamental value, and significance within the frameworks of horticulture, landscape forestry, and shelterbelt afforestation. Employing an integrative approach, the research examined the morphological traits and biological characteristics of domestic apple, European

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wild apple, Siberian crab apple, hybrid crab apple, and plum-leaved apple. Comparative analysis was carried out to evaluate the susceptibility and resistance of these species to scab pathogens and other diseases. The findings indicated that the domestic apple is characterised by large fruit size, with an average fruit mass of no less than 150 g. In contrast, the average fruit mass for Siberian crab apple, cherry crab apple, and hybrid crab apple does not exceed 0.7 g, 1.8 g, and 3.2 g, respectively. The authors have developed an integrated scale for the comparative evaluation of *Malus* species (or crab apple varieties) based on overall ornamental value. This scale included five criteria: crown appearance, leaf aesthetics, floral attractiveness, fruit visual appeal, and resistance to apple scab. For the first time, fruits of different *Malus* species have been analysed for seed productivity. Among these, crab apple varieties, particularly the European wild apple and the plumleaved apple, were identified as having the highest average number of seeds per fruit – 10 and 8 seeds, respectively. It was also shown that the seeds of the wild apple are relatively large, with the 100-seed weight exceeding 3.9 g. The study highlighted findings that confirm the ornamental value of certain *Malus* species, notably the Siberian crab apple and the hybrid crab apple, which received the highest overall ornamental scores of 4.5 and 5. This contrasts with the European wild apple, cherry apple, and domestic apple, which scored lower for ornamental attributes (3.2-3.9). It was noted that crab apple species such as *Malus sylvestris* (L.) Mill. and *Malus baccata* (L.) Borkh. are well-suited for use in the creation of forest-park landscapes. Under the conditions of the Northern Forest-Steppe of Ukraine, *Malus* species were differentiated by their resistance to the scab pathogen (*Venturia inaequalis* Cooke). The results established that domestic apple (cultivar Dozhnytsia), hybrid crab apple, and plum-leaved apple exhibited high resistance to this pathogen, which affects both foliage and fruit. The practical application of these findings lies in enriching the informational database on *Malus* species with updated data, enabling their utilisation in various thematic studies

Keywords: *Malus*; morphology; plant physiology; resistance to phytopathogens; comparative evaluation

INTRODUCTION

The rational utilisation, introduction, and preservation of fruit and ornamental plant species, particularly those belonging to the genus *Malus* L., is a pressing issue in modern fruit and ornamental horticulture. Apple orchards have traditionally held not only practical but also aesthetic value. Apple trees possess a wide range of adaptive traits, including high winter hardiness, frost resistance, and drought tolerance, and are also prized for their ornamental qualities. These qualities contribute significantly to human psychological and emotional well-being and create visually pleasing, harmonious, and aesthetically appealing environments. However, like all plant species, apple trees are susceptible to a variety of fungal, bacterial, and viral diseases that can negatively impact yield, aesthetic quality, and the lifespan of orchards. As reported by P. Abbasi *et al.* (2019) and S. Nabi *et al.* (2023), one of the most dangerous diseases affecting apple trees is scab (caused by the fungus *Venturia inaequalis* (Cooke) Winter), as well as powdery mildew (caused by the sac fungus *Podosphaera leucotricha* Salm) and fruit rot or moniliosis (caused by *Monilinia fructicola* (G. Winter) Honey). Diseases such as crown gall, caused by the gram-negative bacterium *Agrobacterium tumefaciens* Stevens, and powdery mildew can significantly reduce apple yields by up to 50% or more. Powdery mildew infections are particularly problematic due to their chronic nature, which can reduce not only the current but also future yields of an orchard. Despite the wide range of apple diseases, scab and fruit rot remain the most commercially significant diseases worldwide.

As noted by R. Spengler (2019) and E. Greaves and B. Husband (2022), many species and hybrids of the genus *Malus*, such as *Malus baccata* (L.) Borkh., *Malus prunifolia* (Willd.) Borkh., *Malus sieversii* (Ledeb.) Borkh., *Malus baccata* (L.) Borkh., *Malus prunifolia* (Willd.) Borkh., *Malus sieversii* (Ledeb.) Borkh., *Malus sylvestris* (L.) Mill., *Malus praecox* (Pall.) Borkh., *Malus domestica* (Borkh.) Borkh., *Malus* × *domestica* × *Malus sieversii*, are capable of hybridisation. This capability allows for the creation of a diverse range of hybrid materials with promising applications in horticulture and landscape forestry. While the primary purpose of apple trees is fruit production, as highlighted by J. Ji *et al.* (2021), certain species are cultivated for their ornamental value. These are often referred to as flowering or ornamental apples. However, species and cultivars that combine both fruit production and ornamental qualities, such as high disease resistance and attractive growth habits, flowers, leaves, and fruits, are particularly valuable.

In the context of global climate change, the domestic apple remains a primary fruit crop worldwide, including Ukraine. As of 1 January 2023, apple orchards in Ukraine covered an area of 95,100 hectares, with a total fruit production of 1.17 million tonnes (FAO, 2023). According to C. Bragard *et al.* (2021) and Y. Khajuria *et al.* (2022), there is a continuous need for new theoretical knowledge regarding the domestic apple, particularly concerning its biometric and morphometric characteristics, such as fruit quality, yield, and resistance to fungal pathogens.

The genus *Malus* Mill. comprises approximately 36 species and 4 hybrids (although some sources suggest

closer to 70), which are classified as small, deciduous trees or shrubs within the rose family (*Rosaceae* Juss.). Apple trees of summer and autumn cultivars exhibit a wide range of adaptive traits, tolerating significant temperature drops in air temperature to as low as -30 to -40°C. Notably, as A. Cebulj *et al.* (2022) have observed, apple cultivars grafted onto seedling rootstocks exhibit higher frost resistance compared to those grafted onto clonal rootstocks. Additionally, D. Gómez-Candón *et al.* (2022) have highlighted the high drought tolerance of apple trees, enabling their cultivation in arid southern regions. A. Arabzada and A. Sadigov (2023), and M. Hardie *et al.* (2024) have noted that most apple species can thrive in various soil types, although soils with shallow groundwater tables, deep sands, or stony compositions are less suitable. Breeding programs focused on the genetic diversity of the genus *Malus* Mill. (1768), agricultural traits such as yield, fruit quality (both quantitative and qualitative), and resistance to fungal diseases are prioritised. Despite their high vitality, apple trees are vulnerable to adverse abiotic and biotic environmental factors (Woodall *et al.*, 2023). The authors propose a method for evaluating the ornamental value of plants on a seasonal basis. Each ornamental feature is assessed visually using a 4-12-point scale, and various coefficients are suggested to determine the significance of each specific feature, taking into account its degree of expression. Common criteria for evaluating ornamental value include: the architecture of the trunk and crown, crown shape, bark colour, leaf (or needle) size and colour, leaf vitality, flower and inflorescence size and colour, duration of flowering, attractiveness

of fruits and inflorescences, fruit and inflorescence retention, fragrance, and three indicators of plant vitality (damage) and natural growing conditions (winter hardiness, frost resistance).

Despite existing approaches to assessing the ornamental value of certain woody plants, there remains a gap in knowledge regarding a comprehensive approach to evaluating the aesthetic qualities and resistance of various apple species and cultivars to adverse abiotic and biotic environmental factors. This gap defined the aim and objectives of the current research. Therefore, the aim of this study was to evaluate representatives of the genus *Malus* based on a complex of morphological features and bioecological characteristics, which are important for the future development of horticulture and landscape forestry.

MATERIALS AND METHODS

The research was conducted at the experimental field of the Laboratory of Breeding and Technology of Growing Berry Crops at the Institute of Horticulture of the National Academy of Agrarian Sciences of Ukraine (Northern Forest-Steppe of Ukraine, Kyiv) during 2017-2021. The experimental plot is characterised by a moderately warm and insufficiently moist climate. The hydrothermal coefficient (HTC) ranges from 1.8 to 2.1. Notably, approximately 70% of precipitation occurs during the warm period of the year, while 30% falls during the cold period. Based on personal observations and data from the Hydrometeorological Service, the key climatic parameters for the research area at the Institute of Horticulture of NAAS are presented in Table 1.

Table 1. Long-term average climatic parameters for the village of Novosilky, Fastiv District, Kyiv Region

Indicator	Value
Sum of active temperatures, t°C	2,671-2,695
Sum of effective temperatures > 5°C	1,949-2,059
Average annual air temperature, t°C	6.7-7.0
Minimum air temperature, t°C	-34.5
Maximum air temperature, t°C	+38.0
Frost-free period duration, days	141-146
Date of autumn frosts	8-11 October
Date of last spring frosts	23-25 April
Average soil freezing depth, cm	56
Annual precipitation, mm	581-634
Precipitation during the growing period, mm	368-425
Duration of snow cover, days	87-90
Average maximum snow cover depth, cm	14-15
Vegetation period duration, days	199-205
Predominant wind direction	North-western

Source: developed by the authors

The terrain of the research area is a gently undulating plain. The soil is classified as dark grey, podzolized, medium loamy on carbonate loess, typical of the northern part of Ukraine's Forest-Steppe zone. The agrochemical properties of the soil are as follows:

humus content in the arable layer (0-40 cm) is 2.3%, easily hydrolysable nitrogen is 78.4-98.0 mg/kg, mobile phosphorus forms are 93.2-180.9 mg/kg and exchangeable potassium ranges from 106.1 to 202.8 mg/kg. The soil's pH is heterogeneous, ranging from 5.3 to 6.0. The

physical and hydrological characteristics indicate a ratio of physical sand to physical clay of 69:31, with groundwater located at a depth of 56 metres. The analysis of weather conditions began with an assessment of apple tree conditions in the experiments. In October 2020, the air temperature averaged 9.4°C, exceeding the long-term average by 1.4°C. Precipitation during the first and third decades of October amounted to 58 mm, 26 mm more than the long-term average. November was also warmer, with an average temperature of 1.5°C above the long-term norm. Total precipitation for these autumn months reached 104.8 mm, exceeding the long-term average by 28.4 mm. Spring 2021 commenced in the third decade of March, marked by rising temperatures in April and May, reaching 18.9°C, which was 7.9°C higher than the long-term average. Total precipitation during this period amounted to 105.2 mm,

62.2 mm above the climatic norm. The coldest month of 2021 was January, with minimum temperatures as low as -13.2°C. May and June experienced substantial rainfall. Over the course of the year, total precipitation reached 521 mm, constituting 80% of the climatic norm.

The resumption of vegetation in 2021 and the timing of the onset of the fruits' technical ripeness were observed to occur 14-16 days later compared to 2019 and 2020. The flowering phase of apple trees was recorded during the second decade of May when the threat of spring frosts had passed, and sunny weather prevailed. Consequently, the fruit set percentage was high. The weather conditions in 2019 and 2020 were more conducive to the development of apple scab compared to 2021. Therefore, it was reasonable to compare years with more contrasting weather conditions (Table 2).

Table 2. Temperature regime during the growing season of apple trees in years with the most contrasting weather conditions

Year	Indicator	Month of the year					
		April	May	June	July	August	September
2020	t, °C	9.7	12.5	22.4	22.1	21.8	14.8
	Σo, mm	28.4	106.4	46.5	47.6	19.0	48.2
	HTP	1.76	1.40	1.61	2.67	3.51	1.11
2021	t, °C	8.7	14.1	21.8	21.7	22.3	21.8
	Σo, mm	46.3	53.9	76.0	35.4	20.3	16.4
	HTP	0.83	0.85	1.92	2.78	2.95	1.09
Long-term average	t, °C	7.8	14.9	18.3	19.3	18.6	22.2
	Σo, mm	49.1	53.3	70.9	88.9	24.3	39.8
	HTP	1.05	0.90	2.07	2.99	3.27	1.78

Note: t, °C – average monthly air temperature, Σo – monthly precipitation, HTP – hydrothermal potential

Source: developed by the authors

The study included various species of the genus *Malus* (European wild apple, Siberian crab apple, plum-leaved apple, hybrid crab apple, cherry crab apple, and three cultivars of *Malus domestica* Borkh. of Ukrainian and American selection: Reinette Symyrenko,

Dozhnytsia, and Jonagold) located in different sites, including an experimental field and the territory of the village of Novosilky. These plants were studied for their morphological characteristics and physiological properties during 2020-2021 (Fig. 1).

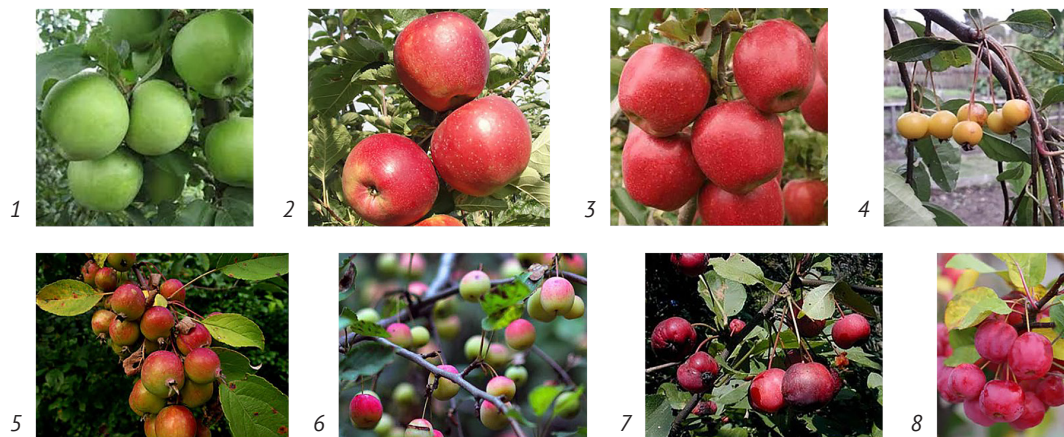


Figure 1. Species diversity of *Malus* representatives involved in the study

Note: 1 – Reinette Symyrenko, 2 – Dozhnytsia, 3 – Jonagold (*Malus domestica* Borkh.); 4 – Siberian crab apple (*Malus baccata* (L.) Borkh.); 5 – European wild apple (*Malus silvestris* (L.) Mill.); 6 – cherry crab apple (*Malus cerasifera* Spach.); 7 – plum-leaved apple (*Malus prunifolia* (Willd.) Borkh.); 8 – hybrid crab apple (*Malus hybridus* (Red Sentinel))

Source: compiled by the authors

It should be noted that the studied apple species (cultivars) have North American, European, and Asian origins (Table 3).

Phenological observations were conducted according to the methodology of S. Tkachuk (2016). Biometric parameters of apple trees (trunk height, crown diameter, number of skeletal branches, leaf, fruit, and seed parameters, fruit yield) were determined according to B. Hulko (2020). The assessment of apple tree resistance

to adverse biotic environmental factors was conducted according to (Methodology of phytopathological studies, 2017). Specifically, the incidence of apple scab on blossoms and ovaries was recorded in May and June, on leaves throughout July and August, and on fruits during harvest (depending on the maturity group of the studied plant). For each apple species (cultivar), 100 fruits were collected from four opposite sides of several trees and evaluated according to the scale (Table 4).

Table 3. Origin of *Malus* species and cultivars

No.	Species (Cultivar)	Geographic origin	Genetic origin	Chromosome count
1	<i>Malus baccata</i> (L.) Borkh.	Asia (China)	Not determined	2n = 34
2	<i>Malus prunifolia</i> (Willd.) Borkh.	Asia (Northern China)	Not determined	2n = 34
3	<i>Malus cerasifera</i> Spach.	Asia (Japan)	Not determined	2n = 34
4	<i>Malus hybridus</i> (Red Sentinel)	Central Asia	Not determined	2n = 34
5	<i>Malus silvestris</i> (L.) Mill.	Europe	Not determined	2n = 34
6	<i>Malus domestica</i> Borkh. (Reinette Symyrenko)	Europe (Ukraine)	Seedling of the Wood's Greening variety	2n = 34
7	<i>Malus domestica</i> Borkh. (Jonagold)	North America	♀Jonathan × ♂Golden Delicious	2n = 47
8	<i>Malus domestica</i> Borkh. (Dozhnytsia)	Europe (Ukraine)	♀Rubin Duky × ♂Florina	2n = 34

Source: compiled by the authors

Table 4. Scale for assessment of apple plant infection by scab

Degree of scab infection on leaves and fruits	Scab spot coverage on leaves and fruits, %	Resistance score
Absent	0	0
Very weak	Up to 5	1
Weak	Up to 15	2
Moderate	Up to 30	3
Severe	Up to 50	4
Very severe	Over 50	5

Source: Methodology of phytopathological studies... (2017)

The conducted assessments allowed for the calculation of the number of infected plant parts (leaves, fruits, etc.) in a specific experimental variant and the calculation of the average infection score for a species (cultivar). This was done by multiplying, for example, the number of fruits by the corresponding infection score. The obtained results were summed and divided by the total number of infected fruits. The assessment of plant ornamentality was performed according to S. Tkachuk (2016). The evaluation employed a scale based on a scoring system for ornamental value, where

0 points indicate negative ornamental value (lack of attractiveness), and scores range progressively as follows: 1 point – very low (minimal ornamental appeal); 2 points – low (ornamental qualities are noticeable but not pronounced); 3 points – moderate (distinct ornamental features that stand out against the background of other plantings); 4 points – high (above-average attractiveness); 5 points – very high (exceptional appeal, evoking strong emotional reactions and admiration from observers). The assessment was conducted using five criteria (Table 5).

Table 5. Assessment of ornamental value on a 5-point scale

Scale	Criterion	Scale
I	Ornamental value of the crown	0-5
II	Ornamental value of flowers	0-5
III	Ornamental value of leaves	0-5
IV	Ornamental value of fruits	0-5
V	Resistance to disease agents	0-5

Source: S. Tkachuk (2016)

The reliability of the research results and the degree of variation of the traits were evaluated using MS Excel 2007. 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

It is worth noting that, according to phenological observations for the conditions of the Northern Forest-Steppe of Ukraine, the average onset of sap flow for the studied representatives of the genus *Malus* falls on the third decade of March – the first decade of April, while the

beginning of flowering, depending on the species (cultivar), is on 8-14 May, the end of flowering – on 20-24 May; the onset of technical ripeness of fruits – on the third decade of August - the first and second decades of September; the beginning of leaf fall – on the second half of August (Table 6).

Table 6. Features of the passage of phenophases of apple trees

Species (Cultivar)	Sap flow resumption		Flowering onset		Fruit ripening onset	
	2020	2021	2020	2021	2020	2021
<i>Malus baccata</i> (L.) Borkh.	27 March	04 April	11 May	22 May	08 September	12 September
<i>Malus prunifolia</i> (Willd.) Borkh.	25 March	30 March	07 May	18 May	20 August	25 August
<i>Malus cerasifera</i> Spach.	22 March	28 March	09 May	16 May	25 August	27 August
<i>Malus hybridus</i> (Red Sentinel)	21 March	27 March	12 May	20 May	15 September	20 September
<i>Malus silvestris</i> (L.) Mill.	20 March	25 March	09 May	19 May	10 September	15 September
<i>Malus domestica</i> Borkh. (Reinette Symyrenko)	25 March	27 March	07 May	16 May	28 September	30 September
<i>Malus domestica</i> Borkh. (Jonagold)	22 March	29 March	11 May	18 May	25 September	28 September
<i>Malus domestica</i> Borkh. (Dozhnytsia)	22 March	28 March	12 May	18 May	20 September	22 September

Source: developed by the authors

Experimental trees of the winter variety Dozhnytsia have a spreading habit. The annual shoot has an average number of lenticels, short internodes, moderate pubescence on the peripheral part, is thick, and the bark colour is red-brown (on the sunny side). The leaf blade is deep green, medium in length and width, with a frequently serrated edge. The petiole is medium in length and green with a slight anthocyanin colouration. The flowering phase falls at the end of the first decade - the beginning of the second decade of May. The flower at the bud stage is dark red. The flower diameter is medium, i.e., the petals are spread out, and their arrangement is intermediate. Fruits are formed on short shoots. Young fruits are characterised by a strong anthocyanin colouration (Fig. 2).



Figure 2. Young fruits of the domestic apple cultivar Dozhnytsia

Source: photographed by the authors

The fruits are medium in size, height, and diameter. The calyx lobe is long. The calyx is of medium size. The skin colour is whitish-yellow with a dominant red hue and a continuous blush with weakly distinguished stripes. The bloom on the skin is absent or weak. The area

of russeting around the peduncle, cheeks, and calyx is absent or small. The peduncle is medium in length and thickness. The flesh is firm in texture and cream in colour. Notably, the Dozhnytsia cultivar demonstrates drought resistance (9 points), winter hardiness (8 points), and resistance to powdery mildew and apple scab (8-9 points).

The Reinette Symyrenko cultivar is characterised as a tree with a height of 4.3 m (on rootstock mm 106). The skeletal branches of the lower tier are strong and diverge from the trunk at an angle of about 60°, while the branches of the upper tier are almost at a right angle. The bark of the skeletal branches and the trunk is dark grey. Biometric analysis of shoots, leaves, and fruits revealed that the shoots are straight, of medium thickness, with green-brown bark covered with small, few lenticels. The annual shoot growth is 40-60 cm. The leaves are glossy, finely serrated at the edges, light green in colour, elongated-ovoid in shape, and bent in the shape of a boat at a sharp angle (Fig. 3).

For the plants of this cultivar, the flowering phase occurs during the end of the second and the beginning of the third decade of May. Notably, the flowers are large or above average in size, with white petals. Fruits form on spurs and fruit spurs, depending on the tree's load, and are large or medium in size, regularly round or flat-rounded or rounded-conical in shape with a smooth surface, deep green or light green (at technical maturity), with a slight blush on the sunny side. The average fruit weight is 142 g. Over the years 2018-2021, the fruit weight was 93 g, 195 g, 156 g, and 126 g, respectively. The fruit skin is thin, and light green in colour with warty formations and numerous white dots, which is characteristic of this cultivar. The apple flesh is tender, firm, juicy, white with a greenish tint, wine-sweet, with a pleasant spicy aftertaste. Under the conditions of the Northern Forest-Steppe of Ukraine, the technical maturity of Reinette Symyrenko fruits occurs

in the second and third decades of September. Reinette Symyrenko apple trees are also characterised by high

drought resistance and wind resistance, early fruiting, and high yield.



Figure 3. Reinette Symyrenko plants during the phenophase of fruit ripening

Source: photographed by the authors

The studied plants of the Jonagold cultivar are characterised as fast-growing trees grafted onto the 54-118 rootstock. As a result, they grow and develop without support, reaching a height of 2.5 metres due to formative crown pruning. In commercial orchards, trees of this cultivar can grow up to 4.5 metres tall. The bark of the trunk and skeletal branches is grey-brown. The crown is spreading, medium-dense, broadly oval in young trees, and rounded in 10-year-old trees. The skeletal branches extend from the trunk at an angle of 30°. One-year-old shoots have high growth vigour and are of medium thickness. The leaves are light green with a yellow tint and oval in shape. A notable feature of the leaves is their tendency to remain on the branches for an

extended period in autumn. The flowering phase occurs in the second decade of May. The flowers are fragrant, large, with white or pale pink petals, and form on spurs, fruit spurs, and one-year-old growths. Apples mature in late September to early October. The fruits are round or slightly elongated with slight ribbing in the calyx area. The apple skin is shiny with a characteristic waxy bloom, smooth, elastic, of medium thickness, greenish-yellow with a blurred, striped blush of orange or red colour, covering more than 50% of the fruit surface (Fig. 4). The flesh of the fruit is yellowish, juicy, firm, granular, crisp, sweet with a slight acidity, and exhibits excellent taste qualities (rated 4.6 on a 5-point scale). The average fruit weight in the experiment was 159.5 g (Table 7).



Figure 4. Jonagold plants during the phenophase of fruit ripening

Source: photographed by the authors

Table 7. Morphological characteristics of various *Malus* species (cultivars), average for 2019-2021

Species (Cultivar)	Fruit weight, g	Peduncle length, mm	Number of seeds per 1 fruit, pcs.	100-seed weight, g
<i>Malus baccata</i> (L.) Borkh.	25.5	17	10	3.9
<i>Malus prunifolia</i> (Willd.) Borkh.	0.7	31	6	0.8
<i>Malus cerasifera</i> Spach.	4.9	26	8	2.2
<i>Malus hybridus</i> (Red Sentinel)	1.8	20	6	1.8
<i>Malus silvestris</i> (L.) Mill.	3.2	26	7	2.8

Table 7. Continued

Species (Cultivar)	Fruit weight, g	Peduncle length, mm	Number of seeds per 1 fruit, pcs.	100-seed weight, g
<i>Malus domestica</i> Borkh. (Reinette Symyrenko)	159.5	23	9	3.5
<i>Malus domestica</i> Borkh. (Jonagold)	142.5	12	12	3.6
<i>Malus domestica</i> Borkh. (Dozhnytsia)	165.5	19	11	3.8

Source: developed by the authors

Plants of the Siberian crab apple, *Malus baccata* (L.) Borkh. var. *baccata*, are typically tall trees (around 6.6 m) and are estimated to be around 15 years old. However, they often form a wide, semi-spherical shrub with branched limbs. The crown is almost oval in shape. The bark of the trunk and main branches is grey or grey-black, while that of two-year-old branches is red-brown, purplish-brown, or brown. The buds are reddish-brown, ovoid, around 3 mm in size, and covered in scales. The annual growth of shoots is above average. The leaves are simple and entire, oval or ovate with a wedge-shaped base and serrated to crenate margins, and are green and glossy (turning yellow, yellowish-brown, or light orange in autumn). They are approximately 6.5 cm long and 3.5 cm wide (with a range of 1.8-10.5 cm by 0.7-6.2 cm). The average petiole length is 2.4 cm. The inflorescence is umbellate, consisting of 3-5, rarely 4-8 flowers. The pedicel is about 2.5 cm long and is initially downy but later becomes glabrous. The petals are 1.3 × 0.7 cm, white or light pink, and obovate. There are approximately 15-17 stamens per flower, and the gynoecium consists of five carpels with a lower ovary.

Flowers are self-pollinating. It is worth noting that flowers are often visited by flying insects, primarily bees. The flowering phase falls at the end of the first – beginning of the second decade of May. The fruit is a somewhat spherical-elongated pome, about 1 cm long with a stalk up to 2.5 cm long. The fruit skin is initially green, and at technical maturity – yellow or dark yellow. The flesh is edible but sour. The seeds are yellow-brown, semi-spherical, measuring 0.7 × 0.6 cm, and are located in a papery core. The phase of technical ripeness is extended in time – from the end of August to the beginning of September, and the fruits remain on the branches throughout the winter period. It has been found that Siberian crab apple plants are photophilous (although they can tolerate partial shade), moderately hygrophilous, winter-hardy and drought-resistant (8-9 points), and are little susceptible to pathogens, but are damaged by leaf-eating pests (mainly leaves suffer). Having evaluated the ornamental value of Siberian crab apple plants, they are recommended for extensive use in landscaping. These plants are suitable as specimen trees (solitaires), in group plantings on lawns, in mixed compositions with coniferous species, or for creating hedges and alley plantings.

In the "Teremky" tract of the Fastiv District of Kyiv Region (2 km from the Institute of Horticulture of the NAAS of Ukraine), European wild apple trees were studied.

It was found that these plants, in terms of their biomorph, are deciduous trees with numerous shoots, reaching a height of about 11 meters. Their crown is irregular, rounded, and broad. The trunk diameter is about 40 cm. The bark of the trunk and skeletal branches is greyish-brown with spots, while that of two-year-old branches is light brown. Some specimens were distinguished by a branched crown, very knotty and twisted branches, on which numerous thorns were recorded. Others, in terms of biomorph, represented a semi-shrub with a dense crown up to 3 meters in diameter. Vegetative buds are brown and pointed. Leaves are simple, oval or rounded-oval with a pointed apex, green and glossy, up to 5.7 cm long with rounded teeth along the edges, formed on short petioles, with characteristic pubescence at the base. The flowering phase falls in the second decade of May. The flowers are fragrant, medium-sized, with pink-white perianth, and the stigmas mature 2-4 days earlier than the anthers. The sepals are relatively narrow, elongated, and close together. The flowers are often visited by pollinating insects.

The fruits are small apples, less than 4 cm in diameter, often with a wrinkled, yellowish-green rough skin, sometimes covered with white or red spots. The core of the fruit is small, and the calyx and base are shallow. The apples ripen in early September. The flesh is greenish, and very sour with a bitter aftertaste (due to the high tannin content). It is noteworthy that European wild apple trees are highly winter-hardy, drought-resistant, and shade-tolerant. The plum-leaved apple is a deciduous tree, reaching a height of 4.3 meters. The bark of the trunk and main branches is greybrown, while that of two-year-old branches is greyish-brown with a purple hue and downy, a characteristic also found on one-year-old shoots. The buds are bright brown and slightly downy. The leaves are ovate or elliptic, measuring 6.8 × 4.3 cm, with a pointed apex and sharply serrated margin, resembling plum leaves. Young leaves have downy hairs along the veins, while older leaves are almost hairless. The leaf stalk is, on average, 3 cm long (occasionally up to 5 cm). A characteristic feature is the presence of lanceolate, small stipules up to 5 mm long, pointed at the apex, which eventually fall off. The flowers are arranged in umbellate inflorescences of 4-10 flowers. The flowers are up to 5 cm in diameter and located on downy pedicels no longer than 3.5 cm. The petals of the perianth are white or light pink, obovate or elliptic with a rounded apex, and 2.5 cm long. The stipules are linear-lanceolate, membranous, and slightly

downy, unlike the lanceolate or triangular-lanceolate sepals (about 8 mm long), which eventually fall off. There are 20 stamens per flower. The flowering phase begins in the first decade of May.

The fruits are round or slightly egg-shaped, small, up to 2.2 cm in diameter, with a greenish-yellow skin (with a blush on the sunny side). In the Northern Forest-Steppe of Ukraine, the fruits reach technical maturity in the first decade of September. Notably, the apples, clustered in groups of 3-7, remain on the tree until late autumn or even the end of winter, serving as a food source for resident and migratory birds. It is worth noting that plum-leaved apple trees exhibit high frost and winter hardiness. The cherry crab apple tree, a complex hybrid (*Malus prunifolia* × *Malus baccata*) commonly found in cultivation, is a tall tree (over 4.5 m) with a loose and broad crown, reaching a diameter of 3.5 m. The leaves are simple, about 7.5 cm long, oval, ovate or elliptical in shape, with a rounded or slightly pointed apex and a serrated margin. Notably, the veins of the leaf are downy. The petioles are 3-3.5 cm long. In autumn, the leaves turn yellow or yellowish-grey. Leaf fall occurs in the second decade of October.

Incidentally, the generative buds open before the vegetative buds. Therefore, the fragrant flowers with pale pink or white petals are the first to adorn the branches abundantly. It should be noted that the sepals fall off. The fruits are small apples, 1.5-2 cm in diameter, with yellow or dark yellow skin with a blush at technical maturity. The average fruit weight was 1.8 g, although fruits weighing 2.3 and 2.5 g were found. It was noted that in some years (2019), one-year-old shoots suffered significantly from the green apple aphid (*Aphis pomi* Deg.) and the apple sucker (*Psylla mali* Schmdb.), but they showed high winter hardiness and resistance to apple scab. The hybrid apple cultivar Red Sentinel grows to a height of 2.5 m and is characterised as an upright tree, though it can occasionally take the form of a shrub. The tree's crown is spreading and branched, about 2 meters in diameter, and oval or egg-shaped, although pruning can change it to an asymmetrical shape. The annual growth of shoots is vigorous. Incomplete shoots are susceptible to frost damage but can regenerate intensively in spring.

The leaves are simple, oval or ovate, green, often with red hues, turning yellow-red and red in autumn. The buds are light pink, and the petals are pale pink or pink. The flowers reach a diameter of 3 cm. The flowering phase falls at the end of the second or third decade of April. The variety is self-fertile and is a good pollinator for self-infertile cultivars of the domestic apple (such as Ligol, Early Geneva, Champion, Jeromini, Polka, Piros, and others). The fruits are round, small, up to 4 cm in diameter, with dark yellow or orange skin with a blush (on the sunny side). The fruit stalks are 2-2.7 m long with a characteristic anthocyanin colouration. The apples are edible (can be consumed fresh or processed),

ripen in the second decade of September, and remain on the branches for a long period. It is worth noting that during flowering, the hybrid apple resembles a Japanese cherry, emphasising its high ornamental value.

It should be noted that plants of this species prefer moist conditions but suffer from waterlogging, especially on clay soils. They respond well to mineral and organic fertilisers and sunlight, although they can also grow well in shade. Overall, the Red Sentinel variety prefers well-drained, moderately moist, fertile soils. Based on an evaluation of the ornamental qualities of the Siberian crab apple, it is recommended to plant these trees in parks, gardens, and squares either as solitary specimens or in group plantings as part of larger landscape compositions with trees and shrubs of other species. Additionally, the studied species and cultivars of the genus *Malus* were assessed for seed morphological characteristics (Fig. 5).



Figure 5. Morphological characteristics of seeds from the studied *Malus* species and cultivars

Note: 1 – European wild apple; 2 – domestic apple (cultivar *Dozhnytsia*); 3 – plum-leaved apple; 4 – Siberian crab apple; 5 – hybrid crab apple; 6 – cherry crab apple

Source: photographed by the authors

As shown in Figure 5, the seed colour of various *Malus* species ranges from light brown to dark brown. Notably, the darkest seeds are found in the hybrid apple, followed by the plum-leaved apple. The seeds of the Siberian crab apple and cherry crab apple are lighter in colour. In terms of seed production, the European wild apple and plum-leaved apple stand out, with 10 and 8 seeds, respectively. Interestingly, the seeds of the wild apple are larger and have a more natural appearance (100-seed weigh 3.9 g), compared to other species.

It is noteworthy that among the studied apple species, some exhibit a “mechanical immunity” to scab, particularly those with a downy underside of the leaf, in

contrast to the smooth surface of cultivated varieties like Reinette Symyrenko and Jonagold. Another characteristic of the plumleaved apple, Siberian crab apple, and cherry crab apple is the thickened and tough leaf blade and petiole, which acts as a buffer against apple scab. The causal agent of apple scab is the ascomycete fungus *Venturia inaequalis* (Cooke) Wint. (in the conidial stage – *Fusicladium dendriticum* (Walr.) Fuck.), which infects several plant genera, including *Pyrus*, *Sorbus*, and *Cotoneaster*, but is primarily associated with *Malus* species. Initial signs of scab on apple trees were observed on leaves and fruits, and in rainy weather, the disease also affected flowers and young fruits. Although apple scab rarely kills the plant, it can cause up to 70% yield losses, posing a significant risk to apple producers. To reduce yield losses associated with this disease, chemical and biological fungicides are applied, and immune cultivars (such as Goldrush, Prima, and Jonafree) are being developed, most of which were created through

controlled crosses between cultivated varieties and wild *Malus* species, especially those from East Asia.

It was found that apple scab manifests on leaves as round spots that eventually turn dark grey with a characteristic olive-velvety fungal spore coating. Notably, in the absence of precipitation, these spots have a diameter of 0.5-15 mm, but under high humidity (rainy conditions), they merge into a continuous dark grey coating. For example, the Reinette Symyrenko cultivar was observed to be more susceptible to scab during bud break, flowering, and fruit set. The first signs of scab on leaves usually appear at the end of apple blossom, while on fruits, the disease becomes evident in late June-July, particularly in dense, poorly ventilated plantings, and with high crown density. In 2019, the first signs of apple scab on leaves were noted at the end of April, and on fruits at the beginning of the third decade of May. In contrast, during 2018 and 2021, the initial symptoms on leaves were observed in late May to early June (Fig. 6).

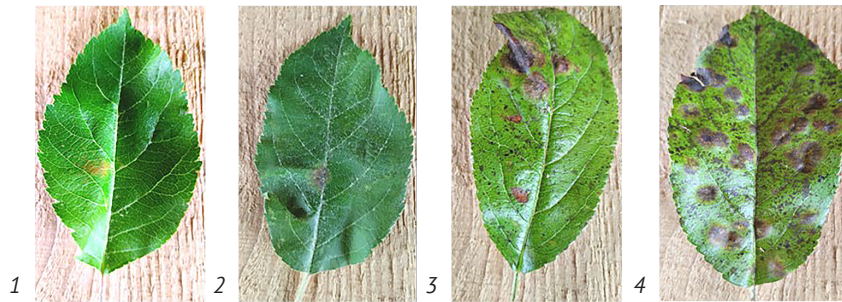


Figure 6. Example of scab-affected leaves

of the Reinette Symyrenko apple cultivar during the second and third decades of May

Note: 1 – 12 May; 2 – 19 May; 3 – 25 May; 4 – 31 May

Source: photographed by the authors

The harm caused by apple scab lies in premature leaf fall (infected leaves begin to fall during July-August). The scab fungus overwinters in the ascospore stage on infected leaves and as mycelium in the bark tissues of infected branches. Notably, leaf loss reached about 40%, which is inextricably linked to the suppression of one-year-old shoot development, specifically by reducing their resistance to adverse

abiotic environmental factors (current year's growth does not mature before the cessation of sap flow and suffers from low and high temperatures). On fruits of certain cultivars (Reinette Symyrenko) of the genus *Malus*, scab manifests as dark grey round spots of varying sizes – from small, a few millimetres in diameter, to large, diffuse spots up to 0.3-2 cm in diameter (Fig. 7).

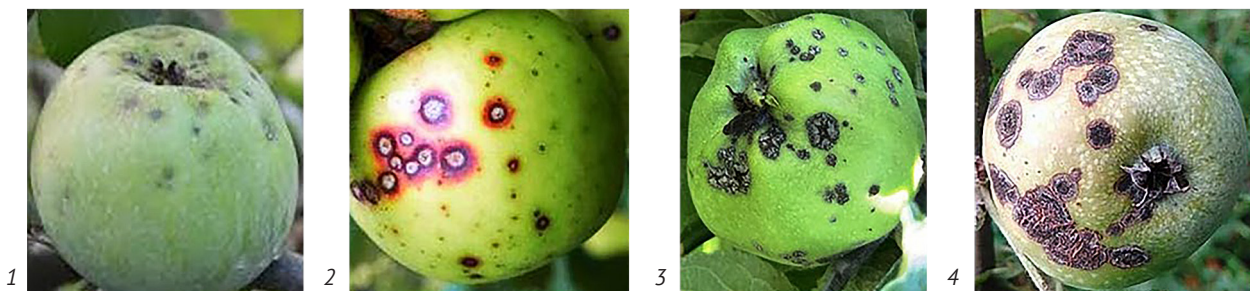


Figure 7. Fruits of the Reinette Symyrenko cultivar exhibiting varying degrees of scab-affected surface areas

Note: the maximum permissible level of apple scab development on fruits is no more than 5%

Source: photographed by the authors

At the sites of scab infection, the outer layer of the fruit, represented by the skin, is destroyed, and the surface tissue of the middle layer becomes corky, which subsequently limits the penetration of the pathogen into the middle and inner layers of the fruit. However, this does not prevent the uneven growth of the fruits,

resulting in their deformation and cracking (which reduces the marketability of the fruits), followed by rotting and dropping (Fig. 8). It should be noted that in 2020, the infection of developed fruits by the apple scab pathogen resulted in up to 35% fruit damage, while in 2019 and 2021, it was up to 18% (Table 8).



Figure 8. Cracked and deformed fruits infected with apple scab

Source: photographed by the authors

Table 8. Scab infection of leaf and fruit surfaces concerning plant species (cultivars), % average for 2018-2021 (n = 5)

Species (Cultivar)	Percentage of surface infection	
	Leaves	Fruits
<i>Malus baccata</i> (L.) Borkh.	12	18
<i>Malus prunifolia</i> (Willd.) Borkh.	5	2
<i>Malus cerasifera</i> Spach.	0	0
<i>Malus hybridus</i> (Red Sentinel)	4	0
<i>Malus silvestris</i> (L.) Mill.	0	0
<i>Malus domestica</i> Borkh. (Reinette Symyrenko)	0	0
<i>Malus domestica</i> Borkh. (Jonagold)	15	10
<i>Malus domestica</i> Borkh. (Dozhnytsia)	10	7

Source: developed by the authors

The table shows that different species (cultivars) of the genus *Malus* have varying percentages of leaf and fruit surface affected by the disease, indicating different levels of resistance to the apple scab pathogen. It was found that *Malus prunifolia* (Willd.) Borkh., *Malus hybridus* cultivar Red Sentinel, and *Malus domestica* Borkh. cultivar Dozhnytsia were immune, as the percentage of surface affected by apple scab was zero. It is worth noting that the high resistance of the earlywinter cultivar Dozhnytsia to apple scab is associated with the presence of the scab resistance gene *Malus floribunda* 821 Vf (Fig. 9).



Figure 9. Fruits (apples)

of the Dozhnytsia cultivar, immune to apple scab

Source: photographed by the authors

Incidentally, the Dozhnytsia cultivar is part of a group of other apple cultivars immune to scab developed by the Institute of Horticulture of the NAAS of Ukraine (Harant, Edera, Amulet, Skifske zoloto, Perlyna Kyieva, etc.), which have been included in the State Register of Plant Varieties suitable for distribution in Ukraine since 2006 (Boldyzheva, 2020). It is characterised by a very compact crown, harvest maturity in the second decade of September, high yield (fruits weighing 165 g, yield – 41.3 t/ha, with an average yield per tree of about 25 kg), but a tendency to overload.

Returning to the tabular data, it can be seen that for *Malus baccata* (L.) Borkh., a low level of fruit infection (up to 5%) was observed. Similarly, low levels of leaf scab infection (up to 15%) were observed for *Malus silvestris* (L.) Mill. and *Malus domestica* Borkh. cultivar Jonagold (a latewinter cultivar of American selection, developed in 1943 at the Geneva Experiment Station, New York). *Malus silvestris* (L.) Mill. and *Malus domestica* Borkh. cultivar Reinette Symyrenko exhibited a moderate level of fruit infection, with more than 15-18% of the fruit surface affected by scab spots. A comparison of the studied species (cultivars) of the genus *Malus* for resistance to apple scab prompted an evaluation

of their ornamental qualities. To assess the ornamental value of apple trees, the following criteria were considered: crown habit, leaves (colour, leafiness), flowers (size, petal colour), and fruits (size, colour), taking into account the level of surface infection by the scab fungus (Table 9). Based on the tabular data, nearly all studied species (cultivars) received the maximum score for crown decorativeness, except for *Malus silvestris* (L.) Mill., as its plants had grown for about 3 years in natural conditions under severe compaction. The European wild apple, Siberian crab apple, plum-leaved apple, and

hybrid crab apple were characterised by high leafiness, elegance, and a pleasant range of green leaf colours, receiving the maximum score (5). The plum-leaved apple received only 3 points for leaf decorativeness, as it did not evoke a high emotional response. For the studied cultivars of domestic apple, leaf decorativeness was reduced to 4 points due to the high abundance of fruits. In terms of flower decorativeness, the maximum score (5) was obtained by the wild apple, cherry crab apple, hybrid crab apple, and the domestic apple cultivar Dozhnytsia (Fig. 10).

Table 9. Ornamental assessment of *Malus* species (cultivars)

Species (Cultivar)	Criteria, points					Overall ornamental rating, points
	I	II	III	IV	V	
<i>Malus baccata</i> (L.) Borkh.	3	5	4	4	4	4.0
<i>Malus prunifolia</i> (Willd.) Borkh.	5	5	5	5	5	5.0
<i>Malus cerasifera</i> Spach.	5	5	4	3	4	4.2
<i>Malus hibridus</i> (Red Sentinel)	5	3	5	4	5	4.4
<i>Malus silvestris</i> (L.) Mill.	5	5	5	5	5	5.0
<i>Malus domestica</i> Borkh. (Reinette Symyrenko)	5	4	5	5	4	4.6
<i>Malus domestica</i> Borkh. (Jonagold)	5	4	5	4	4	4.4
<i>Malus domestica</i> Borkh. (Dozhnytsia)	5	4	5	5	5	4.8

Note: I – crown ornamentation; II – leaf ornamentation; III – flower ornamentation; IV – fruit ornamentation; V – resistance to apple scab

Source: developed by the authors



Figure 10. Studied *Malus* species (cultivars) during the flowering phase

Note: 1 – *Malus baccata* (L.) Borkh.; 2 – *Malus hibridus* (Red Sentinel); 3 – *Malus cerasifera* Spach.; 4 – *Malus silvestris* (L.) Mill.; 5 – *Malus prunifolia* (Willd.) Borkh.; 6 – *Malus domestica* Borkh. (Jonagold); 7 – *Malus domestica* Borkh. (Dozhnytsia); 8 – *Malus domestica* Borkh. (Reinette Symyrenko)

Source: photographed by the authors

For the remaining studied species (cultivars) of apples, flower decorativeness was at the level of 4 points, particularly for the Reinette Symyrenko cultivar, which was associated with the manifestation of apple scab.

The fruits of the Dozhnytsia cultivar were distinguished by their large size, colours, and shape against the background of leaves and crown, which contributed to increased overall decorativeness. The miniature,

beautiful in colour, shape, and numerous fruits of *Malus baccata* (L.) Borkh., *Malus cerasifera* Spach., and *Malus hybridus* (Red Sentinel) provided high decorativeness to the plants. In summary, the berry apple and hybrid apple had the highest overall decorativeness (5 points). Among the domestic apple cultivars, the Dozhnytsia cultivar also received a high decorativeness score (4.8). For other studied species (cultivars) of the genus *Malus*: *Malus silvestris* (L.) Mill., *Malus prunifolia* (Willd.) Borkh., *Malus cerasifera* Spach., *Malus domestica* Borkh. (Reinette Symyrenko), and *Malus domestica* Borkh. (Jonagold), the decorativeness score was above average – 4.0; 4.2; 4.4; 4.4, and 4.6, respectively.

DISCUSSION

Plants of the genus *Malus* exhibit varying levels of susceptibility to fungal and bacterial infections, viruses, mycoplasmas, and nematodes. Notably, over 70 pathogens of fungal diseases affecting domestic apple trees have been identified. Furthermore, it is known that pathogens, pest damage, and various abiotic factors are the primary causes of significant damage to apple trees. Overall, apple trees are considered long-lived plants, with the average lifespan of domestic apple trees being 50-60 years, and in some cases exceeding 100 (Reig et al., 2019). Interestingly, the lifespan of domestic apple trees on seedling rootstocks exceeds 30 years, and on vegetative rootstocks up to 20 years or more, but this also depends on crown formation and pruning methods and timing, which influence fruit growth and quality (Kviklyk et al., 2022).

According to A. Chaploutskyi and R. Butsyk (2023), the most recognised *Malus* species include: *Malus angustifolia*, *Malus asiatica* (Chinese pearleaf crab apple), *Malus baccata* (Siberian crab apple), *Malus baccata* var. *baccata* (Chinese crab apple), *Malus baccata* var. *mandshurica* (Manchurian crab apple), *Malus coronaria* (Sweet crab apple), *Malus doumeri*, *Malus florentina* or *Malus floribunda* (Japanese flowering crab apple), *Malus fusca* (Oregon crab apple), *Malus halliana* or *Malus ioensis* (prairie crab apple), *Malus niedzwetzkyana* (Niedzwetzky's apple), *Malus orientalis* (eastern crab apple), *Malus prunifolia* (plum-leaved apple), *Malus pumila* (domestic apple), *Malus sargentii* (Sargent crab apple), *Malus sieboldii* (Siebold's crab apple), *Malus sieversii* (large-fruited apple), *Malus sylvestris* Mill. (European crab apple or European wild apple), *Malus sylvestris* var. *praecox* (Pall.) Borkh. (early crab apple), *Malus toringoides* (cut-leaf crab apple), and *Malus pumila* (domestic apple).

In Ukrainian forests, species such as the European wild apple (*M. sylvestris*) and early crab apple (*M. praecox*) can be found. The former is typically a tall tree (up to 10 meters) with smooth leaves, while the latter is also a tree, but smaller (up to 5 meters) with hairy undersides to its leaves. According to A. Arnal et al. (2022), the cultivated range of apple trees is constantly expanding. Biologically, members of the genus *Malus* are

typically trees, occasionally large shrubs, characterised by alternate, petiolate, simple or lobed leaves, and early-shedding stipules. Flowers are perfect, white, pink, or red, and arranged in corymbs or umbels. There are five sepals and five petals. There are 20-50 stamens. The ovary is inferior, five-chambered, with two ovules in each chamber, from which seeds with a dark brown coat develop. There are five styles, fused at the base, less commonly nearly free, and mostly hairy. The fruit is a pseudocarp (apple), fleshy, most often globose, depressed at the ends, with flesh lacking stone cells (Konratenko & Kuzminets, 2018; Hulko, 2020).

According to Z. Chen et al. (2021), most cultivated apple varieties (subspecies, cultivars), numbering over 20,000 known worldwide, are classified within the complex cultigen species *M. domestica*, which has a complex hybrid origin due to extensive breeding and nursery practices. The large-fruited apple (*Malus sieversii* (Ledeb.) M. Roem., 1847), predominantly found in southeastern Kazakhstan, is the sole ancestor of most domestic apple cultivars developed over the past 2,000 years, except a few cultivars resulting from hybridisation between the crab apple and the Japanese flowering crab apple (*Malus floribunda* Siebold ex Van Houtte, 1865). T. Davies et al. (2021) reported that only five parental cultivars – McIntosh, Jonathan, Red Delicious, Golden Delicious, and Cox's Orange Pippin – were involved in the creation of 60% of the 439 commercial cultivars examined.

According to M. Ruhsam et al. (2022), the European wild or crab apple (*Malus sylvestris* (L.) Mill., 1768) is a wild species native to Europe and grows as a tree. The genome of this species is largely derived from the Central Asian wild apple (*Malus sieversii*). Another species, Siebold's crab apple (*Malus toringo* Siebold), is a small tree or shrub with light pink flowers and orange fruits, 6-8 mm in diameter. This species is used in ornamental horticulture and, less commonly, as a rootstock for apple trees (Lou et al., 2020). Similar arguments can be made for other species. For instance, the plum-leaved apple or Chinese apple (*Malus prunifolia* (Willd.) Borkh., 1803) has a hybrid origin, forming ovate or elliptical leaves and small red fruits (5 cm in diameter), and is native to China. It is used as an ornamental tree, rootstock, and as a parent in breeding programs. Notably, this species has been used to develop frost- and winter-hardy, large-fruited (up to 200 g), and high-quality cultivars such as Pepin Shafrannyi, Kytaika Zolota early, and Belfler-kytaika (Li et al., 2022).

According to X. Chen et al. (2019), the Siberian crab apple (*Malus baccata* (L.) Borkh., 1803), native to North Asia (China, Mongolia, etc.), has ornamental qualities due to its numerous white fragrant flowers, grouped in clusters of 4-6, and spherical, cherry-like red-yellow fruits. It is important to note that the seeds of this species are considered toxic due to their high content of hydrocyanic acid. These plants are characterised by

their undemanding nature regarding soil types and light conditions, high frost resistance, and resistance to fungal diseases. Despite their small fruits, they are sometimes used in hybridisation programs to create promising forms of domestic apple. The Siberian crab apple is also a good pollinator for all species of the genus *Malus*, as its plants have a longer flowering period. On the other hand, the Japanese flowering crab apple (*Malus floribunda* Siedold ex Van Houtte), native to China and Japan, as noted by scientists from the L.P. Simirenko Horticulture Research Station of the IH NAAS of Ukraine, V. Voloshina and V. Gomenyuk (2021), is a natural species or a hybrid of Siebold's crab apple (*Malus toringo* Siebold or *Malus sieboldii* Rehder) and *Malus baccata*. It produces beautiful pink flowers and red apples. The aforementioned authors emphasise that *Malus floribunda* Siedold ex Van Houtte is a frost-resistant species of apple, capable of withstanding temperatures as low as -25°C , and is moisture-loving, with low susceptibility to powdery mildew, scab, and bacterial blight. Therefore, in addition to its ornamental value (including in bonsai culture), this species is widely used in hybridisation to create cultivars of commercial importance (such as the cultivars Ariane and Evereste).

Many species of the genus *Malus* are used in ornamental gardening. These include the narrow-leaf crab apple (*Malus angustifolia* (Aiton) Michx, 1803), native to the southeastern United States, which is a tree with highly fragrant flowers and fruits (Mansfeld *et al.*, 2023), and the transitional crab apple (*Malus transitoria* (Batalin) CK Schneid, 1906), found in China, growing as a 7-8-meter-tall tree with light pink flowers and dark yellow or orange fruits (Guo *et al.*, 2022). Additionally, Niedzwetzky's apple, which has been used in hybridisation with small-fruited apple species to create ornamental forms, should be considered. As noted by V. Mezhenskyj and L. Mezhenska (2021), the dominant gene controlling anthocyanin pigmentation in apples originated from *Malus niedzwetzkyana* Dieck ex Kohne, 1891, which is used in colourful compositions and as a solitary plant on lawns or as a hedge. On the other hand, the shrubby crab apple (*Malus brevipes* Render) is represented by only one cultivar in cultivation, and its origin is unknown. However, in breeding programs, more domesticated species are often used, such as the Chinese pearleaf crab apple (*Malus asiatica* Nakai, 1915), which is widely distributed in northern and northeastern China and has been cultivated for a long time. According to researchers B. Liu *et al.* (2019), this species is a tree with ovate or elliptic leaves, light pink petals, red pollen, and spherical yellow fruits with a blush or yellow-green skin and a fragrant, refreshing flesh. Another long-domesticated species is the eastern crab apple (*Malus orientalis* Uglitzk), which, according to Ł. Walas *et al.* (2024), is distributed across a significant area of Turkey, through the Caucasus to the mountain ecosystems of Iran.

However, the most popular species is the domestic or cultivated apple (*Malus domestica* Borkh., 1803) (Brite, 2021), one of the most widespread species of the genus *Malus*. It is believed that the centre of origin of the domestic apple is Central Asia (where its ancestor, *Malus sieversii*, can still be found) due to the genetic diversity of samples found there. A. Kumar *et al.* (2022) report that over 7,500 cultivars of this species are cultivated worldwide, varying in yield and plant habit, and are propagated by clonal grafting onto rootstocks. Depending on their intended use, they are grown for fresh consumption, processing, and the production of juices, beverages, jam, jelly, dried products, and more. According to D. Maharani and T. Mursitama (2023), global apple production in 2023 amounted to 83 million tonnes, with almost half (47%) of total production coming from China. A. Olivares *et al.* (2020) report that domestic apple cultivars are diploid in terms of ploidy (although triploid cultivars such as Rhode Island Greening, Cortland, Jonathan, Crispin (Mutsu), and Spur Gold exist, producing sterile pollen and requiring pollinator cultivars), and have 17 chromosomes (allopolyploid $2n = 2x = 34$), with a complete genomic complex.

It is worth noting that apple cultivars are cross-pollinated and are sometimes classified based on their peak bloom day within a 30-day blooming period. Depending on the climate, there are 4 to 7 pollination groups for the domestic apple: A – early bloom, e.g., between 1-3 May; B – early midseason, 4-7; C – mid-season, 8-11; D – late mid-season, 12-15; E – late, 16-18; F and H – very late, between 19-23 and 24-28 May, respectively. Pollinators are selected from cultivars within a 6day overlap period. Compatible pollination for a given cultivar occurs with the same or a nearby group (A with A or A with B, but not A with C or D). O. Havryliuk *et al.* (2023) consider Golden Gem and Professor Springer to be universal pollinators for columnar apple cultivars. In general, commercial apple production relies on pollinators, and their contribution to apple production is significant. Among pollinator plants, *Malus sylvestris* (L.) Mill. is an important species. Overall, apple species diversity has further decreased due to the use of a limited number of desirable specimens in breeding programs (Mbovora *et al.*, 2021).

In summary, the close attention of scientists and researchers to members of the genus *Malus*, the search for and selection based on productive, morphological, physiological, and biochemical characteristics, and the identification of economically valuable species (forms, cultivars) in the creation, distribution, and evaluation of new genetic diversity that meets the modern requirements of horticultural and landscape management systems remain relevant.

CONCLUSIONS

An integrated scale has been proposed to assess species (cultivars) of the genus *Malus* based on their overall

ornamental value, which includes five indicators: crown attractiveness, leaf attractiveness, flower attractiveness, fruit attractiveness, and resistance to apple scab. Based on the developed scale, a comparative assessment of a group of ornamental apple species (cultivars) or crabapples was conducted based on morphological, biological, and physiological characteristics, which is important for the priority directions of fruit and ornamental horticulture in the conditions of the Northern Forest-Steppe of Ukraine.

To expand the genetic diversity of tree stands in ornamental and fruit gardening systems, it is recommended to introduce crab apple cultivars (forms) characterised by a small above-ground part, decorative habitus, including the size and colour of leaves, flowers, and fruits, increased immunity to fungal pathogens, and versatile pollinator plants, which contributes to the formation of effective garden ecosystems. Morphological studies have shown that crab apple cultivars, compared to cultivars of the domestic apple, are characterised by weak (<15-20 cm/year) or moderate (>21-25 cm/year) growth and a compact crown, anthocyanin leaf colouration (*Malus hybridum*), white, light pink, and pink petals, small fruits (< 5 cm in diameter) with long stalks (>2 cm), high male fertility, a longer flowering period (>14 days), and fruit retention on branches, as well as undemanding growth conditions.

It has been found that, in terms of fruit size, in addition to cultivated cultivars, the European wild apple stands out, with an average fruit weight of 25 g, while the Siberian crab apple (0.74 g), cherry crab apple (1.8 g), and plum-leaved apple (4.9 g) have small fruits. It has been shown that the largest fruits, weighing over 100 g, belong to the cultivars Reinette Symyrenko, Jonagold, and Dozhnytsia, which are characterised by high taste qualities. It has been noted that crab apple cultivars are characterised by weak or moderate growth and a compact crown, undemanding growth conditions, and disease resistance, making them promising tree resources for the formation of ornamental gardening systems, park forestry, and shelterbelt afforestation.

Among the studied cultivars of the domestic apple, it is recommended to cultivate the immune and high-yielding cultivar Dozhnytsia, bred by the Institute of Horticulture of the NAAS of Ukraine, which will allow reducing or avoiding the chemical control of scab and contribute to obtaining environmentally friendly and inexpensive fruits (plantations of such cultivars can reduce fungicide costs by up to 70%).

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CONFLICT OF INTEREST

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Біоекологічні особливості представників роду *Malus* в контексті перспективних напрямків садового і лісопаркового господарств

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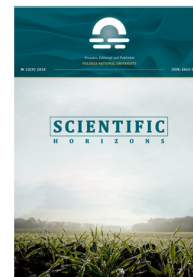
Анотація. Мета дослідження полягала в порівняльному оцінюванні представників роду *Malus* за морфологічними ознаками, біологічними особливостями, фізіологічними механізмами стійкості до збудників грибних хвороб, декоративністю й значимістю в системі садового, лісопаркового господарства, полезахисного лісорозведення. На основі комплексного підходу охоплено морфологічні ознаки і біологічні особливості яблуні домашньої, яблуні лісової, яблуні ягідної, яблуні гібридної, яблуні сливолистої, а також проведене порівняльне вивчення специфіки ураження та стійкості рослин видів роду *Malus* до збудників парші плодів та інших хвороб. Показано, що яблуня домашня характеризується крупноплідністю (середня маса плоду складає не менше 150 г), тоді як для яблуні ягідної, яблуні вишнеплідної і яблуні гібридної середня маса плоду не більше 0,7, 1,8 і 3,2 г відповідно. Авторами статті розроблено інтегральну шкалу для порівняльного оцінювання видів (сортів) або scabapple роду *Malus* за загальним показником декоративності рослин, який включає 5 критеріїв: декоративність крони; листків; квіток; плодів та стійкість до парші рослин яблуні. Вперше проаналізовано плоди різних видів роду *Malus* за насінневою продуктивністю, серед яких виокремлено креби, зокрема яблуню лісову і яблуню сливолисту середня кількість насінин у плоді яких найбільша і становить 10 і 8 насінин, відповідно. Також показано, що плоди яблуні лісової характеризуються крупністю насіння (маса 100 насінин > 3,9 г). Висвітлено результати, які підтверджують декоративну цінність окремих представників роду *Malus*, а саме яблуні ягідної і яблуні гібридної, рослини яких характеризуються найвищим загальним балом 4,5 і 5, порівняно з яблунею лісовою, яблунею вишнеплідною і яблунею домашньою, які мали нижчий бал за декоративністю 3,2-3,9. Зазначено, що рослини креби (*Malus silvestris* (L.) Mill., *Malus baccata* (L.) Borkh. та інші) доцільно використовувати формуванні лісопаркових ландшафтів. В умовах Північного Лісостепу України диференційовано види яблуні за резистентністю до збудника парші (*Venturia inaequalis* Cooke), при цьому встановлено, що рослини яблуні домашньої (сорту Дожниця), яблуні гібридної і сливолистої є високостійкими до вищезазначеного збудника, який уражує листя і плоди. Практичне використання отриманих результатів полягає в доповненні сучасними даними інформаційної бази представників роду *Malus*, що дозволить їх використовувати в різних тематичних дослідженнях

Ключові слова: *Malus*; морфологія; фізіологія рослин; стійкість до фітопатогенів; порівняльна оцінка

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The efficacy of chelated micronutrient fertilisers in tomato cultivation

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Abstract. The study aimed to investigate the impact of foliar fertilisation on the growth and development processes of tomato plants of different maturity groups throughout the entire growing season, as well as on overall yield levels. The research, conducted during 2018-2021 in film greenhouses at the experimental site of the State Biotechnological University, located in the south eastern part of the Left-Bank Forest-Steppe of Ukraine, examined the F1 indeterminate tomato hybrids Berberana (early maturity) and Bostina (mid-early maturity). The results demonstrated that foliar fertilisation accelerated plant development phases compared to the untreated control variant. The treated plants exhibited the most vigorous development during the budding phase, with bud formation occurring two to four days earlier than in the control group. It was observed that plants subjected to foliar fertilisation had superior biometric indicators during the mass flowering phase. The differences in primary biometric indicators during the mass flowering phase, depending on the application

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of foliar fertilisation, ranged from 3% to 18%. During the mass fruiting phase, these differences varied from 2% to 9% with a single treatment and from 5% to 17% with three treatments. Furthermore, the experiment involving three treatments demonstrated the highest monthly yield increases, exceeding the control by 12% to 21%. The findings indicated that the most effective treatment was the application of chelated micronutrient fertilisers three times, resulting in a yield increase of 17.5% (2.8 kg/m²) for the Berberana hybrid and 14.8% (2.2 kg/m²) for the Bostina hybrid compared to the control. These yield improvements provide producers with an opportunity for increased profit. The practical significance of this study lies in identifying the effects of foliar fertilisation on tomato yield in protected soil conditions. Additionally, the study established optimal and scientifically justified rates and application timings for complex fertilisers with chelated micronutrients. These measures ensure the maximum realisation of the crop's genetic potential

Keywords: tomato (*Solanum lycopersicum* L.); mineral fertilisers; chelated complexes; cultivation technology; foliar fertilisation; yield

INTRODUCTION

Modern agriculture faces the pressing challenge of ensuring sustainable production while reducing the reliance on chemical inputs and preserving soil fertility. As a result, there is a growing emphasis on agrotechnical and biological methods for enhancing agricultural productivity in an environmentally friendly manner. Tomato cultivation demands innovative solutions to boost overall yields. Understanding how different tomato hybrids respond to various foliar fertilisation methods and timing can unlock untapped potential for increased productivity. Such research holds both scientific and practical significance. Therefore, the relevance of this study lies in identifying the specific features of yield formation in tomatoes when water-soluble complex fertilisers with chelated micronutrients are applied. Tomatoes are one of the world's most popular vegetables. According to FAO data, global annual production of fresh tomatoes has been around 185-189 million tonnes in recent years, with an average yield of approximately 3.8 kg/m². Tomatoes account for about 16% of global vegetable production. In Ukraine, tomatoes represent an even larger share of total vegetable production at 24.25%, although the average yield is slightly lower at around 2.9 kg/m².

Researchers N. Kosenko and V. Pogorielova (2020) assert that tomato yield is influenced by numerous factors, with the availability of nutrients in an accessible form within the soil being a primary determinant. Optimal yields are achieved through a combination of mineral, organic fertilisers, and foliar fertilisation. One significant challenge hindering tomato production and driving up costs is the limited availability of traditional organic and mineral fertilisers, which are crucial for enhancing crop yield and quality. A. Holodna (2021) highlights that the growing variety of fertilisers coincides with the adoption of modern agrochemical technologies in crop cultivation. This has led to increased demands for higher quality and a wider range of mineral fertilisers to maintain and restore soil fertility. M. Pylak *et al.* (2019) found that tomato plants extract substantial amounts of micronutrients from the soil,

leading to depletion. To support sustainable agriculture and protect crops, it is essential to replenish soil micronutrient levels. However, under current agricultural practices and land-use systems in Ukraine, it is challenging to even maintain soil fertility, let alone improve it, without significant enhancements to state-level control mechanisms and the implementation of more effective, preferably economic, support mechanisms for soil conservation measures (Pisarenko *et al.*, 2020). Among other agronomic practices, the proper organisation of fertilisation is crucial for achieving abundant, stable, and high-quality yields of various crops cultivated in Ukraine. Foliar fertilisation provides plants with a more readily available source of nutrients compared to soil application. Combined foliar fertilisation improves plant growth, maturity, and yield, which can be attributed to the accessibility of essential nutrients and their easy absorption through leaves.

M. Samoraj *et al.* (2024) highlight those fertilisers and biostimulants are crucial in modern agriculture, balancing the growing global demand for food with the urgent need to mitigate environmental impact, especially in regions with degraded soils and limited resources. One key approach is the use of specialised mineral fertilisers, such as chelates (organic acid salts), which exhibit high biological activity and enhance nutrient uptake by plants (Aliksieiev, 2020). D. Humenyyi *et al.* (2024) note that the global trend towards using biopreparations is driving domestic vegetable growers to seek alternative fertilisation systems for crop cultivation, promoting the development of effective systems that harness the full potential of plants using biopreparations of various types. U. Karbivska *et al.* (2024) emphasise the importance of rational and systematic fertiliser use to increase crop yields and improve product quality. Further advancements in production can only be achieved through the implementation, utilisation, and continuous improvement of innovative methods and the latest cultivation technologies.

Based on this analysis, the problem addressed by this study was the evaluation of the effects of foliar

fertilisation on tomato yield in protected soil conditions, particularly in spring film greenhouses, to maximise crop productivity. By establishing optimal and practical dosages and application timings for a water-soluble complex fertiliser with chelated micronutrients for tomatoes, this research contributed to realising the genetic potential of tomatoes and advancing practical vegetable cultivation.

MATERIALS AND METHODS

Experimental research was conducted from 2018 to 2021 at the experimental plot of the State Biotechnological University, located in the southeastern part of the Left-Bank Forest-Steppe region of Ukraine. The experiments were carried out in unheated spring film greenhouses. Tomato plants were cultivated in spring-summer crop rotations. The soil cover of the experimental plot and greenhouse consisted of typical chernozem on clayey carbonate loess. The Kharkiv area is characterised by variable temperatures, varying amounts of annual precipitation without a dry season, and warm summers (Beck *et al.*, 2018), making it suitable for growing tomatoes in protected ground. The average long-term sum of active temperatures is 2,669°C. Winter begins in mid-November. The average daily air temperature crosses 15°C in early April. Snowmelt usually begins in early March and ends in the first decade of April. Soil thawing to its full depth ends in the first decade of April, and warming to a depth of 20 cm to +10°C occurs at the end of the third

decade of April. The summer months are characterised by high air temperatures. The average annual air temperature for the period was: June +17.9°C, July +20.2°C, and August +19°C. The maximum soil surface temperature reached +54°C. Autumn typically begins in the third decade of October. Weather conditions during the study period, according to data from the Rogan meteorological station located on the experimental field, did not significantly differ from the longterm average. The maximum deviation of temperature from the monthly average was recorded in March 2019, which was the highest during the study period and 4.6°C above the norm.

For foliar fertilisation, the Plantafol product line from Valagro, Italy, was used. Plantafol is a range of foliar fertilisers with various concentrations, characterised by high solubility and rapid, complete absorption by leaves. The product line includes formulations with different ratios of nitrogen, phosphorus, and potassium to support both the vegetative and reproductive stages of crop growth and ensure high-quality produce. In the experiment, products with N, P₂O₅, and K₂O percentages of 10.54.10; 20.20.20; and 5.15.45 were used. All products in the line contain EDTAchelated micronutrients (Cu, Fe, Mn, Zn) and can be combined with the most common pesticides. The experimental materials were the indeterminate tomato hybrids Berberana F1 (early) and Bostina F1 (mid-early). To achieve the research objectives, plants were treated with Plantafol according to the following treatments (Table 1).

Table 1. Experimental designs

Variant No.	Treatment	Concentration and application timing
I variant	No fertilisation (Control)	-
II variant	1 fertilising	10.54.10 at the three-leaf phase
III variant	2 fertilising	10.54.10 at the three-leaf phase + 20.20.20 at the beginning of flowering
IV variant	3 fertilising	10.54.10 at the three-leaf phase + 20.20.20 at the beginning of flowering + 5.15.45 during fruiting phase

Source: compiled by the author based on experimental research

To correctly interpret the results obtained from the field experiment, analysis of variance (ANOVA) was used. Logical-theoretical approaches were applied to interpret the data. During the study, the authors also used their previous findings (Yarovyi *et al.*, 2020). The research was conducted following generally accepted methodological recommendations for growing tomatoes in protected ground. Experimental research on plants, including the collection of plant material, complied with institutional, national, and international

guidelines: the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

The study assessed the impact of foliar fertilisation on the progression of tomato plants through developmental phases. Foliar fertilisation accelerated the progression of plants through their developmental phases compared to the untreated control variant (Table 2).

Table 2. Impact of the treatment on the duration of interphase periods compared to the control (average for 2018-2021)

Factor A (Hybrid)	Factor B (Treatment)	Days from sowing to			First to final harvest, days
		emergence	beginning of flowering	onset of fruiting	
Berberana	No fertilisation (Control)	5.3	60.8	130.0	89.0

Table 2. Continued

Factor A (Hybrid)	Factor B (Treatment)	Days from sowing to			First to final harvest, days
		emergence	beginning of flowering	onset of fruiting	
Berberana	1 fertilising	5.3	58.8	128.0	88.8
	2 fertilising	5.3	58.5	127.5	88.8
	3 fertilising	5.3	56.8	126.3	90.0
Bostina	No fertilisation (Control)	5.8	61.0	131.0	88.5
	1 fertilising	5.8	59.3	128.8	88.3
	2 fertilising	5.8	58.5	128.5	88.5
	3 fertilising	5.8	57.0	126.5	88.8

Source: compiled by the author based on experimental research

The type of hybrid had a less significant impact, with the early-maturing hybrid Berberana generally developing slightly faster, although the difference was minimal. Observations showed that plants treated with Plantafol developed most intensively during the budding phase (56-59 days from germination to the onset

of flowering), with bud formation occurring two to four days earlier than in the control. The treatment also accelerated the onset of mass fruiting in all experimental variants. Plants treated with Plantafol in the three-treatment variant were the most developed, with the largest biometric parameters at the flowering phase (Table 3).

Table 3. Impact of the treatment on plant biometric parameters at the mass flowering phase compared to the control (average for 2018-2021)

Factor A (Hybrid)	Factor B (Treatment)	Length of central stem, cm	Plant mass, g	Number of leaves, pcs.	Leaf surface area, cm ² per plant
Berberana	No fertilisation (Control)	111.3	1,255.0	15.8	3,367.5
	1 fertilising	115.0	1,387.5	16.5	3,680.0
	2 fertilising	125.0	1,482.5	17.3	3,837.5
	3 fertilising	126.5	1,457.5	17.5	3,800.0
Bostina	No fertilisation (Control)	110.0	1,244.0	15.5	3,170.0
	1 fertilising	116.3	1,331.3	16.3	3,365.0
	2 fertilising	120.3	1,397.5	17.5	3,550.0
	3 fertilising	126.3	1,387.5	17.5	3,592.5

Source: compiled by the author based on experimental research

During the study period, the greatest stem length was observed in plants subjected to a threetreatment variant, averaging 126.3-126.5 cm across hybrids, which was 14-15% higher than the control. All other treatments also exceeded the control but to a lesser extent than the threeapplication variant. Plant mass ranged from 1,244.0 to 1,482.5 g, depending on the Plantafol treatment. Berberana hybrid plants treated with two applications had the highest mass (1,842.5 g), 18% more than the control, while Bostina hybrid plants in the control group had the lowest mass (1,244.0 g). The average number of leaves per plant ranged from

15.5 for the control (Bostina) to 17.5 for the three-treatment variant in both hybrids. Leaf surface area was smallest in the control group: 3,170.0 cm² for Bostina hybrid and 3,367.5 cm² for Berberana hybrid. The maximum increase over the control was observed in Berberana hybrid plants treated with two applications, reaching 3837.5 cm², which is 14% more than the control. Depending on the treatment, there was a 3-18% difference in the main biometric parameters of tomato plants during the mass flowering phase. Plants treated with Plantafol three times had the highest biometric values (Table 4).

Table 4. Impact of the treatment on plant biometric parameters at the mass fruiting phase compared to the control (average for 2018-2021)

Factor A (Hybrid)	Factor B (Treatment)	Length of central stem, cm	Plant mass, g	Number of leaves, pcs.	Leaf surface area, cm ² per plant	Average fruit mass, g
Berberana	No fertilisation (Control)	277.5	2,267.5	27.8	12,807.5	131.3
	1 fertilising	278.5	2,377.5	28.3	13,357.5	141.3

Table 4. Continued

Factor A (Hybrid)	Factor B (Treatment)	Length of central stem, cm	Plant mass, g	Number of leaves, pcs.	Leaf surface area, cm ² per plant	Average fruit mass, g
Berberana	2 fertilising	287.5	2,502.5	28.5	13,375.0	146.3
	3 fertilising	293.8	2,615.0	29.3	13,900.0	151.3
Bostina	No fertilisation (Control)	276.3	2,245.0	27.8	11,135.0	107.5
	1 fertilising	282.5	2,288.8	28.3	12,118.8	116.3
	2 fertilising	290.0	2,287.5	28.8	12,257.5	123.8
	3 fertilising	299.3	2,412.5	29.5	12,605.0	126.3

Source: compiled by the author based on experimental research

For the control treatment, the average stem length for both hybrids was the shortest at 276.32775 cm. Plants of the Bostina hybrid treated with three applications were the tallest at 299.3 cm, 8% more than the control. Berberana hybrid plants also had the longest stems (293.8 cm) under the same treatment. Plant mass, depending on the number of treatments, ranged from 2245.0 to 2615.0 g. Berberana hybrid plants treated with three applications had the highest mass (2,615.0 g), 15% more than the control, while Bostina hybrid plants in the control group had the lowest mass (2,245.0 g). Plants of both hybrids showed a similar trend in terms of leaf number and fruit mass, depending on the number of foliar applications. The highest average leaf number (29.3-29.5 leaves/plant) was obtained with three

applications, which was 5-6% higher than the control, while the lowest (27.8 leaves/plant) was observed in the control for both hybrids. The highest leaf surface area (13,900 cm²) was recorded for Berberana hybrid plants treated with three applications, which is 9% more than the control, and for Bostina hybrid (12,605 cm²) also with three applications, which is 13% more than the control. The lowest leaf surface area was observed in the control treatment. The highest average fruit mass (151.3 g) was determined for Berberana hybrid with three applications, which is 15% more than the control, and the lowest (107.5 g) for Bostina hybrid in the control. During the mass fruiting phase, a strong positive correlation was observed between the length of the main stem and the number of leaves ($r = 0.98 \pm 0.57$) (Table 5).

Table 5. Correlation between plant biometric parameters during the mass fruiting phase (average for 2018-2021)

Parameters	Length of central stem, cm	Plant mass, g	Number of leaves, pcs.	Leaf surface area, cm ² per plant	Average mass of 1 fruit, g
Plant mass, g	-0.78 ± 0.28	x			
Number of leaves, pcs.	0.98 ± 0.57	-0.68 ± 0.33	x		
Leaf surface area, cm ² per plant	-0.68 ± 0.57	0.98 ± 0.59	-0.58 ± 0.65	x	
Average mass of 1 fruit, g	-0.92 ± 0.18	0.95 ± 0.13	-0.85 ± 0.26	0.90 ± 0.20	x

Source: compiled by the author based on experimental research

Other biometric indicators exhibited strong and moderate inverse correlations. The study of yield dynamics by month revealed that, in July, the yield of the Berberana hybrid ranged from 6.1 kg/m² in the control variant (untreated) to 6.8 kg/m² in the three-treatment variant. For the Bostina hybrid, the yield varied from 5.6 kg/m² in the control to 6.1 kg/m² in the three-treatment variant (Fig. 1).

In August, Berberana hybrid yielded 5.2 kg/m² in the control and 6.0 kg/m² in the three-treatment variant, while Bostina hybrid yielded 5.0 kg/m² in the control and 5.4 kg/m² in the three-fertilising variant.

Similarly, in September, Berberana hybrid yielded 4.4 kg/m² in the control and 5.2 kg/m² with two- and three-treatment variants, while Bostina hybrid yielded 4.1 kg/m² in the control and 4.8 kg/m² two- and three-fertilising variants. In October, the difference in yield between the experimental variants was 1-2% of the average yield. The lowest total yield was recorded in 2018: 13.3 kg/m² for Bostina hybrid in the control and 16.5 kg/m² for Berberana hybrid with three-fertilising variants. The highest total yield was recorded in 2021: 16.7 kg/m² for Bostina hybrid in the control and 20.4 kg/m² for Berberana hybrid with three-fertilising variant (Table 6).

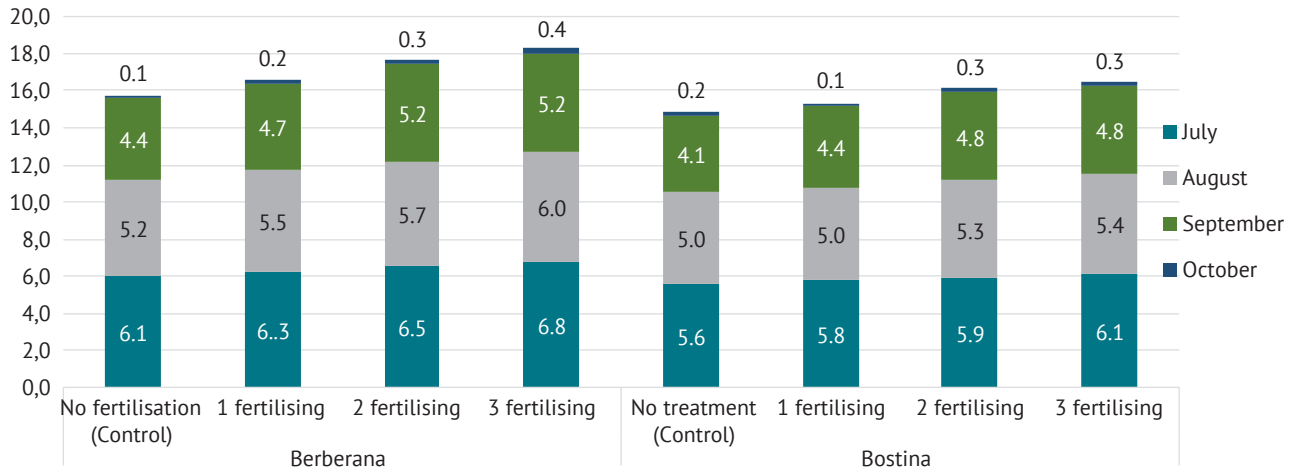


Figure 1. Dynamics of fruit yield formation by month under different treatments compared with the control, kg/m² (average for 2018-2021)

Source: compiled by the author based on experimental research

Table 6. Total yield formation under different treatments compared with the control (2018-2021)

Factor A (Hybrid)	Factor B (Treatment)	Yield, kg/m ²				on average	± compared to control	
		2018	2019	2020	2021		kg	%
Berberana	No fertilisation (Control)	14.5	15.2	14.9	18.1	15.7	-	-
	1 fertilising	15.2	16.3	15.9	19.0	16.6	0.9	5.9
	2 fertilising	15.9	17.1	18.2	19.5	17.7	2.0	12.8
	3 fertilising	16.5	18.3	18.2	20.4	18.4	2.7	17.1
Bostina	No fertilisation (Control)	13.3	15.1	14.2	16.7	14.8	-	-
	1 fertilising	14.0	15.6	14.3	17.4	15.3	0.5	3.3
	2 fertilising	14.4	15.9	16.6	17.7	16.2	1.3	8.9
	3 fertilising	14.8	16.8	16.4	18.0	16.5	1.7	11.3

Source: compiled by the author based on experimental research

Depending on the treatments applied using the Plantafol preparation, the total yield increased for the Berberana hybrid from 15.7 kg/m² in the control to 18.4 kg/m² in the three-fertilising variant, and for the Bostina hybrid from 14.8 kg/m² in the control to 16.5 kg/m² under the same variant. To evaluate the results of the field experiment, correct use and interpretation of the obtained data is necessary.

Although there are no significant differences between the results of using different statistical analysis methods, depending on the experimental data, each has its advantages and disadvantages. For the analysis of data obtained in the field experiment, ANOVA is a suitable method for correctly assessing the impact of experimental factors on tomato yield (Table 7).

Table 7. Results of analysis of variance of data by factors of the field experiment

Variance	SS	df	MS	F	p-value	Critical F-value	
						0.95	0.99
Factor A (Hybrid)	7.60	1	7.60	4.70	0.04	4.26	7.82
Factor B (Treatment)	45.31	3	15.10	9.34	0.00028	3.01	4.72
Interaction of AB factors	1.06	3	0.35	0.22	0.88	3.01	4.72
Model error	38.79	24	1.62	x	x	x	x
Total	92.76	31	x	x	x	x	x

Source: compiled by the author based on experimental research

The actual Fisher criterion for F_A is 7.60, which exceeds the theoretical criterion at the 0.95 probability level. This indicates that the variability of the hybrid has a statistically significant effect on tomato yield at this significance level. For Factor A, the null hypothesis of no effect of the factor levels is rejected – demonstrating that the use of tomato hybrids from different maturity groups significantly influences yield. The actual Fisher criterion for F_B is 15.10. The null hypothesis of no effect of the factor levels for Factor B is

also rejected, confirming that the number of fertiliser applications has a statistically significant impact on tomato yield. However, since the actual Fisher criterion for F_{AB} is 0.22, which is lower than the theoretical value, the interaction of these factors does not have a statistically significant effect on yield in the field experiment. The least significant difference was calculated at various significance levels (0.01 and 0.05) for the experimental factors to further characterise the field experiment (Table 8).

Table 8. Results of analysis of variance by factors of the field experiment

Experimental factor	Mean, kg/m ² A	Difference by factor		Sx%	T%
		B			
A (Hybrid)	Berberana	17.1	-	x	
	Bostina	15.7	1.4	x	
	No fertilisation (Control)	15.3	x	-	
B (Treatment)	1 fertilising	16.0	x	0.7	5.5
	2 fertilising	16.9	x	1.7	
	3 fertilising	17.4	x	2.2	
	LSD _{0.95} by factor		1.3	0.9	
	LSD _{0.99} by factor		1.8	1.3	

Source: compiled by the author based on experimental research

The difference in mean sample values cannot be attributed solely to randomness. Using tomato hybrids from different maturity groups in the experiment resulted in a yield increase at a reliable probability level of 0.05 against the background of foliar fertilisation. Moreover, a significant increase in total yield was observed at both levels of reliable probability with tomato hybrids of varying maturity. This increase was achieved through the application of Plantafol 10.54.10 at the three-leaf phase, Plantafol 20.20.20 at the beginning of the flowering phase, and Plantafol 5.15.45 during the fruiting phase under the three-treatment variant.

Traditional chemical fertilisers have low plant availability, leading to soil degradation and environmental pollution. As a result, as noted by F. Areche *et al.* (2023), there has been a growing demand for safer and more environmentally friendly fertiliser application formulas. Scientific research by J. Chipomho *et al.* (2018) has shown that the use of foliar fertilisers that improve the bioavailability of various types of fertilisers and minerals and stimulate plants to grow faster and improve nutrient uptake has a positive overall impact on plant development. Researchers N. Gruda *et al.* (2024) and H. Dasgan *et al.* (2024) have demonstrated that, due to their greater efficiency, foliar application of mineral fertilisers with amino chelates can be a sustainable approach to plant nutrition management, especially in drought conditions. Recent studies have revealed the critical role and complex functions of micronutrients in optimising vegetable production. Research by J. Gui *et al.* (2022) and Z. Jia *et al.* (2022) has expanded the understanding of the profound effects of micronutrients such as Fe, Zn, and Cu on plant nutrient use, growth,

and development. An element like Mn also plays an important role. In studies by A. Nazir *et al.* (2024) and M. ElMogy and H. Abd El-Gawad (2023), it is noted that the practice of applying micronutrients is vital for processes such as photosynthesis and carbohydrate metabolism, emphasising its effectiveness in increasing overall vegetable yields and improving fruit quality during post-harvest storage. These results indicate the potential of foliar application of mineral fertilisers with amino chelates as an effective means of increasing tomato yield and correlate with the original study.

In a study by G. Disciglio *et al.* (2024), the effects of biostimulants (containing auxins, cytokinins, and micronutrients such as Zn, Mg, and Mn) applied three times during the growing season (during transplanting, before flowering, and during fruit enlargement) on spring-grown tomatoes were investigated. Significantly higher marketable yields were observed in both experimental fields with foliar fertilisation, increasing by 6.8-16.1% (an average of 10.312.1 kg/m²) compared to the control (no treatment). The results obtained in this study align with their findings.

In an experiment conducted by Bulgarian scientists G. Patamanska *et al.* (2021) in a film greenhouse, a two-factor trial was carried out with the Big Beef F1 greenhouse tomato hybrid. The experimental factors in the study were irrigation and foliar fertilisation with mineral fertilisers. Foliar fertilisation was studied by spraying tomato leaves with a complex mineral NPK fertiliser at three different concentrations. The results of the experiment determined that the maximum total tomato yield was obtained with the highest fertiliser rate under both full and deficit irrigation conditions –

at 12.8 and 9.07 kg/m², respectively, which is 43.9% and 29.3% higher than the control (no treatment). This is also confirmed by the research of J. Olivarez-Rodríguez *et al.* (2021), who studied foliar fertilisation of tomatoes with nanoparticles (NPs) consisting of ZnO, Fe₂O₃, and CuO, applied individually and in combination: Zn, Fe, Cu, Zn+Cu, Zn+Fe, Cu+Fe, Zn+Cu+Fe, and a control without application, for a total of eight treatments. It was found that when plants were treated with combinations of Zn+Cu, Zn+Fe, and Cu+Fe, the yield increased by 24.5-34.3% compared to control plants, recording a value of 2.15-2.32 kg/plant. The highest productivity was shown by plants treated with a complex of Zn+Cu+Fe, at a level of 2.88 kg/plant, which was 66% higher than the yield of untreated plants. Three variants of foliar treatment with the use of preparations and a separate control were studied by authors L. Vultaggio *et al.* (2022). Treatments were organised in a randomised complete block design with three replicates per treatment, totalling 12 experimental units. In this study, plant biostimulants containing phytohormones and two preparations containing NPK and micronutrients K, Ca, Mg, Fe, Mn, B, Zn, and Cu in different concentrations were used. Foliar fertilisation improved the early yield of fresh tomatoes by 14.130.0% compared to untreated plants, without a significant difference between treatments with biostimulants. These data confirm the results of the current study, which also recorded an increase in tomato yield of 14.8-17.5% due to foliar fertilisation.

M. Nighat *et al.* (2018) demonstrated the effectiveness of foliar fertilisation with micronutrients in tomato plants. Foliar application of micronutrients was conducted 15 days after transplanting and repeated at 15-day intervals. A total of three foliar sprays were applied during the growing season. Significant differences were observed between treatments in terms of leaf count, number of branches, and root length per plant. The maximum number of leaves (76.35), branches (10.27), and root length (37.16 cm) per plant was observed with the maximum concentration of micronutrients and three applications, and the highest yield (4.5 kg/m²) was also recorded. The minimum number of leaves (54.05), branches (4.13), and root length (28.16 cm) per plant was observed under natural conditions in the control. These results support current findings that foliar fertilisation has a significant impact on overall plant development and yield. A similar trend was observed in the research of B. Essa *et al.* (2024), where cherry tomatoes showed a positive response to foliar application. The study examined four genotypes of cultivated cherry tomatoes treated with salicylic acid and methyl jasmonate. Treatment of plants with an aqueous solution of methyl jasmonate proved to be the most effective in increasing yield, providing a yield of 3.02-6.74 kg/m², which is 8.6-25.7% higher than the untreated variant.

The study by O. Kuts *et al.* (2023) revealed that the use of mineral fertilisers and fertilisation systems

incorporating microbial preparations for foliar application of tomato variety Chaika resulted in a significant increase in the number of clusters per plant. This increase ranged from 10.6% to 77.5% at the beginning of flowering and 17.0% to 52.8% at the full fruiting phase. Additionally, on average over the years of the study, applying fertilisers and foliar application three times contributed to a 50.8-142.0% increase in tomato seed yield. W. Lakshari *et al.* (2023) conducted a similar experiment in Sri Lanka. Foliar treatments were applied at the growing, flowering, and fruiting phases using chitosan at three different concentrations (70, 80, and 120 ppm). Foliar fertilisation positively influenced vegetative growth, leaf area, plant height, chlorophyll index, and dry matter. Moreover, it increased the total soluble solids, fruit weight, and diameter. The researchers concluded that foliar application at the maximum concentration of the preparation yielded the highest crop (almost 2.7 times higher than other variants) and better fruit quality.

Overall, most practical studies also indicate that the application of micronutrients in foliar fertilisation is beneficial not only for shoot and root growth but also acts as a catalyst for nutrient absorption processes, thus contributing to increased yields of vegetable crops. In conclusion, the results of determining the impact of foliar fertilisation on tomato yield under protected ground conditions demonstrate the effectiveness of foliar fertilisation with water-soluble complex micronutrients and contribute to the enrichment and deepening of agronomic science.

CONCLUSIONS

The research established that foliar fertilisation with Plantafol was highly effective when cultivating the tomato hybrid. The study of plant biometric parameters showed a positive impact of foliar fertilisation on plant growth and development throughout the entire vegetative period. Plants treated with Plantafol exhibited the most intensive development during the budding phase, leading to a faster growth rate compared to the control. During the mass flowering phase, the studied hybrids under the foliar fertilisation treatment had the most developed plants, on average 3-18% more than the control. In the mass fruiting phase, the highest biometric indicators among those studied were recorded for the treatment with three foliar applications.

The application of foliar fertilisation resulted in increased tomato yields. The dynamics of monthly yield formation across treatment variants revealed the highest monthly yield levels for both hybrids in the treatment with three foliar applications, exceeding the untreated control by 12-21%. The most effective treatment was the variant with three applications, which led to yield increases of 17.5% (by 2.8 kg/m²) for the Berberana hybrid and 14.8% (by 2.2 kg/m²) for the Bostina hybrid compared to the control.

The calculation of the least significant difference for both experimental factors at a 95% confidence level confirmed the significance of these results. For Factor A – the cultivation of indeterminate tomato hybrids of different maturity groups (F1 hybrid Berberana, early, and F1 hybrid Bostina, mid-early) – 1.4 kg/m² (LSD_{0.95} = 1.4). For Factor B – foliar fertilisation with Plantafol – 1.7 kg/m² (LSD_{0.95} = 0.9) for the two-application treatment (Plantafol 10.54.10 during the three-leaf phase and Plantafol 20.20.20 at the beginning of flowering) and 2.2 kg/m² (LSD_{0.95} = 0.9) for the three-application treatment (Plantafol 10.54.10 during the three-leaf phase, Plantafol 20.20.20 at the beginning of flowering, and Plantafol 5.15.45 during the fruiting phase). By influencing the processes of yield structure formation through foliar

fertilisation, it is possible to affect the crop yield of tomatoes. This provides an opportunity for producers to increase their profits. The results of the study indicate the need for further research aimed at studying the specific effects of different complexing agents on plant development and evaluating the agrochemical effect of applying such fertilisers through foliar fertilisation, as well as selecting the optimal fertiliser composition for further use in the full cycle of tomato cultivation.

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CONFLICT OF INTEREST

None.

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Ефективність застосування хелатних мікродобрив при вирощуванні помідора

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Анотація. Метою дослідження було дослідження впливу позакореневих підживлень на процеси проходження росту та розвитку рослин помідора різної групи стиглості протягом всього вегетативного періоду та рівень загальної врожайності. У досліді проведеному у 2018-2021 роках у плівкових теплицях на дослідній ділянці Державного біотехнологічного університету у південно-східній частині Лівобережного Лісостепу України вивчали індетермінантні гібриди F1 помідора Берберана (ранній) та Бостіна (середньоранній). Встановлено, що застосування позакореневих підживлень порівняно з контрольним варіантом без обробки пришвидшувало проходження рослинами фаз розвитку. Розвиток оброблених препаратом рослин був найбільш інтенсивним у фазу бутонізації, на дві-чотири доби раніше за контроль відбувалось формування бутонів на рослині. Відзначено, що перевищення біометричних показників у фазу масового цвітіння мали рослини, які отримували позакореневі підживлення. Різниця між основними біометричними показниками, в залежності від проведених позакореневих підживлень, у фазу масового цвітіння відзначена на рівні 3-18 %, у фазу масового плодоношення від 2-9 % за варіантом з одним до 5-17 % за варіантом з трьома обробками. Також у досліді з трьома обробками рослин визначено максимальний врожайності за місяцями – на 12-21 % більше контролю. За результатами досліджень визначено, що найкращим виявився варіант досліді з трьома обробками хелатними мікродобривами, за яким отримано підвищення врожайності для гібриду Берберана на 17,5 % (на 2,8 кг/м²) порівняно з контролем та для гібриду Бостіна на 14,8 % (на 2,2 кг/м²) порівняно з контролем, завдяки чому виробники матимуть можливість отримувати додатковий прибуток. Таким чином, практична цінність даного дослідження полягала у виявленні впливу позакореневих підживлень на врожайність помідора в умовах захищеного ґрунту та визначення оптимальних та практично обґрунтованих доз та строків застосування комплексного добрива з мікроелементами у хелатній формі, що забезпечить максимальну реалізацію генетичного потенціалу культури

Ключові слова: помідор (*Solanum lycopersicum* L.); мінеральні добрива; хелатні комплекси; технологія вирощування; позакореневі підживлення; урожайність

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Determining the germinative qualities of red clover seed samples with varying biological status

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Abstract. The development of forage crop varieties that adapt to changing environmental conditions is an effective strategy to mitigate the impact of climate change with minimal losses. Temperature influences both the timing and rate of seed germination, which in turn ensures uniform seedling emergence, compatibility of red clover with other crops, and the ability to exploit optimal sowing conditions. This study aimed to determine the temperature and time required to achieve maximum germination,

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as well as the range within which germination occurred, for four red clover samples of varying biological status (cultivars, wild and local populations). Germination capacity and energy of red clover samples were assessed according to the standards outlined in DSTU 4138 2002 and DSTU 2949-94 at temperatures ranging from 3°C to 33°C in 10°C increments. It was established that the optimal temperature for the germination of red clover seeds among the four studied samples ranges from 13°C to 33°C on filter paper and from 13°C to 23°C on sand. The research identified the Vytis cultivar as outperforming other samples in all measured parameters when germinated on filter paper, while the Truskavchanka cultivar demonstrated superior traits when germinated on sand. The best germination rates were observed in the wild population at a temperature of 13°C. These findings explain the uneven emergence of red clover samples of varying biological status in collection and breeding nurseries, as observed under field conditions. The results of this study can inform the development of sowing technologies for red clover under various temperature regimes

Keywords: *Trifolium pratense* L.; cultivar; wild population; local population; temperature; germination

INTRODUCTION

Red clover (*Trifolium pratense* L.), a perennial legume belonging to the Fabaceae family, thrives in a wide range of climates and is widely distributed in temperate and subtropical regions of both the Northern and Southern Hemispheres. It is easily cultivated on acidic and moist soils, both in pure stands and in mixtures with cereal species. Red clover plays a crucial role in sustainable forage production through biological nitrogen fixation, soil fertility restoration, efficient use of phosphorus and potassium fertilisers, and reducing the environmental impact of agriculture. With the changing climate, there is a growing need for new cultivars with high adaptive potential. The foundation for developing new cultivars lies in the establishment and study of germplasm collections, which include cultivars, wild, and local populations from various eco-geographic origins. The Precarpathian Department of Scientific Research of the Institute of Agriculture of the Carpathian Region of the National Academy of Sciences has established a red clover collection comprising 330 samples with diverse biological statuses.

The value of red clover in agriculture and the study of its genetic resources have been the subject of numerous studies by prominent scientists. B. Sawicka et al. (2023) demonstrated that *Trifolium* species effectively counteract agricultural degradation, restore soils, and support forage production. C. Harris and F. Ratinieks (2022) argue that concerns over the rising costs and environmental impact of high inorganic nitrogen (N) inputs have led to a renewed interest in legumes, particularly clover, for maintaining soil fertility and improving natural hay meadows. A major limitation of red clover in cultivation, as highlighted by the authors, is its low persistence due to high plant mortality caused by a complex of biotic and abiotic factors.

In studying red clover samples of diverse ecological and geographical origins, researchers such as G. Petrauskas et al. (2020) and M. Tucak et al. (2021) identified superior red clover populations, which they recommend for improving the nutritional value of forage crops in breeding programmes aimed at developing

new cultivars. According to I. Radinovic et al. (2022), to assess the level of genetic diversity and identify the best genotypes for developing new cultivars, it is necessary to obtain information about the germplasm, which is the primary basis for breeders. Therefore, the evaluation of genetic resources is based on morphological, phenological, and agronomic traits. Since breeders use different forms when studying the initial material, it is advisable to know the response of their seeds to temperature during germination.

Seeds represent a crucial stage in a plant's life cycle, serving as the vital link for the continued existence of a species. They encapsulate the genetic information necessary for the dispersal, establishment, development, and reproduction of the next generation. Seeds possess the ability to maintain life in a dormant state when dry and to resume metabolic activity under favourable environmental conditions. Climatic factors are significant determinants, playing a pivotal role in influencing various stages of a plant's life cycle, from seed germination to development (Baxter et al., 2019; Talwar et al., 2023). Temperature, light, and moisture are critical factors influencing seed germination. These abiotic factors are major limiting factors that significantly affect the timing and rate of clover seed germination, ultimately impacting its compatibility with other crops, ability to suppress weeds, and capacity to capitalise on optimal sowing conditions.

J. Yu et al. (2020) assert that the germination of beggarticks (*Bidens alba* L.) seeds decreases with reduced moisture availability. The seeds germinated more effectively in the presence of light than in continuous darkness at temperatures ranging from 15°C to 35°C. However, the optimal germination temperature for beggarticks seeds was 15°C under light conditions. Better seedling emergence was observed when seeds were sown on the soil surface. The number of germinated seeds decreased sharply when the sowing depth was 1 cm or more. Identifying the minimum, maximum, and optimal temperatures for clover germination enables researchers to fine-tune sowing recommendations

for successful establishment. A. Szczerba *et al.* (2021) emphasised the importance of analysing the characteristics of cultivars, not only in terms of the length of the growing season but also their ability to germinate at lower temperatures. This would allow for earlier sowing, resulting in earlier seed harvest, as confirmed by their studies on four soybean samples.

Therefore, temperature has a significant impact on the maximum percentage, uniformity, and speed of germination. Consequently, clover should be sown under optimal environmental conditions to avoid soil and climatic factors that negatively affect seed germination and seedling emergence. There is a need to evaluate the impact of various factors on the germination of red clover seeds and seedling emergence in the early stages of breeding programs when studying the initial material. Thus, this study aimed to investigate the seed quality of red clover samples with different biological statuses (cultivar, local and wild populations) under various temperature regimes.

MATERIALS AND METHODS

The study utilised red clover seeds from the cultivars Vytis (Lithuania) and Truskavchanka (Ukraine), as well as wild and local populations. These seeds, harvested in 2021, were stored under uncontrolled conditions (*ex situ*) at the Precarpathian Department of Scientific Research. Germination and germination energy were determined according to the Ukrainian State Standards (DSTU 4138-2002, 2004; DSTU 2949-94, 1996). Samples (32 per batch, each containing 100 seeds) were drawn from the breeding material to evaluate seed quality, including germination energy and laboratory germination rates. For the experiment, 100 seeds of each red clover sample were evenly distributed in 9 cm Petri dishes lined with filter paper saturated with 4 mL of distilled water. The dishes were then placed in a dry-air thermostat TS-80 (Ukraine, 2019). To determine the impact of temperature on seed germination, the Petri dishes were maintained in complete darkness at constant temperatures of 3°C, 13°C, 23°C, and 33°C with a relative humidity of 70%. The experiments were conducted in four replicates. Seeds were considered germinated once the radicle was visibly protruding.

The germination of seeds from the four aforementioned samples was also assessed on sand. The sand

was prepared as a substrate for seed germination by sieving it through a 1 mm mesh, washing, and heating until a piece of paper placed within it charred. The following method was applied: "on sand" (oS) – seeds were pressed into the sand's surface to a depth of 1 mm. For the experiment setup, a 1.5 cm layer of sand was added to the base of a Petri dish and moistened with 7 mL of distilled water, after which 100 seeds were evenly distributed on the surface. On the fourth day, an additional 2 mL of distilled water was added. The Petri dishes were kept in complete darkness at constant temperatures of 3°C, 13°C, 23°C, and 33°C with a relative humidity of 70%. The experiments were conducted in four replicates.

Two types of assessments were conducted: the first to evaluate germination energy and the second to measure germination rates and determine the root, hypocotyl, and total length of 25 randomly selected seeds. Results were expressed as percentages, rounded to the nearest whole number, for each observed category. The accuracy of the analysis was established by comparing the extreme values of the replicates with the arithmetic mean. The result was deemed reliable if the difference between the extreme values and the arithmetic mean, rounded to a whole number, did not exceed the permissible deviations. Statistical analysis was performed using analysis of variance (ANOVA). Throughout the study, the authors adhered to the standards established by the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

Germination energy refers to the proportion of seeds that germinate within the first four days, expressed as a percentage. Seeds with high germination energy exhibit rapid germination, leading to uniform seedling emergence. Such seedlings are less suppressed by weeds and exhibit greater resilience to adverse conditions. The germination energy of red clover seeds on filter paper under varying temperature regimes ranged from 61% in the Truskavchanka cultivar (at 3°C) and the local population (at 33°C) to 78% in the Vytis cultivar (at 33°C). The highest germination energy was observed in all studied samples at 13°C, with an $LSD_{0.05} = 0.02$ (Table 1).

Table 1. Germination energy, germination rate, and seedling length of red clover seeds germinated on filter paper under varying temperature regimes

Sample	Temperature regime (°C)				Average
	3	13	23	33	
	Germination energy, % (Day 4)				
Local population	64	73	62	61	65
Truskavchanka	61	70	66	67	66
Vytis	68	75	68	78	72
Wild population	62	71	70	63	67

Table 1. Continued

Sample	Temperature regime (°C)				Average
	3	13	23	33	
Average	64	72	67	67	68
LSD _{0.05}	0.01	0.02	0.02	0.02	
Germination, % (Day 10)					
Local population	86	93	81	86	87
Truskavchanka	84	91	86	90	88
Vytis	89	96	90	96	93
Wild population	87	92	90	92	90
Average	87	93	87	91	90
LSD _{0.05}	13.32	11.15	14.09	10.67	
Root length, mm (Day 10)					
Local population	3.5	5.0	4.9	3.9	4.3
Truskavchanka	3.1	4.8	4.6	3.7	4.1
Vytis	3.6	5.3	4.8	4.1	4.5
Wild population	3.4	5.6	5.1	5.3	4.9
Average	3.4	5.2	4.9	4.3	4.5
LSD _{0.05}	0.01	0.38	0.49	0.02	
Hypocotyl length, mm (Day 10)					
Local population	4.1	6.2	7.0	5.9	5.8
Truskavchanka	3.8	5.9	7.2	6.3	5.8
Vytis	3.5	6.4	7.7	6.1	5.9
Wild population	4.0	6.9	7.1	7.0	6.3
Average	3.9	6.4	7.3	6.3	6.0
LSD _{0.05}	0.01	0.03	0.49	0.07	
Total length, mm (Day 10)					
Local population	7.6	11.2	11.9	9.8	10.1
Truskavchanka	6.9	10.7	11.8	10.0	9.9
Vytis	7.1	11.7	12.5	10.2	10.4
Wild population	7.4	12.5	12.2	12.3	11.1
Average	7.3	11.5	12.1	10.6	10.4
LSD _{0.05}	0.38	0.43	0.81	0.12	

Source: created by the authors

When germinating the studied seeds on the sand, germination energy ranged from 53% in the local population (at 3°C) to 87% in the Vytis cultivar (at 13°C). The highest germination energy was observed across all samples at 23°C, with an LSD_{0.05} = 0.02 (Table 2).

Germination rate, a critical indicator of seed quality, was determined by counting the number of normal seedlings after 10 days. On filter paper, germination ranged

from 81% (local population) to 96% (cultivar Vytis) with LSD_{0.05} = 10.67-14.09. The best germination (91-96%) was observed at 13°C. On sand, germination was lower compared to filter paper, with the highest values (92-98%) at 23°C. The Vytis cultivar consistently showed the highest germination on filter paper across all temperatures (89-96%), while the Truskavchanka cultivar performed best on sand at all temperatures (76-96%).

Table 2. Germination energy, germination rate, and seedling length of red clover seeds germinated on sand under varying temperature regimes

Sample	Temperature regime (°C)				Average
	3	13	23	33	
Germination energy, % (Day 4)					
Local population	53	71	80	64	67
Truskavchanka	71	85	82	68	77
Vytis	69	87	84	61	75
Wild population	58	81	79	69	72
Average	63	81	81	66	73
LSD _{0.05}	0.01	0.03	0.02	0.02	
Germination, % (Day 10)					
Local population	66	77	92	74	77

Table 2. Continued

Sample	Temperature regime (°C)				Average
	3	13	23	33	
Truskavchanka	79	99	96	76	88
Vytis	74	92	96	69	83
Wild population	63	89	92	77	80
Average	71	89	95	74	82
LSD _{0.05}	21.32	25.13	19.34	21.17	
Root length, mm (Day 10)					
Local population	2.6	5.4	6.7	2.3	4.3
Truskavchanka	2.9	5.6	6.9	2.5	4.5
Vytis	3.1	5.8	7.1	2.9	4.7
Wild population	2.9	6.1	7.6	3.4	5.0
Average	2.9	5.7	7.1	2.8	4.6
LSD _{0.05}	0.02	0.45	0.38	0.01	
Hypocotyl length, mm (Day 10)					
Local population	3.2	7.1	7.9	3.5	5.4
Truskavchanka	3.4	7.5	8.3	3.1	5.6
Vytis	3.0	6.9	8.1	3.7	5.4
Wild population	3.3	7.8	7.7	4.0	5.7
Average	3.2	7.3	8.0	3.6	5.5
LSD _{0.05}	0.01	0.03	0.29	0.08	
Total length, mm (Day 10)					
Local population	5.8	12.5	14.6	5.8	9.7
Truskavchanka	6.3	13.1	15.2	5.6	10.1
Vytis	6.1	12.7	15.2	6.6	10.2
Wild population	6.2	13.9	15.3	7.4	10.7
Average	6.1	13.1	15.1	6.4	10.2
LSD _{0.05}	0.47	0.67	0.08	0.24	

Source: created by the authors

The root length of the studied samples germinated on filter paper was greater at 13°C (4.85.6 mm), while the shortest roots were observed at 3°C (3.1-3.6 mm). The hypocotyl length was longest at 23°C (7.0-7.7 mm) and shortest at 3°C (3.5-4.1 mm). The overall seedling length was greatest at 23°C (11.8-12.5 mm) and smallest at 3°C (6.9-7.6 mm), with LSD_{0.05} = 0.12-0.81. When germinated on sand, root length was greatest at 23°C (6.7-7.6 mm) and shortest at 33°C (2.3-3.4 mm). The hypocotyl length was longest at 23°C (7.7-8.3 mm) and shortest at 3°C (3.0-3.4 mm). The overall seedling length was greatest at 23°C (14.6-15.3 mm) and smallest at 3°C (5.8-6.3 mm), with LSD_{0.05} = 0.08-0.67. A comparison of the seed quality (germination energy and rate) and seedling traits (root and hypocotyl length, total seedling length) across samples under different temperature regimes highlighted the Vytis cultivar as superior across most parameters when germinated on filter paper. The Truskavchanka cultivar, however, excelled in most traits when germinated on sand. These findings indicate varying levels of germination energy and germination rates among the samples of different biological status (cultivar, wild and local populations).

Therefore, understanding the biology of clover seed germination about environmental factors is crucial for achieving good seedling emergence. Several authors

have conducted various studies to determine the seed quality under controlled and uncontrolled conditions, in different environments, and at varying temperatures and stress levels across a range of agricultural crops. For instance, L. Chu *et al.* (2022) carried out a series of experiments to investigate the impact of light, temperature, sowing depth, drought, and salt stress on the germination of white clover (*Trifolium repens* L.) seeds. The seed germination rate was on average 63-66% under both light and complete darkness, measured four weeks after sowing. At temperatures of 15-25°C, the authors observed a significantly higher germination rate compared to lower temperatures of 5 and 10°C. The results indicate that the germination rate of white clover decreased with increasing sowing depth. Therefore, the authors recommend sowing seeds on the soil surface or burying them to a shallow depth of ≤1 cm to achieve optimal germination, which was taken into account in the sand germination experiments.

Numerous studies have been conducted to investigate the germination characteristics of various perennial grass species. For instance, A. Lina and A. Escobar-Gutiérrez (2022) studied the germination of eight samples of perennial ryegrass (*Lolium perenne* L.) of different biological origins at temperatures ranging from 5 to 40°C. They found that wild populations exhibited

higher germination rates at higher temperatures, while local populations performed better at lower temperatures. Similarly, V. Oleksiak *et al.* (2023) researched perennial ryegrass, focusing on germination and germination energy of five samples. The authors also concluded that the germination of seed varieties was higher than that of local and wild populations. A. López *et al.* (2019) corroborated these findings, suggesting that the optimal germination temperature for different populations is influenced by the environmental conditions in which they evolved. Furthermore, W. Chaleb *et al.* (2021) examined 38 alfalfa (*Medicago sativa* L.) samples and observed that cultivars exhibited high germination rates at 5 and 34°C, while wild populations showed lower germination rates, likely due to adaptations to their specific geographic origins. P. Vivanco *et al.* (2021) highlighted the challenges in assessing the viability of wild perennial grass populations due to seed dormancy and high variability among populations. They determined that the optimal germination temperature for wild populations was 15°C. These results were confirmed by current studies, where the best germination of wild population seeds was observed at 13°C.

G. Herman *et al.* (2022) claim that the temperature during the initial phase of germination affects both the germination of seeds and seedlings of crimson clover. The best results for absorbent capacity and electrical conductivity were obtained at 22°C, while the highest germination energy, seedling emergence, root length, and total seedling length were observed at the lowest temperature of 10°C. Authors Ç. Bayram *et al.* (2024) conducted studies in controlled conditions to examine the effect of salt stress on flax germination, a key industrial plant with diverse uses worldwide. The experiment involved three flax varieties (Somme, Midin and Norman) and four salt concentrations (control, 50 mm, 100 mm, and 200 mm). They investigated the germination rate, radicle length, plumula length, seedling length, and seedling fresh weight characteristics of seedlings under salt stress conditions. The study showed that the control group (pure water) had the highest values for all examined traits, but these values significantly decreased as the salinity intensity increased. Similar studies were conducted by S. Büyükyıldız *et al.* (2023) on bird's-foot trefoil (*Lotus corniculatus* L.) and S. Shiade and B. Boelt (2020) on tall fescue (*Festuca arundinacea* Schreb). The authors assert that increased salinity negatively impacts seed germination.

I. Buranji *et al.* (2019) studied the effect of pH levels (4.5, 5.5, 6.5, 7.5, and 8.5) and temperature (10, 15, and 20°C) on the germination of flaxseed and the morphological parameters of the seedlings. The experiment was conducted under controlled conditions on rolled filter paper with four repetitions over seven days. The highest germination rate (88%) was observed at 20°C, which was statistically significant ($P < 0.01$) compared to the germination rate at 10°C, which was 9% lower.

The highest percentage of normal seedlings (70%) was recorded at pH 5.5, while the lowest (59%) occurred at pH 8.5. The effect of pH on the morphological characteristics of the seedlings (root length, stem length, and total length) was statistically insignificant. In contrast, temperature significantly affected seedling length: at 20°C, after seven days, the average length was 14.4 cm, whereas at 10°C, it was only 2.1 cm ($P < 0.01$). Overall, the lowest (4.5) and highest (8.5) pH values resulted in a reduction in the proportion of normal seedlings (63% and 59%, respectively), as well as less development of the root and stem.

A. Costa *et al.* (2019) obtained somewhat different results in their study of the impact of seed colour on the sowing qualities of red clover. The seeds of this species exhibit a heteromorphic nature, with two visually distinguishable morphs: light purple and yellow, which are determined by heterozygosity and recessive homozygosity at two loci. The study analysed seed germination and the initial growth of seedlings in distilled water, sodium chloride solution, and nutrient medium. It was found that seed sensitivity to treatment increased at later stages of development, indicating a cumulative effect. No differences in water absorption between the morphs or treatments were observed. However, at the seedling growth stage, treatments proved effective, with differences between the morphs only observed when using the nutrient medium. At the intermediate stage of germination, differences between the morphs were also evident in distilled water and sodium chloride solution. The yellow morph, which had an advantage at the initial germination stages, was overtaken by the light purple morph during the active seedling growth phase.

Overall, all researchers highlight the importance of studying the sowing qualities of agricultural crops, including red clover, especially in the context of climate change. The results obtained should be considered when establishing field conditions for nursery studies of the initial material and improving the elements of red clover cultivation technology. During sowing, temperature plays a crucial role in achieving rapid germination and successful establishment of the crop. The mid-summer period in the Western region of Ukraine is characterised by high temperatures and a soil moisture deficit. Therefore, determining the optimal temperatures for sowing red clover is of critical importance, particularly in the breeding process, when the amount of seed from the initial material is limited.

CONCLUSIONS

The study examined the germination characteristics of four samples of red clover with different biological statuses (cultivars Truskavchanka (Ukraine) and Vytis (Lithuania), and wild and local populations) under various temperature regimes of 3, 13, 23, and 33°C, and different substrate types (filter paper and sand). The

results indicated that the optimal temperature for seed germination on filter paper ranged from 13°C to 33°C, while on sand it ranged from 13°C to 23°C. Seeds of the red clover cultivars Truskavchanka and Vytis generally demonstrated higher germination rates compared to the local and wild populations. These results should be considered when studying initial material of various biological statuses and eco-geographical origins under field conditions, as well as when improving cultivation techniques in breeding nurseries for red clover.

Research on the sowing qualities of red clover seeds will continue, taking into account the obtained results, under different temperature regimes, and will assess the impact of soil acidity on seed germination and energy.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Визначення посівних якостей насіння зразків конюшини лучної різного біологічного статусу

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Анотація. Процес створення сортів кормових культур, які адаптуються до мінливих умов навколишнього середовища, є ефективним способом подолання зміни клімату з мінімальними втратами. Температура впливає на час і швидкість проростання насіння, а це в свою чергу забезпечує рівномірність сходів та сумісність конюшини при вирощуванні з іншими культурами, здатність скористатися ідеальними умовами посіву. Метою дослідження було визначення температури та часу, необхідних для досягнення максимальної схожості, та діапазону, в якому проростання відбувалося для чотирьох зразків конюшини лучної різного біологічного статусу (сорт, дикоросла та місцева популяція). Визначення схожості та енергії проростання зразків конюшини лучної проводили відповідно до діючих методик ДСТУ 4138-2002 та ДСТУ 2949-94. при температурі від 3 до 33 °C з кроком 10 °C. Встановлено, що оптимальна температура для проростання насіння конюшини лучної чотирьох досліджуваних зразків на фільтрувальному папері становить від 13 °C до 33 °C, на піску – від 13 °C до 23 °C. В результаті проведених досліджень виділився сорт Vytis, який за всіма показниками перевищив інші зразки при пророщуванні на фільтрувальному папері, та сорт Трускавчанка, який виділився за досліджуваними ознаками при пророщуванні на піску. Кращі показники схожості відмічено в дикорослої популяції при температурі 13 °C. Отримані висновки дають пояснення нерівномірних сходів при посіві зразків конюшини лучної різного біологічного статусу в колекційних та селекційних розсадниках, що спостерігається в польових умовах. Результати, отримані в цьому дослідженні, можуть бути використані для розробки елементів технології посіву конюшини лучної за різних температурних режимів

Ключові слова: *Trifolium pratense* L.; сорт; дикоросла популяція; місцева популяція; температура; схожість

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The efficiency of short-term crop rotations with different sunflower saturation

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Abstract. The study aimed to determine short-term crop rotations' economic and energy efficiency with varying sunflower saturation. The economic and energy efficiency of crop rotations saturated with sunflower under the conditions of the Left-Bank Forest-Steppe region of Ukraine was calculated using technological maps and prices as of 2024. The study employed the following methods: bibliometric analysis – a review of other researchers' findings on the economic and energy efficiency of sunflower cultivation; grouping – an assessment of the economic and energy effects of varying sunflower saturation in crop rotations; and monographic – the generalisation of the results. The optimum sunflower share in crop rotations was found to be 20% and 40%, at which the production cost remained consistently high at 1,218.0-1,240.8 USD/t. Increasing the sunflower share to 60% led to a decline in the production cost, not only for other crops but also for the sunflower itself. This negatively impacted overall price stability, reducing crop competitiveness and the economic efficiency of crop rotations.

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Winter rye exhibited the lowest production costs among all crops, regardless of the crop rotation, at 268.9-321.1 USD/ha. The production costs of soybeans and winter wheat remained stable irrespective of sunflower share, at 413.5 USD and 553.7 USD, respectively, indicating their adaptability. A 20% sunflower share in the crop rotation exhibited the highest energy intensity at 63,348 MJ/ha, while a 60% saturation slightly reduced this figure to 63,279 MJ/ha. However, the 60% sunflower saturation resulted in lower energy consumption compared to other crop rotation options, at 30,293 MJ. These findings indicate the high efficiency of crop rotations with a 60% sunflower share, as evidenced by the energy efficiency ratio of 2.65. As a result of implementing the optimised crop rotation system across 78.9 hectares, sunflower seed yields increased by 0.16 t/ha compared to traditional practices. This improvement led to an additional 1,046 UAH/ha in net profit and a 25.6% increase in production profitability.

Keywords: agricultural economy; sunflower share; crop rotation; energy efficiency

INTRODUCTION

Due to its high profitability, sunflower is the most preferred crop for cultivation. As a result, agricultural enterprises are increasing the area allocated for sunflower cultivation and shortening the interval between successive plantings in crop rotations. The oil extraction industry exerts a significant influence on the price of sunflower seeds, as approximately 95% of sunflower is processed within Ukraine's domestic market. The processing capacity for sunflower seeds is estimated at approximately 5 million tonnes (Statistics Service of Ukraine, n.d.). An integrated system of sustainable agriculture relies on the application of technologies that ensure stable and continuous production. This system is founded on scientifically validated measures aimed at achieving high product quality. Such an approach not only satisfies human needs but also preserves natural resources, maintaining ecological balance and biodiversity within the agricultural system. Additionally, the concept of sustainable development encompasses two other dimensions: social and economic. The social dimension focuses on ensuring sufficient food supplies, promoting fair employment, and fostering the development of local communities. The economic dimension prioritises the viability, efficiency, and profitability of agricultural enterprises. In this context, the implementation of crop rotation serves as a key strategy to enhance the productivity and sustainability of agricultural production (Kuts & Makarchuk, 2021).

Crop rotation plays a vital role in agriculture: it optimises resource use, reduces dependency on fertilisers and agricultural inputs, and increases yields. From an economic perspective, crop rotation can lower resource costs and facilitate the optimal organisation of crop cultivation, while addressing the demands of both domestic and international markets. These factors collectively enhance the profitability of cultivated products (De Souza Linhares *et al.*, 2020; Moldavan *et al.*, 2023).

In recent years, the development of agricultural enterprises has largely depended on sunflower production. This is because sunflower is one of the primary oilseeds in high demand in both domestic and international markets. Current climatic trends significantly

impact agricultural productivity in Ukraine and globally. In particular, the effects of climate change are increasingly evident in the cultivation of winter crops, which are more frequently affected by adverse weather conditions. Over the past decade, the average air temperature in Ukraine has increased by 0.8-1.2°C, and globally by 1.45°C (The Intergovernmental Panel on Climate Change, 2024). According to the State Statistics Service of Ukraine (n.d.), rising air temperatures have resulted in a 5-10% reduction in grain yields. Over the past 30 years, the number of days with severe drought in Ukraine has risen by 20-25%, while precipitation in some regions has decreased by 10-15%, creating unfavourable conditions for winter crops. In response to these challenges, Ukrainian farmers have expanded the area devoted to industrial crops, which are more stress-resistant and adaptable to changing weather conditions. In 2021, the area under sunflower cultivation increased by 8.2% compared to 2020. This trend aligns with global patterns: in countries at high risk of drought, industrial crops comprise up to 20% of total agricultural land (Ukraine Common Country Analysis, 2021).

In Ukraine, the expansion of sunflower cultivation began between 2000 and 2014, during which the total cultivated area grew from 8.4% to 28.4%. As of 2024, the area under sunflower cultivation exceeds 4.9 million hectares. However, sunflower acreage statistics for 2023 remain incomplete due to the inability to account for territories affected by military operations (State Statistics Service of Ukraine, 2024). Despite these challenges, the acreage allocated to sunflower in Ukraine currently exceeds scientifically recommended levels. According to estimates by A. Gavrilyuk (2022) and T. Kostiukevych *et al.* (2022), up to 80% of sunflower crops are concentrated in the Steppe zone and adjacent eastern Forest-Steppe regions. These areas, characterised by their climatic conditions, are classified as risky farming zones, with cultivated land in these regions comprising approximately half of Ukraine's total cultivated land. In these regions, sunflower accounts for 30-40% of the sown area, while the remaining 50-57% is devoted to grain crops.

The research conducted by D. Khmelkova (2020) and Yu. Kolupaev *et al.* (2024) have demonstrated that the area of Ukraine dedicated to sunflower cultivation is approximately two million hectares greater than that of the European Union. A higher proportion of high-yielding crops in the structure of sown areas enables the gross harvest to be obtained from a smaller sown area, thereby achieving a significantly higher yield. Consequently, elevated sunflower yields result in increased gross production. However, due to the redistribution of sown areas, the cost of field operations has risen annually. This increase is attributed to higher rents for land shares, rising prices for fuel and lubricants, mineral fertilisers, plant protection products, and growing wages for employees involved in the production process, all of which constitute the most significant costs. The economic efficiency of sunflower production has been extensively researched by numerous Ukrainian and international authors (Revto & Naboka, 2022). As outlined by V. Zuza *et al.* (2022), the evaluation of economic indicators and production components will facilitate the implementation of existing and the discovery of new reserves to improve the economic efficiency of oilseed production.

The sunflower share in crop rotation significantly impacts the economic efficiency of the entire crop production system. Scientists observe that increasing the sunflower share to 50% or more reduces its profitability from 162% to 56%. Therefore, when planning sunflower cultivation, producers should consider its impact on the yield and productivity of the entire crop rotation, as well as the overall cost of production (Dehtiarova, 2022). From this perspective, growing sunflower in crop rotations is of paramount importance.

The study aimed to determine the economic and energy efficiency of sunflower cultivation about its share in the structure of short-term crop rotations.

MATERIALS AND METHODS

The research was conducted between 2020 and 2022 at the Dokuchaevske Experimental Field Training and Research and Production Centre of the State Biotechnological University, situated in the Left-Bank Forest-Steppe region of Ukraine. Variants of five-field crop rotations with differing sunflower saturation levels were investigated:

■ **VARIANT 1** (20% sunflower share): 1. Peas. 2. Winter wheat. 3. Corn. 4. Winter rye. 5. Sunflower.

■ **VARIANT 2** (40% sunflower share): 1. Peas. 2. Winter wheat. 3. Sunflower. 4. Winter rye. 5. Sunflower.

■ **VARIANT 3** (60% sunflower share): 1. Sunflower. 2. Winter wheat. 3. Sunflower. 4. Winter rye. 5. Sunflower

The sowing plot size was 750 m², and the accounting plot was 100 m². The experiment consisted of three repetitions. The location of the plots remained consistent throughout the study. The technology used for sunflower cultivation adhered to standard practices suitable for the Forest-Steppe region of Ukraine. Fertilisation was applied using ammonium nitrate at 150 kg/ha during sowing and 70 kg/ha for inter-row application. Sunflower was sown when the soil temperature reached 8-10°C. The sowing rate was 50-55 thousand seeds/ha. The crop protection system included the application of soil herbicides Teaser and Selefit at 2 L/ha, and Heliantex (45 g/ha) during the growing season. Harvesting was conducted by direct combining when the seed moisture content was 8-10% (Tishchenko *et al.*, 2015).

The impact of sunflower saturation in short-rotation crop systems was assessed in terms of its yield, along with the economic and energy efficiency of increasing the crop area. For this purpose, economic efficiency was calculated using technological maps, yields, unit costs, profit per hectare, profitability levels, and prices as of 2024 (Drobot *et al.*, 2003). Energy efficiency was evaluated using technological maps (Tarariko *et al.*, 2005).

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

RESULTS AND DISCUSSION

Between 2021 and 2023, Ukraine was among the largest producers and exporters of sunflower and sunflower oil globally. The gross harvest of sunflower was approximately 14-15 million tonnes. However, unfavourable weather conditions in some regions resulted in lower yields compared to previous years (Table 1).

Table 1. Sunflower production in Ukraine (2021-2023)

Indicator	Years			
	2020	2021	2022	2023
Gross harvest, thousand tonnes	13,110	16,392	1,138	12,760
Harvested area, thousand hectares	6,480.9	6,665.1	5,238.0	5,201.6
Yield, t/ha	2.0	2.5	2.2	2.5

Source: developed by the authors developed by the authors based on data from the State Statistics Service of Ukraine (2023)

In 2021, sunflower yields increased due to favourable weather conditions. The total gross harvest reached approximately 16 million tonnes, one of the highest recorded in Ukraine's history. Oil exports also remained consistently high. In 2022, due to the war and military operations in Ukraine, a significant portion of sunflower-growing areas was damaged or became inaccessible. This resulted in a sharp reduction in the area under cultivation, negatively impacting the gross harvest. The harvesting campaign was lower than in previous years, partly due to logistical challenges and infrastructure damage. In 2023, the situation remained challenging owing to ongoing hostilities and risks to agriculture. However, producers adapted to the new conditions, and yields partially improved due to the restoration of some cultivated areas and the application of improved agricultural technologies (Statistics Service of Ukraine, n.d.).

Crop rotation with a sunflower saturation of 20% demonstrated high crop yields, particularly for winter wheat and corn, which reached 4.20 and 4.73 t/ha, respectively (Fig. 1). With a 40% sunflower share, crop yields declined slightly. However, the optimal agrochemical parameters of this variant contributed to an increase in sunflower yield to 2.72 t/ha (Dehtiarova, 2023). In the variant with sunflower saturation in crop rotations increased to 60%, yields decreased for all crops, including sunflower, which fell to 2.63 t/ha.

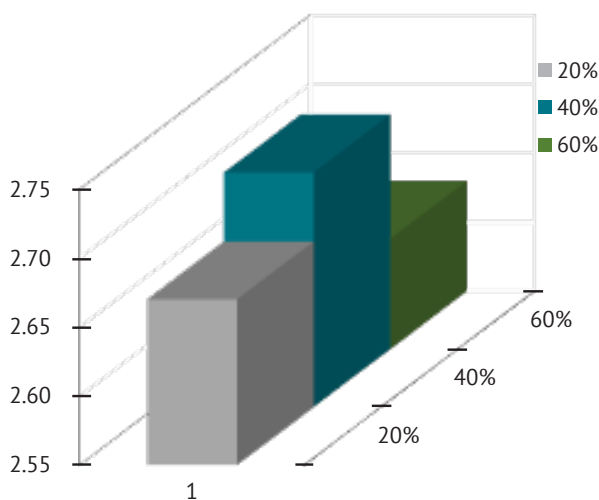


Figure 1. Sunflower yield depending on its share in crop rotation, t/ha

Source: developed by the authors

The high market price of sunflower makes it the most profitable crop in crop rotations. In the variant with 20% saturation, sunflower yielded the highest profitability, while other crops exhibited a relatively stable and lower cost structure. For crop rotations with a sunflower saturation of up to 40%, the cost of production for all crops, except sunflower, decreased. At 60% saturation, a downward trend in the costs of all crops, including sunflower, was observed, with sunflower costs reaching 1,199.8 USD/t. This level of saturation had a notably negative impact on the overall costs of growing crops in rotation, primarily due to low yields. At 20% saturation, the cost of growing sunflower was the highest among all crops, at 618.0 USD/t. A similar trend continued across other variants. The lowest costs were recorded for winter rye, ranging between 268.9 and 315.3 USD/t. The costs of growing soybeans and corn also remained relatively low.

The economic assessment of crop rotations with varying sunflower saturation levels indicated that variants with 20 and 40% sunflower saturation generated relatively high notional net profits, ranging between 600 and 622.8 USD/ha (Table 2). In contrast, in the crop rotation with 60% saturation, profit from sunflower decreased by approximately 18.3 USD. An analysis of the economic performance of the crop rotation with 40% saturation showed that sunflower provided a high notional net profit in the first year, amounting to 622.8 USD/ha. The profitability of an enterprise is a comprehensive indicator that assesses how effectively material, financial, and human resources are utilised to generate profit. It also helps evaluate the competitiveness of the company's goods and services. High profitability often signifies product quality, appropriate pricing strategies, the ability to meet market demand, and the efficient organisation of production processes (Sobolev, 2020; Zbarskyi & Matsybora, 2023). The economic evaluation of crop rotations with 60% sunflower saturation indicated a decline in profitability, primarily due to reduced notional net profits and increased production costs. The profitability of crops demonstrated a downward trend with higher shares of sunflower cultivation, indicating the impact of intensive monoculture practices on economic performance. Among all crops in the rotation, sunflower achieved the highest profitability across different saturation levels, particularly at 20% and 40%, where it exceeded 97%.

Table 2. Economic efficiency of short-term crop rotations with different sunflower saturation levels per 1 ha, (average for 2020-2022)

Sunflower share, %	Crop rotation	Indicator					
		Yields, t	Product cost, USD	Production expenses, USD	Cost of sales, USD	Profit, USD	Profitability level, %
20	Soy	1.78	647.6	413.5	232.3	227.6	55.0
	Winter wheat	4.20	806.7	553.7	131.8	253.0	45.7
	Corn	4.73	678.5	553.0	117.4	125.5	22.7
	Winter rye	3.13	481.0	321.1	102.6	159.9	49.8
	Sunflower	2.67	1,218.0	618.0	231.5	600.0	97.1

Table 1. Continued

Sunflower share, %	Crop rotation	Indicator					
		Yields, t	Product cost, USD	Production expenses, USD	Cost of sales, USD	Profit, USD	Profitability level, %
40	Soy	1.73	623.5	413.5	239.0	209.6	50.7
	Winter wheat	4.11	789.43	553.7	134.7	235.8	42.6
	Sunflower	2.71	1,236.3	618.0	228.01	618.2	90.4
	Winter rye	3.10	476.4	315.3	101.7	161.0	51.1
	Sunflower	2.72	1,240.8	618.0	227.2	622.8	100.8
60	Sunflower	2.58	1176.9	618.0	239.5	558.9	78.6
	Winter wheat	3.84	737.6	553.7	144.2	183.9	33.2
	Sunflower	2.64	1204.3	618.0	234.1	586.3	72.7
	Winter rye	2.97	352.5	268.9	90.5	83.6	31.1
	Sunflower	2.63	1,199.8	618.0	235.00	581.72	94.1

Note: exchange rate – 41.23 UAH per 1 USD as of 01.11.2024

Source: developed by the authors

Increasing the sunflower share to 60% resulted in higher production costs for most crops, particularly for sunflower and winter wheat, which demonstrated the highest production costs compared to the 20 and 40% saturation levels. Winter rye, in contrast, remained the least expensive crop to cultivate and sell, especially at 60% sunflower saturation, indicating its economic efficiency and cost stability. The optimum sunflower saturation level for cost control was 20%, at which point sales costs for all crops remained relatively low, ensuring the stability and cost-effectiveness of the crop rotation. However, at 60% saturation, sunflower efficiency decreased, indicating that excessive sunflower

cultivation can result in resource depletion and reduced economic performance.

Among the options studied, a 60% sunflower saturation yielded the highest notional net profit per hectare – 404.3 USD. This level of saturation resulted in a profitability rate of 69.7%, which was nearly 1.3 times higher than the profitability achieved with the optimal sunflower saturation of 20% (Fig. 2). Reducing the sunflower share to 40% lowered the notional net profit and profitability by 34.8 USD and 0.7%, respectively. These findings underscore a stable market demand for sunflower, which offsets price declines for other crops.

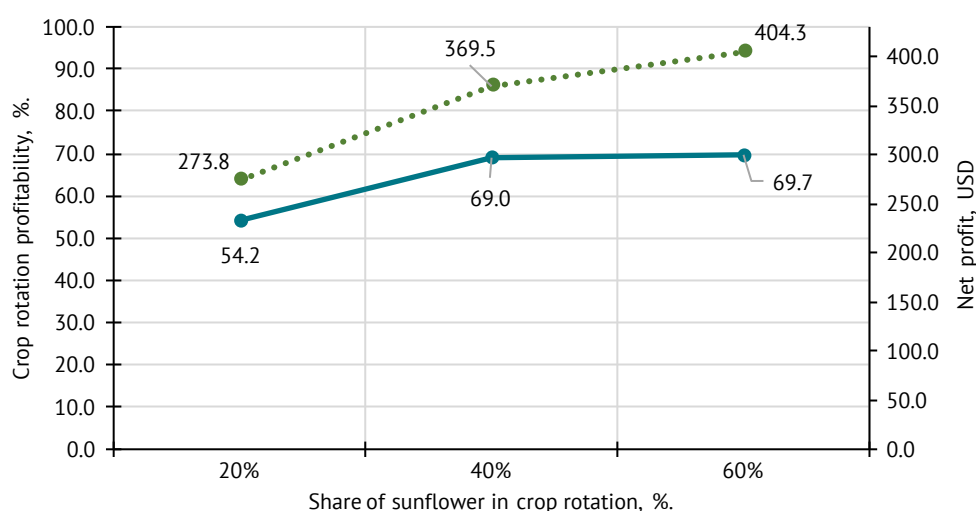


Figure 2. Influence of sunflower share on profitability and net profit of crop rotation, (average for 2020-2024)

Source: developed by the authors

High sunflower yields in the 20 and 40% saturation variants resulted in a substantial notional net profit, with profitability levels exceeding 120%.

Yu.V. Mashchenko & I.M. Sokolovska (2023) reported that saturating crop rotations with sunflower up to 50% increases grain yields to 3.51 t/ha, feed units to

1.93 t/ha, and digestible protein to 0.66 t/ha. Compared to monoculture sunflower cultivation, this approach improved yields by 0.72 t/ha, 0.39 t/ha, and 0.14 t/ha, respectively. The researchers also determined that rotating sunflower with corn increased sunflower yields to 1.75 t/ha, compared to 1.39 t/ha under continuous cultivation. This rotation produced a yield increase of 0.36 t/ha, equivalent to 21.5%. Similarly, A. Slobodanyk *et al.* (2021) noted in their studies that the highest level of profitability in sunflower cultivation is achieved when resource costs for sunflower seeds remain at approximately 55.5 thousand UAH per hectare, with a yield of 2.2 t/ha (18% below the standard level). According to the research conducted by L. Kvasnitska (2020), a high profitability rate of 157% was observed in crop rotations with a 40% saturation of oilseeds. At this level, the value of produced products was maximised while cultivation costs remained low. Scientists generally agree that sunflower holds significant economic importance in agriculture, primarily due to its adaptability to diverse climatic conditions (Khakbazan *et al.*, 2022; Puttha *et al.*, 2023).

The energy assessment is based on the use of the indicator for total energy consumption and determines the value of agrophytocenosis productivity (Tarariko *et al.*, 2005). In the agricultural sector, the efficient use of energy resources is achievable through intensive technologies that promote resource conservation, with sunflower serving as a key crop in this process. When cultivating sunflower, it is important to manage production processes using a system of integrated energy efficiency indicators. Machinery and equipment constituted the largest proportion of energy consumption (29.5%). Seeds, pesticides, fuels, lubricants, agricultural machinery, and fertilisers also contributed significantly to total

energy consumption. The energy costs of short-rotation crop rotations vary depending on the crop mix, their yields, and the use of mineral and organic fertilisers. To identify the most efficient practices, it is advisable to carry out an energy assessment during the planning phase of the process. This enables the recommendation of solutions that ensure optimal energy use.

In this research, an energy assessment was conducted based on the level of energy consumption, accumulated energy by the crop, and the calculation of the energy efficiency ratio (EER). The energy assessment was derived from technology maps by calculating the energy required to grow a crop on an area of 1 ha and the energy intensity of the crop, expressed as the energy efficiency ratio. This was determined by the ratio of the crop's accumulated energy to the energy required by the agricultural technologies. For this purpose, it is important to analyse the level of fertiliser and pesticide use, fuel consumption, types of vehicles and implements employed, as well as the impact of natural resources, soil and climatic conditions, and solar radiation. This research revealed that energy consumption for crop rotations with a sunflower share of 60% and 40% was comparable, ranging between 30,293 and 33,428 MJ/ha (Table 3). Crop rotation with a 60% sunflower saturation resulted in lower energy consumption – 30,293 MJ, while the energy intensity of the crop was 63,279 MJ/t. The highest energy consumption was recorded in the crop rotation with a 20% sunflower share – 45,793 MJ/t, primarily due to the inclusion of corn in this rotation. The calculation of the energy efficiency ratio demonstrated that the most energy-efficient crop rotation was the one with 60% sunflower saturation, yielding an EER of 2.65. A gradual decline in this indicator was observed as the sunflower share in the crop rotation decreased to 40 and 20%.

Table 3. The energy efficiency of short-term crop rotations with different sunflower saturation

Indicator	Sunflower share in crop rotation, %		
	20	40	60
Energy costs, MJ	45,793	33,428	30,293
The energy intensity of the crop, MJ/t	63,348	59,586	63,279
Energy efficiency ratio (EER)	1.53	1.94	2.65

Source: developed by the authors

In the variants studied, the EER was the highest in the crop rotation with 20% sunflower saturation (3.03). A gradual decline in this indicator was observed with an increase in the sunflower share in the crop rotation, reaching 40% and 60%, with values of 2.74 and 2.60, respectively. This suggests that each additional unit of sunflower cultivation incurs diminishing returns in terms of energy output from the crop. Thus, the lowest energy consumption for producing 1 tonne of sunflower seeds was recorded in the crop rotation variant with 60% saturation. Conversely, the highest energy intensity was observed in the variant with 20% sunflower saturation.

Many researchers have studied the energy efficiency of sunflower cultivation. For example, in the experiments conducted by G.V. Pinkovsky and S.P. Tanchyk (2019), the energy efficiency ratio of sunflower cultivation ranged between 3 and 4. For comparison, the study by C. Oguz and A. Yener Ogur (2022) indicates that the energy consumption for producing 1 kilogram of sunflower was 5.06 MJ/kg⁻¹. According to O.K. Medvedovsky and P.I. Ivanenko (1988), the energy efficiency ratio should be at least 2. With such values, the gross energy yield from the harvest exceeds the total energy consumption. The results of the study by

N. Gerasymchuk and T. Mirzoyeva (2017) indicate that in recent years, the economic efficiency of sunflower seed production in Ukraine has improved as a result of production intensification. L. Kvasnitska (2020) has established a high level of energy efficiency in crop rotations with sunflower saturation of up to 40%. At this level, the energy efficiency ratio was found to be 4.57 conventional units.

The results of the study on the economic efficiency of sunflower cultivation conducted by O. Pysmenyi (2018) indicate that the intensification of production in Ukraine has a significant economic impact on sunflower cultivation. The study found that the highest sunflower yields were achieved by enterprises with the greatest expenditure on seeds, fertilisers, and plant protection products. Research by A. Andriienko *et al.* (2024) demonstrated that cultivating high-productivity sunflower hybrids significantly increases profitability and reduces seed costs. In addition, the results of research conducted by E. Vilvert *et al.* (2023) show that, in two regions of Tanzania, sunflower accounts for 12% of the highest income from crop production. This profitability is contingent upon the rate of yield increase for the crop exceeding the rise in production costs per hectare of sown area. Limagrain sunflower hybrids are characterised by strong economic performance. G.V. Pinkovsky and S.P. Tanchyk (2019) determined that net profits from cultivating these hybrids can range between 20,307 and 22,043 UAH/ha.

The results of N. Kondratyuk's (2015) research indicate that, with production costs accounting for 24.5% of sunflower cultivation, a profit of 33% can be achieved. Seeds constituted the largest share of total expenditures (15.0-18.7%), followed by fuel and lubricants (11.3-12.7%). Research by Ye. Domaratskyi and O. Kozlova (2020) revealed that the net profit from sunflower cultivation could reach 26,292 UAH, while the cost price was 3,441 UAH, resulting in a profitability level of 196%. An economic analysis of sunflower cultivation conducted by Y. Tsybmal *et al.* (2022) found that notional net profits can vary depending on crop rotation, ranging between 24.9 and 30.1 thousand UAH/ha, with profitability levels of 176-211%. Sunflower grown in a short rotation crop system with a 20% share provided a notional net profit of 24.9 thousand UAH/ha, achieving profitability of 176%. In this case, the value of gross output was 39.1 thousand UAH. Growing sunflower in eight-field crop rotation with 12.5% crop saturation

generated a profit of 29.3 thousand UAH/ha and profitability of 207%, with expenses amounting to 14.18 thousand UAH. Scientists also determined that growing sunflower in a seven-field crop rotation with 14.3% saturation yielded the highest profits. In this scenario, the notional net profit amounted to 30.14 thousand UAH/ha, with a profitability level of 211%. Crops grown in this rotation generated 5.21 thousand UAH/ha more profit compared to the five-field crop rotation and 0.82 thousand UAH/ha more than the eight-field crop rotation.

CONCLUSIONS

Studies have shown that different levels of sunflower saturation in short-term crop rotations influence economic and energy efficiency indicators. The variants with 20 and 40% sunflower saturation achieved the highest notional net profit of 419.4-432.5 USD, with a profitability level of 120-126%. In contrast, the profitability of growing sunflower in a crop rotation with 60% saturation was 100%. Incorporating sunflower into a crop rotation with a 20% share resulted in high energy intensity (77,798 MJ/t) and the highest energy consumption (25,664 MJ/t), which led to an increase in the energy efficiency ratio to 3.03. The variant with 60% sunflower saturation had a lower energy intensity (65,042 MJ/t) and lower energy costs (24,994 MJ/t), with an EER of 2.60. The ratio of energy intensity to energy costs in the variant with 40% saturation in short-term crop rotations was 2.74. To maintain profitability and ensure consistent returns, it is advisable to keep the sunflower share in crop rotations at no more than 40%. An important direction for future research is to assess the adaptive capacity of sunflower under different crop rotation saturations in response to abiotic and biotic stress factors within the conditions of the Left-Bank Forest-Steppe region of Ukraine.

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CONFLICT OF INTEREST

None.

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Ефективність короткоротаційних сівозмін з різним насиченням соняшником

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Анотація. Метою дослідження було визначення економічної та енергетичної ефективності короткоротаційних сівозмін з різним насиченням соняшнику. Економічну та енергетичну ефективність сівозмін з різною часткою соняшнику в умовах Лівобережного Лісостепу України розраховано за допомогою технологічних карт та цін станом на 2024 р. У дослідженні використано такі методи: бібліометричний – аналіз результатів інших науковців щодо економічної та енергетичної ефективності вирощування соняшнику; групування – визначення економічного та енергетичного ефекту від насичення сівозмін соняшником; монографічний – узагальнення отриманих результатів. Встановлено оптимальну частку соняшнику у сівозміні на рівні 20 і 40 %, при яких вартість продукції залишалася стабільно високою 1 218,0-1 240,8 дол./т. Зростання частки соняшнику до 60 % призводить до зниження вартості продукції не тільки для інших культур, але й для самого соняшнику, що негативно впливало на загальну цінову стабільність, знижуючи конкурентоспроможність культур і загальну економічну ефективність сівозміни. Озиме жито демонструвало найнижчі виробничі витрати серед усіх культур не залежно від сівозміни – 268,9-321,1 дол. Витрати на сою і озиму пшеницю залишалися стабільними незалежно від частки соняшнику – 413,5 і 553,7 дол., відповідно, що свідчить про їх адаптивність. Частка соняшнику у сівозміні 20 % мала найвищу енергоємність серед варіантів – 63,348 МДж/га. Насичення на 60 % знижувало цей показник до 63,279 МДж/га. Однак, така сівозміна забезпечила енерговитрати на нижчому рівні порівняно з іншими варіантами – 30,293 МДж. Отримані дані свідчать про високу ефективність сівозміни з часткою соняшнику 60 %, про що свідчить коефіцієнт енергетичної ефективності на рівні 2,65. У результаті впровадження наукової розробки на площі 78,9 га було встановлено, що за рахунок оптимізації сівозмін порівняно з традиційно прийнятими, врожайність насіння соняшнику зросла на 0,16 т/га. Це дозволило отримати додатково 1 046 грн/га чистого прибутку та підвищити рентабельність виробництва на 25,6 %

Ключові слова: економіка сільського господарства; частка соняшнику; сівозміна; енергоефективність

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Methodological and practical aspects of using satellite imagery to assess the military impact on soils

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Abstract. The military aggression of the Russian Federation has caused significant negative impacts on Ukraine's natural ecosystems, including its soils. Comprehensive assessments of soil conditions, the extent, and the scale of damage caused by warfare are essential for documenting the resulting losses. However, the use of traditional field surveys of soil cover is hindered by the significant threat of landmines in areas

liberated from occupation. This limitation necessitates the widespread adoption of remote sensing methods, such as satellite imagery. This study aimed to assess the condition of soils and the extent of their damage due to military activity within the Chkalovske territorial community of the Chuhuiv District in the Kharkiv Region. The study identified the optimal combinations of optical bands from Sentinel-2 satellites for monitoring the consequences of military impact on soil cover. A spatial layer of objects was developed to represent various types of military-induced soil degradation within the community, including damage from continuous shelling (craters from shells, rockets, and bombs); soil compaction from the movement of military vehicles (tracks and pathways); fortification structures (defensive fighting positions and dugouts); and fires caused by shelling. Using high-resolution satellite imagery, the number of craters and the soil mass loss caused by explosions, the areas of burned and compacted land, as well as the length of anti-tank ditches and defensive fighting positions with dugouts, were calculated at the test site. On the irrigated lands of the Chkalovske territorial community, the areas affected by shelling and those burned due to military-related fires were also estimated. The information derived from satellite imagery serves as a crucial step in developing measures for the restoration of the soil cover in the pilot area affected by military degradation. The study utilised satellite imagery of varying resolutions and geographic information systems to calculate the damage caused by military actions with sufficient accuracy. It also analysed the temporal and quantitative interrelations among different types of military impact. This research will serve as a basis for assessing the scale and spatial distribution of soil damage, calculating the loss of fertile soil layers, and conducting an economic evaluation of the damage inflicted on soil resources

Keywords: remote sensing; Sentinel-2; vegetation index; military degradation; soil damage; craters

INTRODUCTION

Ukraine plays a strategic role in the global food market and in ensuring global food security thanks to its highly developed agro-industrial complex. Soil resources play a crucial role in affirming Ukraine's leading position in the world in terms of agricultural trade volumes. However, these soils are now facing significant damage and destruction due to the ongoing war. Ukraine has a unique soil cover: more than 60% of its territory is occupied by chernozems, which are unmatched in terms of their root-containing layer, properties, fertility potential, and suitability for growing many field crops. The world's particular attention to the state of chernozems is due to their high suitability for agriculture, thanks to their natural fertility, high organic carbon content, and active soil biodiversity. The beginning of Russia's full-scale armed aggression against Ukraine has caused mass damage to the soil cover, the likes of which have not been seen since the Second World War. Over 5 million hectares of chernozems are located in the war zone, resulting in military (war-induced) degradation of varying intensity and direction – physical, physicochemical, mechanical, chemical, and biological (Baliuk *et al.*, 2024).

The EU Soil Strategy for 2030 (2021) aims to protect and restore soils, ensuring soil health and sustainable management. Numerous problems have jeopardised soil health, including declining carbon content, biodiversity loss, salinisation, acidification, pollution, erosion, and others. In Ukraine, these issues are

exacerbated by the ongoing conflict, as the impact of anthropogenic factors on soil condition, properties, and fertility intensifies. It should be emphasised that the availability of reliable information on the condition of chernozems during and after the war will determine the effectiveness of measures to restore their fertility. A necessary condition for assessing the damage and losses from hostilities on agricultural lands is the application of remote sensing of soils, especially high-resolution satellite imagery.

In their research, M. Khalil and J. Satish Kumar (2021) identified the most affected areas in the capital of Syria by analysing two images from the Sentinel satellite using GIS software. The result of the study was a classification of territories into five classes in terms of suitability or unsuitability for reconstruction, as well as determining the percentage of each class. To map and monitor changes in the urban environment due to war, F. Fakhri and I. Gkanatsios (2021) integrated data from Sentinel-1 and Sentinel-2 satellites. The authors determined the percentage of destruction in the city of Mosul (Iraq) using spectral indices, the most important of which is the built-up area index.

A group of studies on the war in Kuwait focused on assessing the impact of hydrocarbons on vegetation resilience, modelling oil pollution in soils, and monitoring reclamation efforts in arid regions. M.M. Abdullah *et al.* (2020) utilised remote sensing to evaluate ecosystem resilience to hydrocarbon pollution caused by the

war in Kuwait and the potential for post-war vegetation recovery in arid landscapes. The study identified correlations between vegetation recovery, soil type, geomorphological features, and precipitation levels. E. Kalandar *et al.* (2021) found that oil pollution is associated with elevated concentrations of heavy metals in soils, which, in turn, affect the stability of plant communities. In research by G. Kaplan *et al.* (2022) the location and extent of oil pollution were determined to guide subsequent soil cleaning and reclamation measures. Based on an analysis of war-affected lands using remote sensing, H.A. Hasab *et al.* (2020) employed Landsat satellite data and decision tree (DT) classification to conclude that salinity and heavy metal concentrations decreased during the summer and increased in the winter.

Combining remote sensing data, field studies, and historical data, Polish researchers J.M. Waga and M. Fajer (2021) assessed the impact of bombing on forests and wetlands in the Koźle basin during the Second World War. They found that around 6000 well-preserved bomb craters, ranging from 5 to 15 meters in diameter and often exceeding 2 meters in depth, still exist in the region. Analysis of these craters revealed that their diverse morphology depends on the weight of the bombs that created them, as well as the type and moisture content of the soil on which the bombs fell. B. Demisie *et al.* (2022) used a comparison of time-series Sentinel-2 images to assess the impact of the Tigray Conflict (Ethiopia) on agricultural activities. By comparing the NDVI on agricultural fields in the pre-war and wartime spring seasons, they recorded an increase in greenness due to weed infestation.

Initial results of assessing the impact of the Russian-Ukrainian war on the environment, particularly soils, using remote sensing data have been revealed in publications by Ukrainian scientists. For example, S.A. Shevchuk *et al.* (2022) found that between 2021 and 2022, vegetation greenness decreased in areas where hostilities were most intense (Luhansk and Donetsk). M. Solokha *et al.* (2023) demonstrated the damage to vegetation cover caused by bombing using the example of the Kharkiv Region. A.B. Achasov *et al.* (2023), using the example of the Rohan community, identified 916 bomb craters as a result of deciphering satellite imagery data in 2022. Maps were created showing the results of recording the consequences of bombing, a heat map of explosion density, and a hydrological analysis map of the territory that could be contaminated as a result of bombing.

When assessing the impact of the war on the ecosystems of protected areas in Ukraine, O. Trofymchuk *et al.* (2023) found numerous fortifications (trenches, defensive fighting positions, dugouts), burnt-out areas, and tracks formed by the active movement of military equipment in places where the topsoil had been disturbed. A comprehensive methodological approach to assessing military damage to soils in a specific

community was proposed in the study of O.S. Bonchkovskiy *et al.* (2023), in which the authors identified the most pronounced physical damage to soils in the form of craters and soil compaction, and identified bombing zones and contamination around craters. The authors concluded that soil reclamation should be carried out taking into account the specific characteristics of each contaminated and disturbed site. Another comprehensive study is the research by A. Sploditel *et al.* (2023), where, using the example of several territorial communities, an assessment of military damage to soils was conducted using high-resolution image analysis, and locations of craters from shelling, fortifications, compaction tracks from heavy military equipment, and fire foci were identified.

The relevance of the chosen topic determined the aim of the study, namely to search for and identify the consequences of military impact using satellite data of various resolutions.

MATERIALS AND METHODS

The study focuses on the soil cover of the Chkalovske territorial community (TC), which has been impacted by military activities. The community is located in the Chuhuiv District of the Kharkiv Region (Fig. 1). The total area of the territorial community is 38,697.0 hectares, including 32,257.81 hectares of agricultural land. The soil cover of the study area is predominantly represented by typical medium-humus heavy loamy and light clay chernozems. The research was conducted on both irrigated and non-irrigated lands within the TC that have been affected by military activities.

To identify various types of military impact on soils, key sites were selected in different parts of the community, focusing on areas with the highest intensity of disturbance. Craters from shell explosions were identified in the western part of the TC near the villages of Korobchyn and Hrakove. Soil compaction traces were studied in the central part, near the village of Nova Hnylytsia. Fire damage caused by shelling was examined in the central area around the settlement of Doslidne and the urban-type settlement of Chkalovske. Fortifications were documented in the northern part of the community near the village of Yurchenkove. The total area of irrigated lands in the Chkalovske TC is 1,754 hectares. For the study, the primary area of these lands, covering 1,145 hectares, was selected. Irrigation in this area had been conducted over an extended period using water with a salinity of 1.9-2.4 g/dm³, leading to secondary salinisation in the chernozem soils. The methodology for detecting and analysing military-induced soil degradation differs from traditional field-based soil surveys. In this context, the extensive use of remote sensing methods is essential for obtaining objective data on soil conditions. A wide range of satellite data sources is currently available, varying in accessibility and spatial resolution.



Figure 1. Chkalovske community on the map of Ukraine

Source: author's mapping scheme

The use of remote sensing methods enables the acquisition of preliminary information on the condition of soils affected by military activities. Satellite imagery can be employed to monitor changes in soil cover over specific periods and to generate cartographic materials based on the data obtained. Notably, remote sensing materials most effectively capture evidence of mechanical and physical soil degradation resulting from combat operations. Other forms of degradation, such as chemical and biological, are typically secondary to these primary types.

Mechanical degradation appears in satellite images as anomalous colour features, often circular shapes (craters) or elongated, irregular patterns representing trenches, ditches, and similar structures. Early identification of these features is essential for accurate assessment. Physical degradation, observed throughout the study period, is evident in tracks left by military vehicles on agricultural fields. Indicators of this type include filamentous lines on fields that were absent prior to the onset of hostilities. Abiotic impacts from fires are identifiable as abrupt changes in vegetation colour, transitioning to an intense black on the affected fields. Over time, the colour becomes lighter as the remains of combustion decompose, meaning identification can occur from weeks to months after the initial impact. Chemical impacts are identifiable in cases where signs of burned military equipment are visible in satellite imagery, typically in a random pattern. These are accompanied by black or white smoke in images captured during active combustion or by abrupt black discolouration in affected areas.

For a preliminary assessment of the presence and extent of soil damage, the use of free, openly accessible

satellite imagery is advisable. Among such sources, the Sentinel-2 satellites of the European Space Agency provide the most detailed information. These satellites offer a maximum resolution of 10 metres per pixel, enabling the identification of areas with clusters of craters from shell explosions, individual craters from airstrikes, soil surface compaction caused by military vehicles, and large fortifications.

Sentinel-2 allows for image updates every 5 days for the same area. To ensure a high-quality analysis of soil surface damage, it is essential to select images captured on cloud-free days. The timing of observations relative to seasonal changes is also significant. When using Sentinel-2 imagery, the period from mid-spring to mid-autumn should be selected to capture vegetation at various stages of growth. During this time, vegetation serves as a clear indicator of mechanical impacts on the soil, allowing such impacts to be traced through uneven vegetation cover. However, it should be noted that during peak vegetation growth in summer, identifying traces of combat activity can sometimes be challenging due to the overgrowth of the targeted areas. Sentinel-2 provides multispectral imagery comprising 12 optical bands. The following bands were selected for image analysis: blue (Blue-B02), green (Green-B03), red (Red-B04), near-infrared (NIR-B08), and shortwave infrared (SWIR-B11, B12).

The majority of the Chkalovske TC was occupied from 7 April to 10 September 2022, a period of approximately five months (DeepStateMAP, n.d.). To assess soil damage, Sentinel-2 satellite imagery was selected from the post-conflict period, spanning from mid-September to the end of the year. For high-resolution images, the following dates were chosen: 23 and 24 January, and

23 March 2023. These dates were selected to ensure cloud-free and snow-free conditions over the study areas. The winter and early spring periods are particularly suitable for assessing soil surface damage due to the absence of vegetation cover. Satellite images from Sentinel-2 were downloaded and initially processed using the EO Browser online platform (Sentinel Hub EO Browser, n.d.). The creation of maps showing soil damage identified in the imagery was conducted using the licensed version of the MapInfo software and the educational version of ArcGIS (ArcGIS Desktop, n.d.).

To compare and identify changes in the soil cover for 2022, satellite images from the corresponding period in 2021, prior to the onset of hostilities, were selected. EO Browser provides a feature for comparing images from different times by displaying a split-screen boundary between two images or overlaying them with adjustable transparency for smooth transitions (Fig. 2). This comparison enables the identification of military impacts, including shell craters, compaction from heavy equipment, fire damage caused by shelling, and fortification structures.

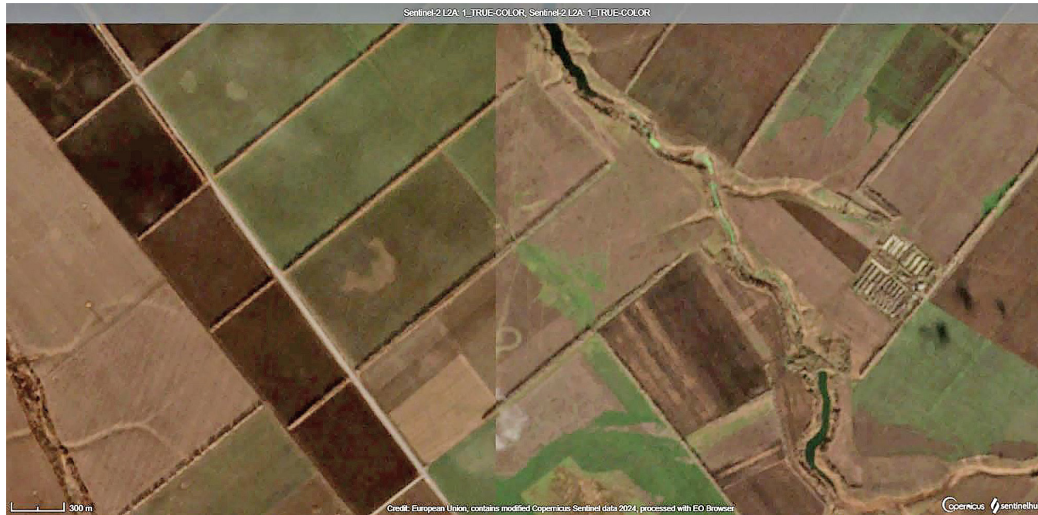


Figure 2. Comparison mode for different-time images in EO Browser

Source: screenshot from Sentinel Hub EO Browser (n.d.)

The identification (interpretation) of different types of soil damage caused by hostilities involves specific considerations. The most common damages are craters resulting from shell explosions of varying calibres and aerial bombs. Explosion sites on the soil surface are characterised by the displacement of subsurface soil masses from deeper genetic horizons, leading to material mixing. This phenomenon, observed universally, is termed “bombturbation” (Bonchkovskyi *et al.*, 2023; Sploditel *et al.*, 2023).

There is a direct correlation between the size of the craters and the calibre of the explosive device. For example, damage from a mortar shell is significantly smaller than that caused by an aerial bomb. Sentinel-2 satellite imagery lacks the resolution required to clearly distinguish small-diameter individual craters. However, small craters typically occur in clusters, which are visually detectable in Sentinel-2 images. Craters from larger calibres and aerial bombs can be identified by the lighter-coloured areas surrounding them, caused by the exposure of lighter subsoil and parent material ejected during the explosion.

The simplest method for analysing satellite images involves using the combination of blue, green, and red channels (RGB composite), known as “True Colour”.

However, for studying military-induced soil damage, employing alternative colour combinations (optical channels) is crucial for a more detailed examination of the soil cover condition. One of the most commonly used combinations is “False Colour”, which incorporates green, red, and near-infrared (NIR) channels. The NIR spectrum is particularly effective for monitoring vegetation, as it has the highest reflectance in this range. In the resulting images, vegetation appears in shades of red. During periods of active vegetation growth, dense plant cover obscures the soil surface, making it challenging to clearly identify craters formed before the peak growth phase, such as in spring. Damage to fields caused during the summer period can still be identified using specific optical channel combinations. One effective combination is known as “Agriculture”, which integrates shortwave infrared (SWIR), NIR, and blue channels. The addition of SWIR expands the analytical range for observing soils and vegetation. When using the “Agriculture” composite, vegetation appears in natural green hues, allowing for clearer identification of soil and vegetation conditions.

Another effective method for analysing soil damage, such as craters, involves the use of indices, particularly vegetation indices. The most well-known and

widely used of these is the NDVI, calculated using the equation:

$$NDVI = \frac{(NIR-RED)}{(NIR+RED)}, \quad (1)$$

where *NIR* is the near-infrared and *RED* is the red spectrum, yielding values between -1 and 1.

For Sentinel satellite channels, the equation appears as:

$$NDVI = \frac{(B08-B04)}{(B08+B04)}, \quad (2)$$

NDVI is best suited for assessing the condition of agricultural crops over relatively large areas. Identifying craters as smaller-scale objects can be more challenging, particularly on images with resolutions lower than the diameter of the damage. The primary scenario where NDVI is useful is during the late autumn period when a significant contrast exists between the weed-covered edges of craters and the surrounding area, which is typically free of vegetation. Other vegetation indices, such as the EVI and SAVI, can also be utilised. EVI is an improved and calibrated version of NDVI, while SAVI is particularly useful in areas with sparse vegetation, where the proportion of vegetation to bare soil favours the latter.

To better highlight signs of military impact in satellite images, it may be necessary to create custom optical channel combinations. The most effective way is to use equations to calculate the resulting raster of optical channels. The first method is the division (ratio) of one channel by another according to the equation:

$$Ratio = \frac{A}{B}, \quad (3)$$

where *A* is the first channel and *B* is the second channel.

There are two rules for such division. If the calculation involves channels of the visible and infrared spectral ranges, then the optical channel with a smaller number is placed first. When both channels are within one of the named ranges, then the channel with a larger number should be placed first. For example, in the case of Sentinel satellites, the substitution into the formula should look like B04/B11 in the first variant, and B11/B08 or B04/B02 in the second. If these rules are not followed, the resulting image will be displayed incorrectly.

The second method involves creating custom indices based on the equation:

$$Index = \frac{(A-B)}{(A+B)}, \quad (4)$$

where *A* is the first channel and *B* is the second channel.

In this approach, the channel with the higher number is placed first, similar to the NDVI index calculation described earlier. Failure to follow this rule will result in an inability to generate the image. Traditionally,

vegetation index images are displayed in shades of green, achieved by applying an RGB colour scheme. However, the output in this case is a monochrome (blackandwhite) raster, which allows for greater detail to be observed when identifying features such as craters caused by shell explosions. The described approaches to using optical channel combinations and calculations based on formulas are also applicable for identifying other types of military-related damage, including traces of military vehicles, fortifications, and fires caused by shelling.

The movement of military vehicles results in soil compaction, the traces of which can also be identified on satellite imagery. Military-induced compaction can often be mistaken for the effects of agricultural machinery on the soil. To accurately distinguish the impact of military vehicles, it is essential to compare images captured before the onset of active hostilities in the area with those taken immediately after their conclusion. Another critical condition for the clear identification of compaction traces is the presence of sparse vegetation. Dense vegetation causes significant overlap between neighbouring pixels in the image of the analysed area, thereby complicating the detection of this type of damage.

The principles for identifying fortifications (such as defensive fighting positions and dugouts) are similar to those for recognising compaction pathways caused by military vehicles. On satellite images, fortifications appear as distinct linear features resembling broken lines with numerous branches. The primary condition for successful identification of fortifications is their size, which must exceed the pixel resolution of Sentinel-2 imagery (10 m or larger). The aftermath of fires is identifiable on satellite images as distinct enclosed areas of irregular dark shapes, resulting from soot deposits on burned surfaces. These features are most evident during active burning due to additional indicators such as rising smoke. Another favourable period for detecting fires is during active vegetation growth, as the vegetation indices decrease sharply in affected areas.

For each type of military-induced soil damage, it is necessary to establish a set of optimal combinations and calculations of optical channels. It should be noted that the set of ratios and indices will vary depending on the season and the specific timeframe following the cessation of hostilities. In this study, it is proposed to use channel combinations that are optimal for the autumn period. After identifying areas of soil damage through the synthesis and calculations of Sentinel-2 optical channels, spatial layer contours of military impact are created within the EO Browser environment. These contours are then transferred to GIS software for further customisation of data layer visualisations representing different types of military-induced degradation.

The next stage, following the identification of damage and the delineation of areas affected by military activity using Sentinel-2 imagery, involves obtaining

higher-resolution images to refine the boundaries of the damage. At the initial stage, satellite imagery in the form of “base maps” in GIS software is sufficient. Currently, satellite images capturing the consequences of military actions with a resolution of 1-5 m are available in open access. However, these images have limitations: they cannot be downloaded for further analysis, and they represent a single timeframe (late August to early September 2022), which prevents tracking changes in soil conditions over time. Such imagery is hosted on platforms like Google Maps, Google Earth, and the ArcGIS Online web service. In Google Earth Pro, it is possible to delineate areas with the highest concentration of soil damage and save them in kml/kmz format for subsequent use. Another resource, ESRI Images, is available as a base map in ArcGIS software, such as ArcMap (educational version). While these images cannot be analysed directly, they can be employed to refine the localisation of soil damage.

In-depth research on the impact of combat activities requires the use of satellite data with a resolution of 1 metre per pixel or higher. To identify small craters and determine the area of soil damage caused by other types of impacts, high-resolution satellite imagery from the Jilin Kuanfu-01 spacecraft (Chang Guang Satellite Technology Co, China) was used. The resolution of these images is 50 cm, which allows for the detection of craters caused by shell explosions with diameters smaller than 1 metre. The methodology for identifying damage in high-resolution images is similar to that used for analysing Sentinel-2 satellite data, but it does not require the use of numerous combinations and calculations of optical channels. This is due to the enhanced clarity of the images, which allows for the detection of

more details. The study of military impact on irrigated lands in the Chkalovske TC was conducted using the same methodologies as for non-irrigated areas, with Sentinel-2 satellite imagery and the ArcMap “base map” being employed.

The publication contains the results of the research obtained during the implementation of the project “Assessment of the Impact of Armed Aggression on the State of Black Soils and the Development of Measures for the Accelerated Restoration of Soil Fertility in the Context of Ensuring Food Security” No. 2022.01/0031 of the competition “Science for the Recovery of Ukraine in the War and Post-War Periods” under the grant support of the National Research Foundation of Ukraine (Draft Plan for the Recovery of Ukraine, 2022).

RESULTS

Using the described methodology, an analysis of military-related soil damage was conducted in the Chkalovske community area with the help of satellite imagery. The study focused on soil damage caused by shell explosions in autumn (15 October), when sparse vegetation is observed. At the initial stage, combinations of optical channels “True colour”, “False colour”, and “Agriculture” were applied. The analysis of satellite images for this period revealed that the NIR values at the edge of craters were higher than in adjacent areas. This is supported by the fact that most of the soil material settles at the edge of the crater after the explosion and serves as a substrate for the growth of herbaceous vegetation, such as weeds. Therefore, the use of the “False colour” combination allowed craters from shell explosions to be more clearly distinguished compared to the “True colour” combination (without NIR) (Fig. 3).

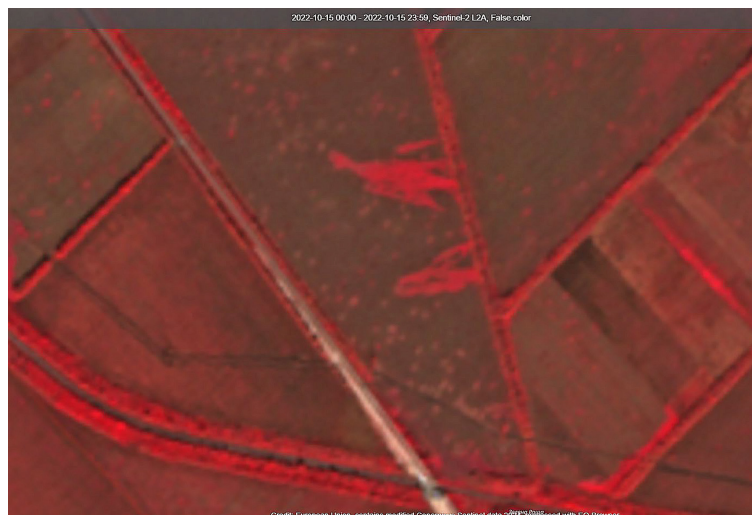


Figure 3. Shell explosion craters in the “False colour” combination

Source: image from Sentinel Hub EO Browser (n.d.)

The use of the “Agriculture” combination, which includes the SWIR range, provides the best tracking of

changes in vegetation and soil, as evidenced by the resulting image (Fig. 4).

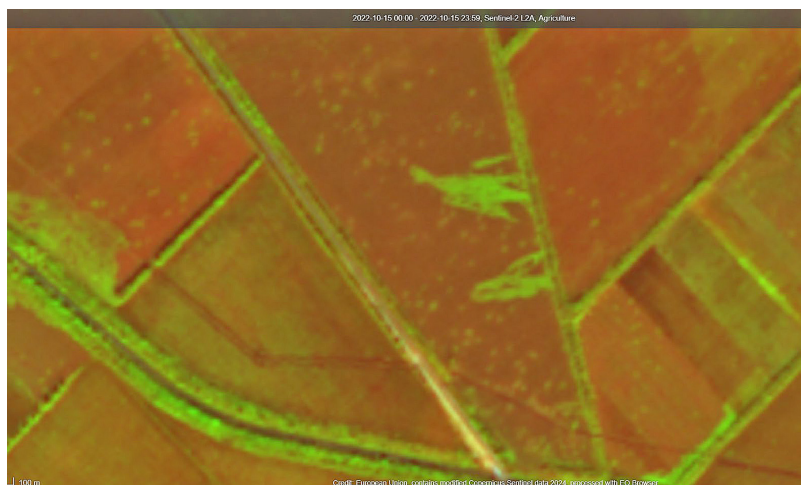


Figure 4. Shell explosion craters in the “Agriculture” combination

Source: image from Sentinel Hub EO Browser (n.d.)

Next, vegetation indices such as NDVI, EVI, and SAVI were tested. Among them, NDVI was found to be most suitable for identifying bombturbated soils in the autumn period. However, none of these indices provided the same level of accuracy in depicting craters as the “False colour” and “Agriculture” combinations. The next stage of crater identification involved the application of custom calculations of optical channels based on

formulas. As a result of the selection, the use of the Red (B04) and NIR (B08) channels was determined to be most optimal. With a ratio of channels (B04/B08), the locations of shell explosions are displayed as black dots, and when using the index formula (B08-B04)/(B08+B04), they are displayed as white dots (Fig. 5). As a rule, this allows for a clearer visualisation of craters compared to using a simple combination of channels.



Figure 5. Appearance of craters depending on the applied optical channel equations

Source: image from Sentinel Hub EO Browser (n.d.)

Beyond detecting shell craters, this study also focused on identifying tracks of heavy military vehicles, fortifications, and fires caused by shelling. Combinations of optical channels and image synthesis based on calculations were used. Unlike craters, military roads are clearly distinguishable on the terrain using channel combinations like “True colour” (Fig. 6), “False colour”, and to a lesser extent, “Agriculture”. However, the use of vegetation indices such as NDVI, EVI, and SAVI did not yield satisfactory results for deciphering vehicle tracks. This can be partially attributed to the lack of dense vegetation in the study fields, which did not

provide the desired contrast between overgrown parts of the fields and compaction tracks. Similar to the previous decryption of craters, custom ratios of optical channels were applied to identify vehicle tracks. The ratio of channels B04/B12 performed quite well, while B04/B08 performed slightly worse. Regarding the use of custom indices, the calculation of a raster using the equation (B08-B04)/(B08+B04) yielded a more or less acceptable result. However, none of the custom combinations of optical channels showed better results in displaying compaction tracks than the already-known “True colour”, “False colour”, and “Agriculture”.



Figure 6. Tracks of military vehicle movement

Source: image from Sentinel Hub EO Browser (n.d.)

The study also involved the identification of various fortification structures (defensive fighting positions, dugouts etc.). Several fortifications were identified within the Chkalovske TC and could be detected in Sentinel-2 imagery due to their significant size (Fig. 7). The combinations and calculations of optical channels described in this study were applied and found to be suitable for identifying fortifications. This can be explained by the significant amount of soil removed during the construction of such structures, resulting in a significant contrast with the surrounding undisturbed areas.



Figure 7. Fortifications in the image

Source: image from Sentinel Hub EO Browser (n.d.)

Analysis of already-known optical channel combinations and indices showed nearly identical clarity in decoding the effects of fires on fields. Among the custom ratios and indices, B04/B08 and B04/B12 yielded

good results. In these cases, the burned areas appeared darker than the surrounding background. However, the most distinct burn areas are highlighted in infrared optical channel ratios – B12/B08 and B08/B12. In the first case, the fire damage appears as a white spot on a grey background. A similar image is provided by the “Barren soil” channel combination, which identifies areas devoid of vegetation (appearing red against a green background). In the second case, the resulting raster exclusively displays areas with fire damage in the form of dark patches, the area of which can be calculated quite clearly, making the B08/B12 ratio the best for decoding this type of damage (Fig. 8).



Figure 8. Fire damage on agricultural land

Source: image from Sentinel Hub EO Browser (n.d.)

However, it should be noted that when using any of the channel sets described above, it is still essential to know the exact location of the fire, as some fields, even in the absence of vegetation, can also stand out

clearly when applying the aforementioned algorithms. The use of vegetation as an indicator of fire is most effective during the active growing season and shortly after the event (until the end of the growing season and

the onset of winter). As a result of selecting different spectral combinations, optimal channel ratios and indices for displaying military-induced soil damage were calculated (Table 1).

Table 1. Optimal combinations of optical channels for different types of military damage

Type of damage	Ratio (A/B)	Index (A-B)/(A+B)
Crater damage from shell explosions	B04/B08	(B08-B04)/(B08+B04)
Compression traces (paths) from military vehicle movement	B04/B12; B04/B08	(B08-B04)/(B08+B04)
Fire damage caused by shelling	B12/B08; B08/B12	(B12-B04,03,02)/(B12+B04,03,02) (B08-B04,03,02)/(B08+B04,03,02)
Fortifications (defensive fighting positions and dugouts)	All combinations listed above	All combinations listed above

Source: author's results

After identifying the features of military impact, contours were drawn around the highest concentration of each type of soil damage. As a result, spatial object layers were created and overlaid on the base map in ArcMap (Fig. 9), specifically showing the consequences of constant shelling (craters from shells, rockets, and bombs); compaction from military vehicle movement (tracks); fortifications (defensive fighting positions and dugouts); and fires caused by shelling (traces). Thus, a

map was prepared depicting the consequences of military soil degradation in the Chkalovske TC.

Based on information about the locations of the most damaged areas due to military impact, further analysis of soil damage was carried out using higher-resolution satellite images. Initially, available high-resolution satellite image sources from ESRI Images were analysed, using ArcMap as the base map (Fig. 10).

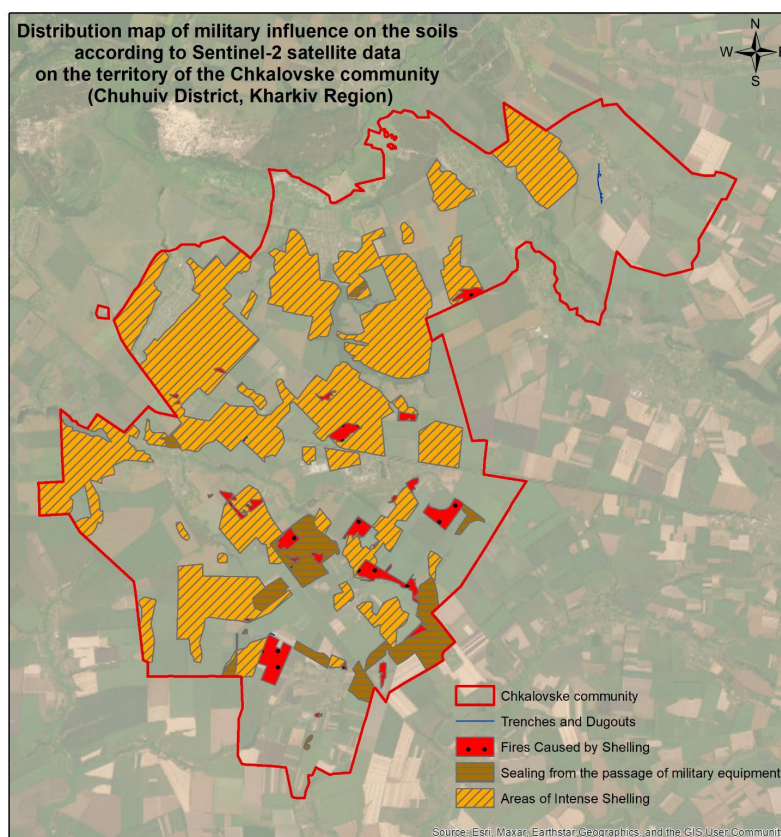


Figure 9. Areas with the most pronounced military impact on soils in the Chkalovske TC, Kharkiv Region

Source: author's mapping scheme

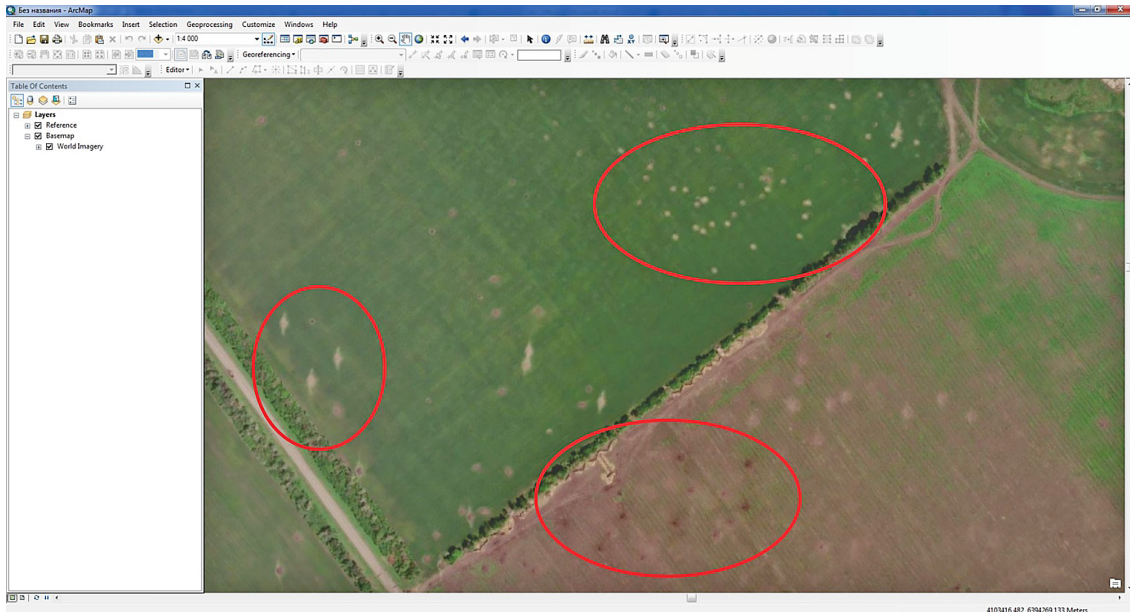


Figure 10. Fragment of ESRI Images clearly showing traces of craters (near Nova Hnylytsia Village area)

Source: image from ArcMap program

Using the specified satellite images, individual contours of areas with military damage, created from Sentinel-2 images, were refined. To conduct a more in-depth analysis of the impact of military actions on the soil cover, a high-resolution satellite image of a 51 km² area of the Chkalovske TC was obtained from the Ji-lin Kuanfu-01 spacecraft (Chang Guang Satellite Technology Co, China) (Fig. 11). According to the authors'

estimates, the area covered by the satellite image exhibits practically all types of military impact on the soil cover and can be used as a pilot area for impact assessment. Approximate calculations of soil damage were carried out based on averaged impact data.

Firstly, the identification of aviation and artillery craters in the pilot area was conducted (Fig. 12). These craters are clearly visible in the high-resolution images.

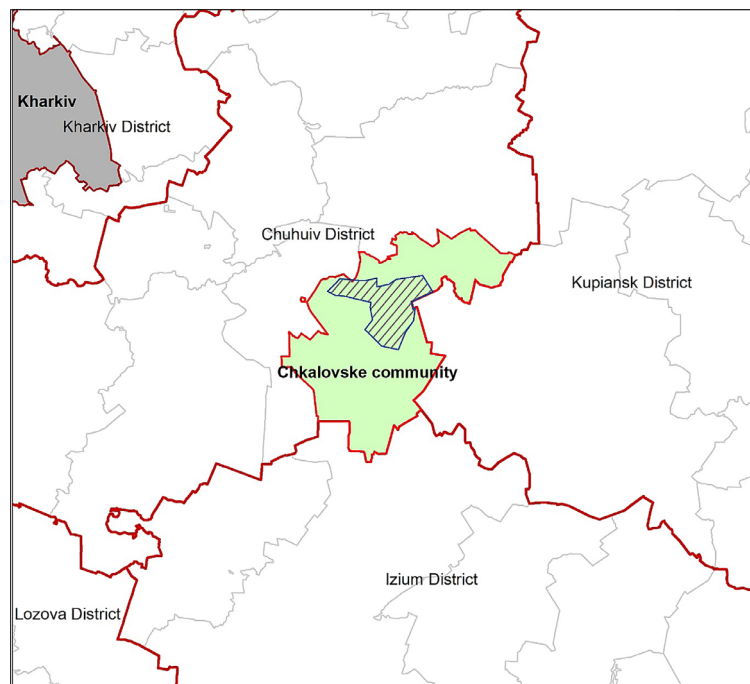


Figure 11. Location of the satellite image within the Chkalovske TC of the Chuhuiv District, Kharkiv Region (marked with hatching)

Source: author's mapping scheme

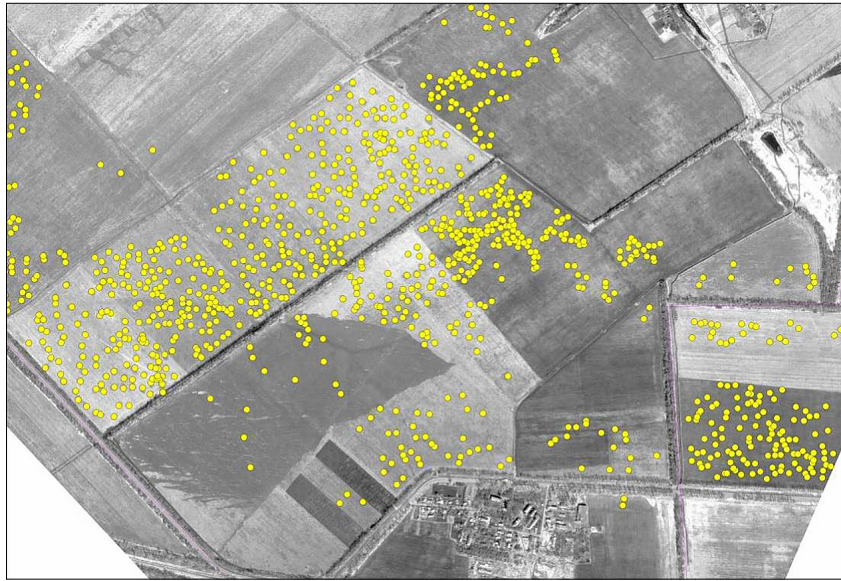


Figure 12. Fragment of the satellite image with identified traces of artillery and aviation damage

Source: author's mapping scheme based on Jilin Kuanfu-01 image

Overall, 3,844 craters of various origins were counted (Fig. 13). In the locations of these craters, anomalies such as secondary explosions or post-strike fires were observed. It is known that the size of the craters is directly related to the calibre of the shells. In the study area, these are mainly 76, 105, 152, and 155 mm calibres, with the diameter of the crater ranging from 6 to 15 meters, averaging 10.5 meters. The average depth of the craters, according to the authors' observations,

is 0.85 meters. Thus, according to calculations, 40,362 cubic meters of soil are damaged in the study area.

The overall distribution of artillery craters is quite varied, but it clearly correlates with the location of military units in forest belts, around dug-in armoured vehicles, and field fortifications. Therefore, adjacent agricultural fields suffer first and foremost. Fields located near paved roads have even more damage, as they were additionally mined even as of late 2023.

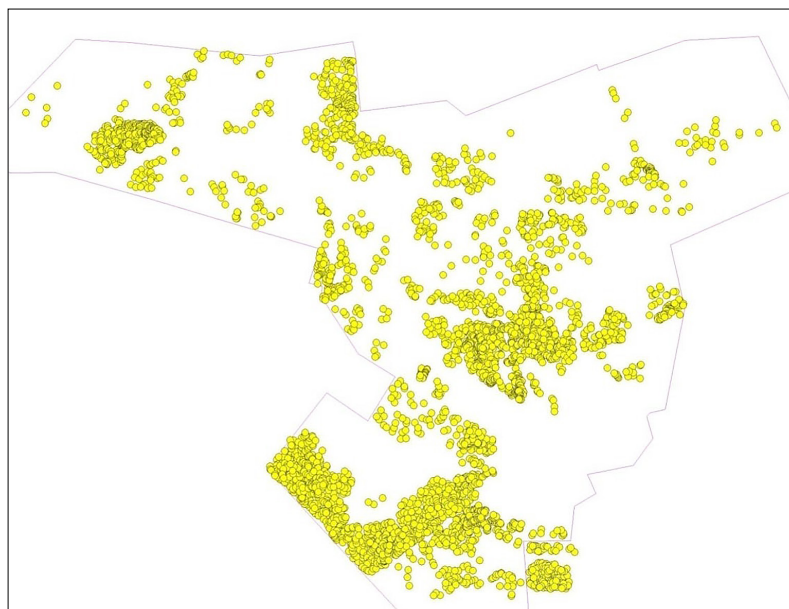


Figure 13. General view of the pilot area with identified traces of artillery and aviation damage

Source: author's mapping scheme

Next, the identification of soil surface compaction caused by the passage of heavy military equipment

was carried out. In the case of the Chkalovske TC, the most compacted soils are found under military roads

and even in residential areas (Fig. 14). According to the authors' calculations, the total length of vehicle tracks in the fields is $7.76 \text{ km} \pm 0.5$ (total road length, m) $\times 3 \text{ m}$ (track width) = 23.28 ha, or the total area of compaction in the pilot area. Burned areas as a result of shelling fires were also identified (Fig. 15). It was established that the

burning of stubble, field crops, and weeds occurred primarily in the locations of personnel and defensive structures. That is, it can be indirectly stated that enemy defensive structures are located around these places, which significantly narrows the search area. According to GIS calculations, the area of burned territories is 1.09 km^2 .

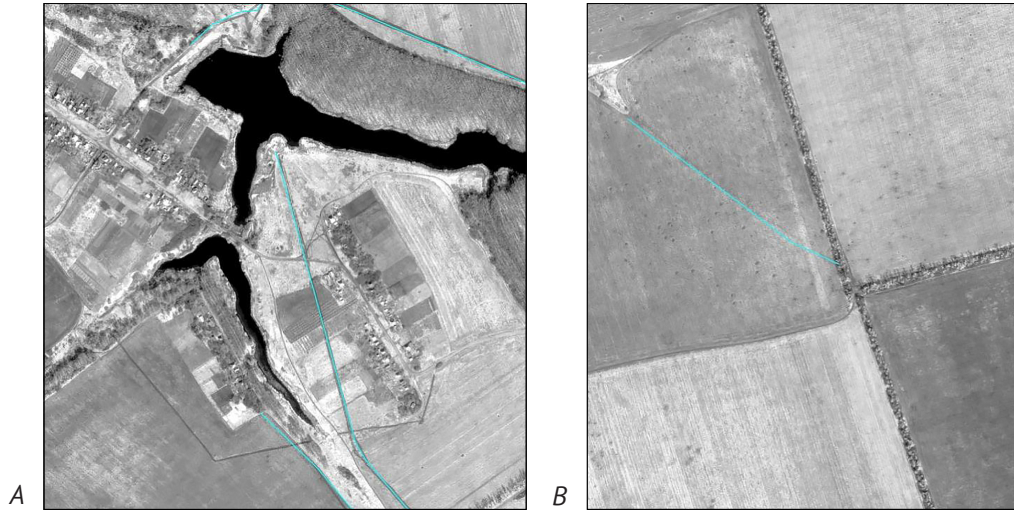


Figure 14. Examples of soil compaction in agricultural land (A – household plots and gardens, B – agricultural fields)
Source: Jilin Kuanfu-01 satellite images

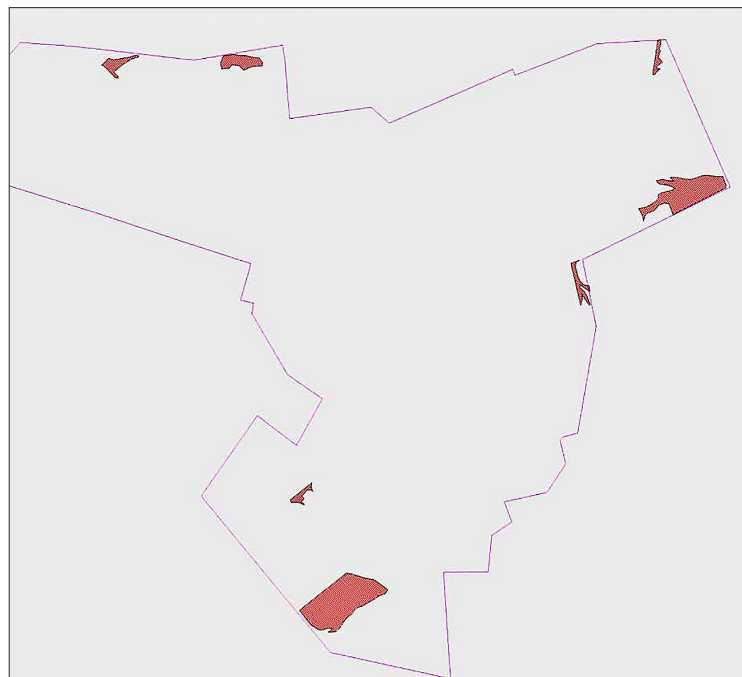


Figure 15. Location of burned areas in the key site of the Chkalovske TC of Chuhuiv District
Source: author's mapping scheme

Examples of burnt areas in the key site are shown in Figure 16. As a result of the analysis of remote sensing data, defensive structures and military checkpoints of the Russian forces were detected (Fig. 17). Calculations show that the length of the trenches is 261 m,

and the anti-tank ditch is 1,694 m. The total volume of excavated soil is $11,730 \text{ m}^3$. Overall, based on the calculations of each type of impact on the soil cover, a general picture of soil losses was formed to further calculate the damage caused (Table 2).

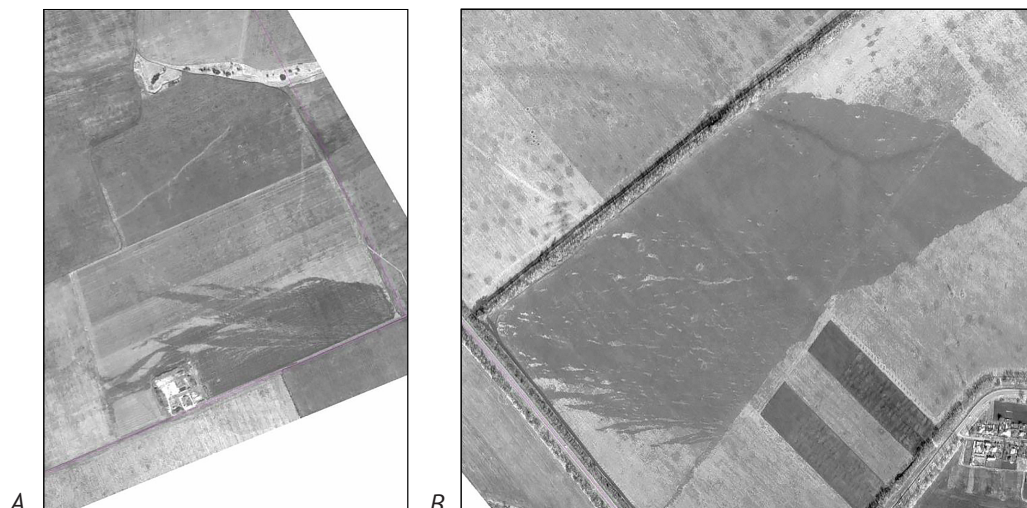


Figure 16. Examples of burnt agricultural land in the key site (A, B)

Source: Jilin Kuanfu-01 satellite images

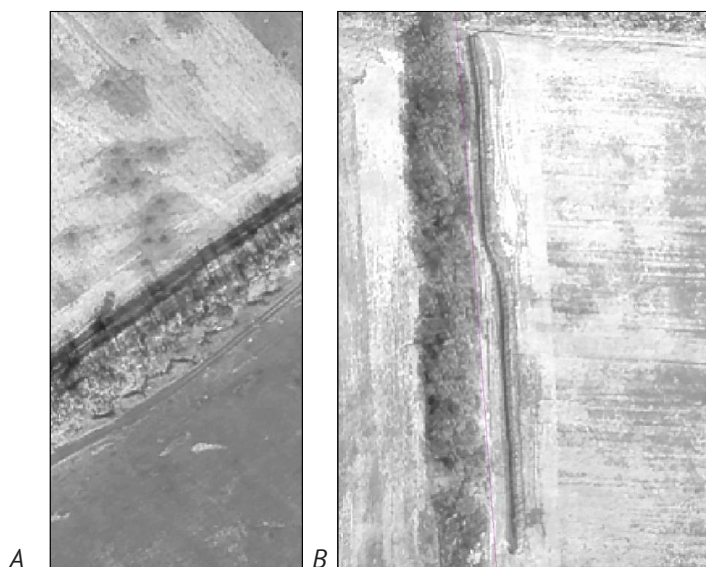


Figure 17. Defensive structures of russian forces: A – trenches, B – anti-tank ditch

Source: Jilin Kuanfu-01 satellite images

Table 2. Calculation of the volume of military impact on the soil cover of part of Chkalovske TC

No.	Impact Type	Type of impact on soil	Quantity/area
1.	Aviation and artillery craters	Mechanical (soil layer inversion) Chemical (contamination with explosives and heavy metals)	40,362 m ³
2.	Military roads	Physical (soil compaction)	23.28 ha
3.	Burning of vegetation	Pyrogenic (burning)	1.09 km ²
4.	Anti-tank ditches	Mechanical (soil layer inversion)	1,694 m
5.	Strongpoints/trenches	Mechanical (soil layer inversion)	216 m
Total for items 4,5 – 11,730 m ³			

Source: author's calculations

An equally important aspect of current research into military degradation is assessing the impact of hostilities on the quality of irrigated chernozems using

Earth remote sensing data. The study involved analysing satellite images of the study area, followed by field surveys, and comparing the obtained data with pre-war

salinity survey materials. In 2023, a remote study of the condition of irrigated lands and an assessment of their

damage as a result of hostilities was conducted using a satellite image (Fig. 18).



Figure 18. Satellite image of irrigated lands in the Chkalovske TC, highlighting areas affected by military actions
Source: author's mapping scheme based on ESRI Images

The map shows areas of irrigated lands in the Chkalovske TC where the soil cover has been subjected to shelling, damage, and destruction as a result of hostilities. According to remote sensing data, the area of land affected by shelling is approximately 80 hectares. As a result, mechanical damage, destruction of the soil cover in the irrigation zone, and disruption of the soil profile integrity have occurred, indicating the development of mechanical degradation. Additionally, remote sensing data clearly identifies areas on the irrigated lands of the study area that have been burned as a result of fires (marked in red), which have damaged the soils and affected their quality. According to the calculations, the area of burned areas on irrigated lands in the Chkalovske TC is approximately 89 hectares. As a result, the development of biological and physicochemical soil degradation is likely in these areas.

DISCUSSION

Modern warfare inflicts significant damage on the environment, and soils, as a component of the environment, are no exception. During hostilities, negative phenomena such as reduced soil fertility, decreased soil organic carbon content and emissions, pollution, erosion, and reduced soil biodiversity, among other degradation processes, intensify. Research by L. Banwari *et al.* (2023) confirms that current agricultural practices contribute to increased degradation and deterioration of "soil health", and that the negative environmental impact of

human activities can be reduced through organic farming. This approach may be beneficial in the post-war period when there is a need for rapid and environmentally safe restoration of soil fertility, including in the lands of the Chkalovske community.

It is worth noting that war not only directly affects the environment but also indirectly hinders research that requires field data and measurements. For example, H. Abdo *et al.* (2022) mapped part of the Syrian territory using the Revised Universal Soil Loss Equation (RUSLE) and remote sensing data in a GIS environment to classify erosion-prone areas in the Al-Khash River basin. The obtained data allowed for a reliable assessment of soil loss rates due to erosion, enabling the development of soil conservation measures even before the end of hostilities. Similar methodological approaches were applied by the authors of this study, where the scale of soil damage was assessed with extensive use of remote sensing methods without conducting fieldwork.

Military activities lead to widespread contamination by explosives, which can be absorbed by plants through the soil. Research by S. Via and P. Manley (2023) focused on the physiological effects of explosives on plant tissues, including disruptions to photosynthesis, gas exchange, and nutrient uptake. The authors also noted that further development of remote sensing technology will provide more data on the impact of explosives on plant health. While current studies do

not offer a detailed picture of this impact, estimates of the intensity of combat operations in the lands of the Chkalovske community suggest areas with the highest concentration of explosive residue products.

It should be noted that in the author's study, similar to the examples above, the main indicator of the military impact on the environment is the assessment of vegetation conditions using remote sensing methods. However, in the Chkalovske TC, the identification was not of chemical contamination, but of mechanical and physical damage to soils. The degree of contamination based on the obtained data can only be assessed by experts using literature data. An example of a study on the impact of military conflicts on agricultural activities is the article of B. Demissie *et al.* (2022) assessing the Tigray conflict (Ethiopia) using freely available Sentinel-2 satellite data. An analysis of the greenness of agricultural fields was conducted using the NDVI index for the pre-war (2020) and wartime (2021) spring seasons, leading to the conclusion about the role of the war in the increased encroachment of weeds on agricultural land. Similar results were obtained in the current study of craters in the fields of the Chkalovske TC, indicating an increase in weed growth in areas subjected to soil disturbance from bombturbation.

The study by J. Rodrigo-Comino *et al.* (2023) examined trenches from the Civil War era, where archaeological excavations led to the development of ravines and gullies. Using the NDVI index, a decline in vegetation quality was recorded as a result of degradation processes. A similar issue could arise in the long term with defensive fighting positions and dugouts, which are widespread in the Chkalovske community in areas of positional battles. Therefore, it is essential to monitor the condition of the fortifications left behind after the war. Research on ecosystem components is often linked to the use of historical cartographic images, which in some cases provide a clear understanding of environmental changes. F. Chen *et al.* (2022) combined historical military operation maps with Landsat satellite imagery to analyse changes in forest area due to human activity. Thus, the use of historical maps allows the determination of forest cover evolution before remote sensing images are available. This methodological approach enables an assessment of the impact of wars (such as the Second World War) that occurred before the first detailed satellite images were taken and provides a comparison with the consequences of the ongoing Russian-Ukrainian war, including on the lands of the Chkalovske community.

Scientific literature increasingly highlights the impact of the Russian-Ukrainian war on environmental components, particularly soils. P. Pereira *et al.* (2022) indicate that military actions in Ukraine have significant consequences for global food security and have also caused economic and political problems. While the impact on the environment is currently difficult to

assess due to ongoing intense fighting, the negative consequences of soil damage, soil contamination, and other degradation processes are already evident. A. Nabisov *et al.* (2024) concluded that the war has led to a reduction in arable land and crop yields, as well as soil and water pollution. The importance of considering regional differences in agricultural productivity is also noted. Assessing the consequences of hostilities helps to determine the scale of the problem and subsequently develop a soil restoration strategy and make the necessary decisions.

Many scholars highlight the issue of using high-resolution satellite imagery to visualise the consequences of armed conflicts. According to M. Bennett *et al.* (2022), very little attention is paid to reflecting the impact of hostilities on rural and forest areas. Using the example of the war in Ukraine, the authors pointed out the advantages of using high-quality images and the importance of archiving such images for scientific purposes to monitor military conflicts. A detailed study of the military impact on the soils of the Chkalovske community also required the involvement of high-resolution images, which, due to their cost, do not allow scientists to obtain the necessary data on a regular basis.

Several scientific studies have been published assessing the impact of the Russian-Ukrainian war on soils using satellite data. For example, in the research of S. Shevchuk *et al.* (2022), the impact of the Russian-Ukrainian war on the environment was analysed using publicly available remote sensing data from NOAA-2, Suomi NPP, Aqua and Terra satellites, Sentinel and Landsat, as well as other open sources. In particular, a combination of channels B3, B8, and B11 of Sentinel-2 satellites was used for a clearer detection of fires compared to the use of visible and infrared spectra separately. Similar conclusions were drawn in the current study, however, in the current study, a more complex approach was used, using not only channel combinations but also spectral ratios and indices.

A comprehensive methodological approach to assessing war-induced soil disturbances was also proposed in the study of O. Bonchkovskiy *et al.* (2023), namely the detection of shell craters and tracks from military equipment. The proposed methodology includes the following stages: geospatial analysis, field research, data synthesis and processing, economic assessment, and recommendations. The methodology combines the following methods: remote sensing analysis, cartographic, soil science, geochemical, ecological, geomorphological, and economic. Unlike this study, the current research has developed a detailed methodology for identifying soil damage based on known combinations and the author's ratios and indices of optical channels of satellites.

Due to the impossibility of conducting detailed soil surveys in the combat zone and the high cost of acquiring and analysing high-quality satellite imagery, there

is a need to forecast military-induced changes in soils. In the article of Y. Dmytruk *et al.* (2023), a preliminary assessment of the consequences of the war in Ukraine was conducted by modelling a predictive soil map at a scale of 1:10,000 in a GIS environment, which was used to estimate the areas of damage to individual soil taxa. This will allow for the initiation of soil restoration, taking into account their resistance to military impact. The current study has a slightly different approach, related to the use of satellite data at a local level within a separate community, which does not involve significant resource expenditure on searching for and analysing remote data.

Thus, to date, scientific research has left unanswered questions about the methodology for assessing the military impact on soils using Sentinel-2 satellite images with the use of an author's approach to combinations of spectral channels. The presented study aims to fill the gaps in the methodological approaches to identifying the consequences of military impact on soils.

CONCLUSIONS

Using the example of Chkalovske TC, with predominantly chernozem soils that have undergone various types of military degradation, the methodological necessity and practical feasibility of using multi-temporal satellite images with different resolutions have been established. Their functional capabilities for diagnosing various types of military degradation of chernozems have been determined. Analysis of satellite images was carried out on the online resource EO Browser, and the display of maps showing the distribution of the consequences of the impact of hostilities on soils was carried out in specialised GIS programs (Mapinfo, ArcGIS-ArcMap).

At the initial stage, freely available data from Sentinel-2 satellites with a maximum resolution of 10 m and an image update frequency of 5 days were analysed. A methodological algorithm for their evaluation was developed and tested in real conditions. Using Sentinel-2 satellite data, the following types of military impact can be established: mechanical, physical, and abiotic – direct identification in the optical range; mined areas by tangent identification of the long-term presence of field plants (weeds) in fields. In the course of the study, 4 types of military impact on soils were identified, which can be identified using Sentinel-2 satellite images: craters on the soil surface from the rupture of munitions, traces of soil compaction due to the passage of heavy military equipment, fires in fields caused by active shelling and burning of equipment, and fortifications of various types (trenches, defensive fighting positions, dugouts). For each type of military impact on soils, the most optimal existing combinations of spectral channels of Sentinel-2 satellites and vegetation indices were selected. Own calculations of channels were

also developed using two types of equations – ratios (A/B) and indices $(A-B)/(A+B)$. For the identification of craters, the ratios $B04/B08$ and the index $(B08-B04)/(B08+B04)$ are optimal; for traces of compaction from the passage of military equipment – $B04/B12$, $B04/B08$ and $(B08B04)/(B08+B04)$; for the consequences of fires caused by shelling – $B12/B08$, $B08/B12$ and $(B12-B04,03,02)/(B12+B04,03,02)$, $(B08-B04,03,02)/(B08+B04,03,02)$; for fortifications – all of the above.

Based on the identified types of military impact on soils, contours were constructed around the highest concentration of damage in the form of layers of spatial objects, which were applied to a base map in ArcMap. The use of Sentinel-2 images allowed for the identification of the main zones of distribution of military soil degradation. For a more detailed analysis of the military impact on soils using satellites with higher resolution, available ESRI Images satellite images were analysed in the form of an ArcMap “base map”, according to which individual contours of areas with military soil damage were refined.

For the analysis of damage using high-resolution commercial satellite data, a plot was selected in the territory of Chkalovske TC, on which all the main types of military impact are presented. As a source of detailed satellite images, data from Jilin Kuanfu-01 satellites with a resolution of 50 cm were used, according to which the locations of explosions of shells of various calibres were determined. This made it possible to identify craters with a diameter of less than 1 m. Also, using Jilin Kuanfu-01 images, the boundaries of the main types of military impact on the selected area were refined. Calculations were made of the volumes of soil losses for all types of military impact for future calculations of the damage caused. The impact of hostilities on the quality of irrigated chernozems of Chkalovske TC was assessed by analysing satellite images, and a mapping scheme was constructed with areas of the main types of military impact on irrigated lands.

Therefore, the complex use of satellite images with different resolutions and GIS platforms has made it possible not only to calculate soil losses with sufficient accuracy but also to analyse the types of military impact both in terms of time and quantity. In this way, a differentiated approach to studying the consequences of military soil degradation is achieved. The information obtained based on satellite images is an important step in developing measures for restoring the soil cover of territories that have undergone military degradation. Further research, is planned to improve the methodology for identifying military-induced soil damage by selecting combinations of optical channels of Sentinel-2 satellites for all seasons of the year.

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CONFLICT OF INTEREST

The authors have no conflicts of interest.

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Методичні та практичні аспекти використання супутникових знімків для оцінки мілітарного впливу на ґрунти

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Анотація. Військова агресія Російської Федерації спричинила масштабний негативний вплив на природні екосистеми України, у тому числі й ґрунтів. Для фіксації збитків, завданих війною, необхідно проводити всебічне обстеження стану ґрунтів, ступеню та масштабів їх пошкодження. Застосування традиційного польового обстеження ґрунтового покриву ускладнене через значну мінну небезпеку на звільнених від окупації територіях. Тому постає необхідність широкого застосування дистанційних методів дослідження, таких як супутникові дані (космічні знімки). Метою даного дослідження було визначення стану ґрунтів та масштабів їх пошкоджень внаслідок ведення бойових дій на території Чкаловської територіальної громади Чугувського району Харківської області. Було визначено найбільш оптимальні комбінації оптичних каналів супутників Sentinel-2 для відстеження наслідків мілітарного впливу на ґрунтовий покрив. Створено шар просторових об'єктів відповідно до різновидів мілітарної деградації ґрунтів громади: наслідки постійних обстрілів (вирви від снарядів, ракет та бомб); ущільнення від проходження військової техніки (сліди шляхів пересування); фортифікаційні споруди (окопи та бліндажі); пожежі, спричинені обстрілами. За допомогою супутникових знімків високої роздільної здатності на тестовому полігоні підраховано кількість вирв (кратерів) та втрати ґрунтової маси від вибухів, площі спалених ділянок та ущільнення, довжину протитанкових ровів та окопів з бліндажами. На зрошуваних землях Чкаловської територіальної громади підраховано площі земель, уражених обстрілами, ділянок, які зазнали спалювання внаслідок пожеж мілітарного походження. Отримана на основі космічних знімків інформація є важливим кроком у розробленні заходів з відновлення ґрунтового покриву пілотної території, що зазнав мілітарної деградації. Були проведені роботи з використанням космічних знімків різної роздільної здатності та геоінформаційних систем для підрахунку збитків від бойових дій з достатньою точністю та аналізу шляхом поєднання видів мілітарного впливу як за часом, так й за кількістю. Дане дослідження стане основою для оцінки масштабів та просторового поширення пошкоджень ґрунтів, підрахунку втрат родючого шару ґрунту та економічної оцінки збитків, завданих ґрунтовим ресурсам

Ключові слова: дистанційне зондування; Sentinel-2; вегетаційний індекс; мілітарна деградація; пошкодження ґрунтів; вирви

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Application of analytical hierarchical process in assessing the suitability of land for growing grain crops

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Abstract. Assessing the suitability of land for growing grain crops is a relevant issue for ensuring sustainable agricultural production and improving food security. The Analytical Hierarchy Process (AHP) is an effective method of multi-criteria evaluation that systematically addresses all parameters. The study aimed to analyse the usage of the AHP method to determine the weight and priorities of different soil and climate

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characteristics to analyse the suitability of land for cereal crop cultivation, using wheat as an example. The study identified key factors affecting yields and developed recommendations for effective land management. An AHP was employed to weight various criteria, including physical, chemical and climatic characteristics. The data were processed to determine the impact of each factor on land suitability, with consistency checks to ensure the reliability of the results. The study showed that Flood and erosion hazard characteristics (32.2%) and Soil physical characteristics (25.6%) are the most important physical factors. Acidity (pH) and Cation Exchange Capacity (CEC) have a significant impact on nutrient availability, while average temperature and precipitation determine the main climatic conditions for wheat growth. Flood and erosion risks are also addressed for the long-term suitability assessment. The AHP was used to assess the suitability of land for wheat cultivation, identifying the most important factors and their weights. Practical recommendations included applying agronomic measures to reduce erosion risks and improve soil fertility. The results of the study can be used by agronomists, land managers and policymakers to improve land management, which will contribute to increased agricultural production efficiency and food security in the face of climate change

Keywords: assessment criteria; soil fertility; erosion risk; climatic factors; land management; agronomic measures

INTRODUCTION

Assessing the suitability of land for growing crops has been a critical process for ensuring food security, sustainable use of resources and optimising land use. In the context of global population growth and limited agricultural land resources, there is a need for accurate and scientifically sound approaches to determining the most efficient use of each plot. The production of cereals such as wheat has become a staple of the diet of many countries, and optimising their cultivation processes has had a significant impact on food independence and ecosystem resilience. Therefore, it was important that the land allocated for this crop met agricultural and ecological criteria and provided the highest yields while preserving soil quality and the environment.

Despite significant advances in the assessment of land suitability for crops, numerous challenges remained related to the objectivity and accuracy of decision-making in this area. The Analytical Hierarchy Process (AHP) method developed by T. Saaty (1980) is widely used in management research, including in the agricultural sector. It ensures the formalisation of multi-criteria decision-making processes and provides by ranking criteria based on their weight. This method was used to address both quantitative and qualitative indicators, making it particularly suitable for complex tasks such as land suitability assessments. However, studies that have applied this method to the valuation of land for growing grain crops have remained limited. Numerous scholars have applied AHP to land valuation in various environmental and economic contexts. S. Abate and M. Anteneh (2024), as well as E. Nungula *et al.* (2024) demonstrated how the physical and chemical characteristics of soils can be assessed using Geographic Information System (GIS) and AHP approaches, which ensures accuracy in determining the optimal conditions for growing grain. J. Oladimeji (2024) highlighted the use of GIS-based AHP to assess land suitability for rice, confirming the importance of multi-criteria analysis in decision-making,

which is also critical for cereals. D. Ming (2024) and K. Nabiollahi *et al.* (2024) emphasised that integrating machine learning into traditional valuation models can further improve the accuracy of the results.

R. Makar *et al.* (2024) and A. Dutta *et al.* (2024) demonstrated the successful application of AHP in various agronomic contexts, showing the potential of the method to improve land suitability assessment. Nevertheless, a gap in the integration of socio-economic factors remains, which highlights the need for further study of this aspect. P. Bazkiaee *et al.* (2024) demonstrated how modern remote sensing technologies can support and improve land suitability assessment, but there is a need to develop standards for the effective integration of different data sources into a single AHP model, which will be an important step for practical implementation in the field of grain production. The study of Ukrainian scientists M. Lubskiy *et al.* (2024) modelled the vulnerability of the steppe landscape and climatic zone of Ukraine to climate change using remote sensing data. Satellite imagery for vulnerability modelling was used to address the impact of climate change on crop productivity, which is also necessary for predicting changes in land suitability in the face of global warming.

The problem of multi-criteria selection of alternatives, which is relevant for land suitability assessment tasks, where various factors (climate, soil, accessibility, etc.) need to be integrated into a single model, was studied by S. Sveshnikov *et al.* (2024). This study provides a methodological framework for the application of multicriteria analysis in agricultural and environmental research and decision-making based on criteria weighting, similar to the application of the AHP method for land suitability assessment. Albanian researchers and world scientists assessed the suitability of land based on a multi-criteria analysis to determine the optimal conditions for agriculture, addressing various factors such as climate, topography, hydrology and infrastructure parameters. The use of multi-criteria

decision-making methods in combination with GIS provides a detailed assessment of environmental and socio-economic parameters that are key to sustainable land use planning in Albania. The study is also carried out by international experts who use various methods to assess land suitability, including a specific approach to structuring multifactorial problems, such as AHP methods, which provides greater transparency in the process of determining the weighting of criteria.

In these studies, the authors concluded that AHP is a consistent way of prioritising factors affecting yield and environmental sustainability. Despite significant progress in the use of AHP to assess land suitability, researchers have noted gaps in the study of specific criteria for growing cereals, namely wheat. For instance, studies have addressed general factors such as soil structure, depth and acidity, but have not sufficiently considered aspects such as erosion risk, water availability and climatic characteristics that are crucial for grain yields. In addition, the study of different environmental conditions, including those in specific regions such as Albania, remained underrepresented, limiting the applicability of existing methods to other climatic zones.

Thus, the study aimed to analyse the weighting coefficients of the criteria for the suitability of land for grain

crops on the example of wheat in the context of Albania and Ukraine in more detail. This study provided a detailed description of the main criteria that influence the productivity of cereal land and weighs them using AHP.

MATERIALS AND METHODS

The study was conducted on the research plots of the Agricultural University of Tirana and Mykolaiv State Agrarian University. The data collection included physical, climatic, chemical and biological soil characteristics, as well as erosion risks, which were used for further analysis using the AHP method. In the current research, AHP was applied to describe the multi-criteria evaluation. AHP is a multi-criteria decision-making approach. AHP technique is the most important point of this assessment, because careful organization of sub-criteria of main criteria if weights properly, represent perfect suitability order and fulfills the goal. The pair-wise comparison matrix (PWCM) was carried out for rating and weighting of sub-criteria in each group as well as for the final main group. For comparing the two sub-criteria the fundamental scales given by T. Saaty (1980) were used. A nine-point rating scale, based on a criterion, used by T. Saaty is showed in Table 1, in making this judgment.

Table 1. Importance ranking of pairwise combination of factors

Scale	Degree of preferences	Explanation
1	Equally	Two activities contribute equally to the objective
3	Moderately	Experience and judgment slightly to moderately favor one activity over another
5	Strongly	Experience and judgment strongly or essentially favor one activity over another
7	Very strongly	An activity is strongly favored over another and its dominance is showed in practice
9	Extremely	The evidence of favoring one activity over another is of the highest degree possible of an affirmation
2,4,6,8	Intermediate values	Used to represent compromises between the preferences in weights 1, 3, 5, 7 and 9
Reciprocals	Opposites	Used for inverse comparison

Source: T. Saaty (1980)

The AHP method was chosen as the main method for weighting and prioritising land suitability criteria. The AHP can be used for a structured division of complex tasks into separate hierarchical levels, starting with the research objective (hereinafter referred to as criteria) and ending with sub-criteria, and provides the possibility of allocating weights based on expert assessment of each criterion.

The following criteria were used to assess the suitability of the land:

1. Climate indicators: average daily temperature during the crop cycle and total rainfall during the crop cycle, which significantly affect crop productivity (Sys *et al.*, 1991).

2. Physical and quality characteristics of the soil: data on soil depth (cm), texture, drainage, water availability (mm/m), and coarse particle content.

3. Biological and chemical characteristics of the soil: fertility class (soil fertility classes are determined by the analysis of 7 agrochemical parameters (pH (H₂O), organic matter %, assimilable P ppm, exchangeable K me/100 g, exchangeable Mg me/100 g, Ca:Mg ratio, K:Mg ratio), electrical conductivity (EC), exchangeable sodium (ESP), and cation exchange capacity (CEC).

4. Flood and erosion risk: slope (%), aspect of the terrain, erosion risk and flood frequency.

5. Availability: distance to water sources (m) and roads (km).

This data was analysed using Excel, where the values were weighted and normalised for each group of criteria to obtain the final weighting factors. The weighting process was carried out employing expert assessments using pairwise comparisons, where each criterion was assigned relative importance according to

its impact on the suitability of land for growing grain crops. The obtained values of the pairwise comparisons were used to calculate the weighting coefficients of each criterion and then to calculate a generalised assessment of land suitability.

The weightings for each criterion were calculated in five separate groups, as well as for all criteria together to provide a comprehensive assessment of suitability. The share of each criterion was presented in tables, which were used to assess the compliance of land plots with the criteria for growing grain crops. To process and analyse the data, Excel was used to calculate weights, which identified the factors affecting land suitability. This methodology provides a comprehensive approach

to assessing land suitability, addressing the various environmental and technical factors that influence the choice of sites for growing grain crops.

RESULTS

General results of the assessment of land suitability for growing grain crops. The results of the assessment of the suitability of land for growing grain crops, using wheat as an example, using the AHP method showed the importance of various factors affecting agricultural production. Five main groups of criteria were considered, each of which contributed to the overall suitability score. Table 2 shows the weights of each group of criteria based on their importance for successful grain production.

Table 2. PWCM for five main groups of criteria

Flood and erosion hazard	Soil physical characteristics	Soil biological and chemical characteristics	Climate	Accessibility	Weights (%)	Rank
1	1	2	3	4	32.2	1
1	1	1	2	4	25.6	2
1/2	1	1	2	4	22.3	3
1/3	1/2	1/2	1	4	14.1	4
1/4	1/4	1/4	1/4	1	5.8	5
Consistency ratio = 4%					$\Sigma=100$	

Source: compiled by the authors

The evaluation of land suitability for grain crop production, exemplified by wheat, was conducted using the AHP. The analysis focused on assessing the importance of various factors that influence agricultural productivity. The criteria were grouped into five major categories, each contributing differently to the overall suitability score. With the highest weighting of 32.2%, flood and erosion hazard are the most critical factor. This category reflects the significant impact of environmental hazards on soil stability and crop sustainability. Ranking second with a weight of 25.6%, the physical properties of the soil, including texture and depth, play a crucial role in determining water retention and root development. Weighted at 22.3% (rank 3), these attributes include organic matter and soil pH, both vital for fertility and nutrient availability.

At 14.1% (rank 4), climatic conditions, such as precipitation, influence water availability and crop viability but are less influential compared to soil-related factors. This criterion has the lowest weight of 5.8% (rank 5), as logistical and infrastructural considerations, while important, are secondary to biophysical and environmental factors. The consistency ratio of the pairwise comparisons was calculated at 4%, indicating reliable and consistent assessments. The weights and rankings underscore the dominant role of soil and environmental hazards in land suitability assessments for grain crop cultivation.

The impact of climatic characteristics on land suitability. To assess the suitability of the land for climatic characteristics, data were collected average daily temperature during the crop cycle and total rainfall during

the crop cycle in the selected areas. Climate parameters, such as temperature and precipitation, have a significant impact on grain production, as they determine the availability of heat and moisture needed for optimal plant growth. The weight in % for temperature and precipitation are 50% for each. Air temperature is a critical factor in determining the development cycle of wheat. The ideal temperature range for growing wheat is usually between 10°C and 25°C. Wheat has an optimum temperature for seed germination (15-20°C) and grain development (20-25°C). If the temperature exceeds or falls below these limits, it can cause plant stress, stunted growth or even complete crop failure. For example, excessively high temperatures during the pollination period can cause grain formation disorders and reduce yields (Kalenska *et al.*, 2023). Low temperatures, especially during germination, can slow down development and make plants more vulnerable to disease.

Precipitation is another important factor that determines the availability of water to plants. Wheat needs sufficient water throughout the growing season, although the requirements vary depending on the stage of development. Optimal rainfall for wheat is typically 350-1250 mm: total rainfall during the crop cycle, depending on the type of soil and climatic conditions in the region (Sys *et al.*, 1991). Insufficient precipitation can lead to drought, which causes the soil to dry out and reduces the availability of water to the root system. This, in turn, significantly reduces yields and can make land unsuitable for cultivation. On the other hand, too much rainfall can be just as damaging as too little.

Excessive moisture can cause waterlogging, increase the risk of diseases such as root rot, and even lead to floods that destroy crops.

These two climate factors do not act separately but interact with each other. For instance, in regions with high temperatures, the need for water increases significantly, and if there is insufficient rainfall, the soil can dry out quickly, which worsens conditions for wheat. In colder regions, where evaporation is less, the same precipitation may be sufficient to maintain an optimal water balance. Therefore, the analysis of these factors

should address their interaction and seasonal fluctuations. The results confirm that average temperature and precipitation levels have a significant impact on land suitability. For instance, areas where the average temperature exceeds 25°C or where rainfall is less than 600 mm had lower suitability scores.

Analysis of the physical characteristics of the soil.

The assessment of the physical characteristics of the soil included parameters such as depth, texture, drainage, overall water availability and coarse particle levels. The weighting factors are shown in Tables 3 and 4.

Table 3. The weight of physical characteristics of soil

Criterion	AHP value	Percentage
Texture	0.37	37%
Soil depth (cm)	0.247	24.7%
Drainage	0.189	18.9%
Coarse particle content	0.122	12.1%
Water availability (mm/m)	0.073	7.3%

Source: compiled by the authors

Table 4. PWCM for physical criteria

Texture	Soil depth	Drainage	Coarse particle content	Water availability	Weights (%)
1	2	2	3	4	37
1/2	1	2	2	3	24.7
1/2	1/2	1	2	3	18.9
1/3	1/2	1/2	1	2	12.1
1/4	1/3	1/3	1/2	1	7.3
Consistency ratio=2%					$\Sigma=100$

Source: compiled by the authors

The physical characteristics of the soil, such as soil depth, texture, drainage, water availability and coarse particle content, are crucial in determining the suitability of land for wheat production. Each of these factors is substantial in providing favourable conditions for crop growth, affecting water balance, aeration, erosion resistance and other important aspects. The depth of the soil determines the amount of space for the development of the root system and moisture reserves. Soils with a depth of more than 100 cm are the best for growing wheat, as they provide sufficient water and nutrients to promote sustainable plant growth. The weight of this criterion is 24.7% which indicates its significant impact on the overall suitability of land. Deep soils also have an advantage in terms of drought tolerance, while shallow soils with a depth of less than 50 cm are often unsuitable for cultivation because they cannot retain enough moisture.

Texture determines water permeability, aeration and nutrient retention. Loamy, clay loam and silty loam soils are the most favourable for wheat due to their ability to hold water well and provide good aeration. Sandy soils have the worst suitability due to their low water-holding capacity. The weight of this criterion is 37%, making texture the most important factor in this assessment. Research shows that loamy soils promote

uniform plant development and yields, while excessively sandy or heavy clay soils create difficulties for the root system. Drainage determines how quickly the soil can remove excess water. Poor drainage can lead to waterlogging, which is harmful to wheat, while too much water can be removed too quickly, causing moisture deficits. A balance in drainage characteristics is key to maintaining optimal moisture. Wheat requires soils with moderate drainage, where water is retained long enough to moisten, but not so long as to cause root rot.

The next indicator determines the amount of moisture that the soil can hold for plant use. High water availability ensures long-term moisture in the root zone, which contributes to healthy plant development and reduces dependence on precipitation. Under conditions of moisture deficit, wheat yields decline sharply, therefore this factor is substantial in the selection of suitable land. The content of coarse particles in the soil determines how well the soil can retain structure and store moisture. A high content of coarse particles such as gravel can reduce the soil's ability to hold water and nutrients, making it less suitable for wheat production. The results of the study show that areas with optimal soil depth, good drainage and water availability have significant advantages for growing grain crops. On the other hand, a high level of coarse particles reduces the suitability score.

Assessment of chemical and biological characteristics of the soil. The analysis of the chemical and biological characteristics of the soil included an assessment

of parameters such as soil fertility, EC, ESP and CEC. Tables 5 and 6 shows the weighting factors and the corresponding suitability indicators.

Table 5. The weight of bio-chemical characteristics of soil

Criterion	AHP value	Percentage
Fertility class	0.5	50%
CEC	0.25	25%
ESP	0.125	12.5%
EC	0.125	12.5%

Source: compiled by the authors

Table 6. PWCM for bio-chemical criteria

Soil fertility classes	CEC	EC	ESP	Weights (%)
1	2	4	4	50
1/2	1	2	2	25
1/4	1/2	1	1	12.5
1/4	1/2	1	1	12.5
Consistency ratio = 1%				$\Sigma=100$

Source: compiled by the authors

The chemical and biological characteristics of the soil have a decisive influence on its fertility and suitability for wheat production. The correct balance of these indicators provides optimal conditions for the development of the root system, nutrient absorption and overall plant growth. The pH value of the soil is one of the most important chemical parameters that affect the availability of nutrients to plants. Wheat grows best in slightly acidic or neutral soil with a pH of 6.5 to 8. At this pH value, nutrients such as nitrogen, phosphorus and potassium are most readily available to the plant root system. If the pH drops below 6.5, the soil becomes too acidic, which can lead to toxicity for plants due to excessive accumulation of metals such as aluminium and iron. Under alkaline conditions (pH greater than 8), the solubility of nutrients such as phosphorus decreases, limiting their availability to plants.

Organic matter plays an important role in improving soil structure, retaining moisture and providing nutrients to the soil. High organic content promotes the development of beneficial microflora, which helps to break down organic compounds and convert them into forms available to plants. Soils with an organic matter content of more than 1.5% are very fertile, providing optimal conditions for wheat cultivation. Reducing the organic content to less than 1% can negatively affect the water-holding capacity of the soil, reduce its aeration and lead to a decrease in fertility. CEC measures the ability of soil to hold cations such as calcium, magnesium, potassium and sodium, which are essential for plant nutrition. A high CEC indicates that the soil can hold more nutrients and supply plants during the growing season. For wheat cultivation, a CEC level of more than 24 resin (+)/kg clay is desirable. This indicates a high content of nutrients, which contributes to good plant growth. A low CEC level (less than 5 resin(+)/kg) means that the

soil is not able to retain enough cations, which leads to rapid leaching of nutrients and a decrease in yield.

Soil EC is an indicator of the concentration of dissolved salts. A high EC level may indicate salinity, which harms wheat growth, as excess salts in the soil can cause osmotic stress in plants, reducing their ability to absorb water. The ideal level of EC for wheat is low to moderate, which ensures normal conditions for plant growth without the risk of salinity. If the EC increases, measures to improve soil quality, such as salt washing or gypsum application, are necessary. The chemical and biological properties of soil are interrelated and together determine its fertility. For instance, organic matter can influence pH and CEC levels, increasing the soil's ability to retain nutrients. At the same time, maintaining a healthy soil microflora helps to decompose organic matter and enrich the soil with nutrients. Assessment of these characteristics is critical for making decisions about land use in agriculture.

Flood and erosion risk assessment. Flood and erosion risk was assessed based on site slope, aspect and flood frequency. Tables 7 and 8 shows the weighting coefficients for each parameter and the suitability indicators under optimal conditions.

The assessment and weighting of slope are a critical indicator as it directly affects soil erosion and moisture loss. Land with a slope of less than 4% is suitable for agricultural use, as it has a minimal risk of erosion and retains moisture better. As the slope increases to 8-16%, the risk of erosion increases, which reduces soil productivity. The weighting value for slope is 22%, emphasising its importance in the overall analysis. When the slope exceeds 16%, soils become almost unsuitable for wheat cultivation, as the rapid washing away of the top fertile layer significantly limits plant growth. Flood risk and erosion are among the most important factors

affecting the suitability of land for agricultural use. These natural phenomena can cause severe crop losses, and soil degradation and adversely affect land fertility. Floods are caused by excessive rainfall, overflowing rivers, or rising groundwater levels, and can lead to significant damage to agricultural land. Wheat is a crop that is

sensitive to stagnant water, and prolonged flooding can cause root rot and plant death. Flood risk assessment includes an analysis of the frequency and intensity of precipitation, proximity to water sources such as rivers, and topographical characteristics that may affect water accumulation.

Table 7. Flood and erosion risk weights and land suitability

Criterion	AHP value	Percentage
Slope (%)	0.372	37.2%
Erosion risk	0.292	29.2%
Flood frequency	0.246	24.6%
Terrain aspect	0.09	9%

Source: compiled by the authors

Table 8. PWCM for flood and erosion risk criteria

Slope	Erosion risk	Flood frequency	Terrain aspect (slope direction)	Weights (%)
1	1	2	4	37.2
1	1	1	3	29.2
1/2	1	1	3	24.6
1/4	1/3	1/3	1	9
Consistency ratio = 2%				$\Sigma=100$

Source: compiled by the authors

To assess flood risk, it is necessary to address factors such as historical data on the frequency and extent of flooding, as well as the geographical location of the land plot in relation to water bodies. For instance, land located in low-lying areas or in proximity to rivers has a significantly higher risk of flooding. This analysis uses flood frequency data to rank land parcels by risk level, from low (where flood risk is minimal) to high (where there is a significant likelihood of flooding). Floods can not only destroy crops but also wash away fertile topsoil, reducing its fertility in the long term. Flooding also causes nutrient leaching and increases the risk of plant diseases, making it essential to consider flood risk when planning agricultural operations. In regions with a high risk of flooding, agronomists can decide to select alternative crops that can better tolerate excess moisture or plan drainage systems to protect crops.

Soil erosion is the process of losing the top, most fertile layer of soil due to water or wind (Yermakov *et al.*, 2021). Water erosion is particularly dangerous on agricultural land where the natural vegetation has been removed for crops. Assessing the risk of soil erosion involves analysing the slope, rainfall intensity, soil structure and vegetation type. Lands with steep slopes or loose soils that lack sufficient vegetation cover are particularly vulnerable to erosion. The slope of the surface is one of the most important factors in erosion. The steeper the slope, the higher the likelihood that the water flowing downhill will wash away the topsoil. In regions with frequent and intense rainfall, the risk of erosion increases even more. The lack of vegetation also contributes to erosion, as plants not only protect

the soil from the impact of raindrops but also help to anchor the soil with their roots.

Erosion leads to the loss of the fertile soil layer that contains the most nutrients and organic matter. This reduces land productivity and requires additional measures to improve soil conditions, such as fertilisation or erosion control. To reduce the risk of flooding and erosion on agricultural land, various management methods are used. These can include planting forest belts, terracing slopes, using cover crops and creating drainage systems. It is also necessary to monitor weather conditions and forecasts to minimise potential damage to crops. Planning land use with flood and erosion risk in mind helps to protect soils from degradation and preserve their fertility for future generations. The results indicate that areas with a slope of less than 10% and low flood levels are more suitable for growing grain crops. The slope has a particularly significant impact, as it significantly affects the risk of erosion.

Assessment of accessibility to water sources and routes. The accessibility of land plots, namely their distance from water sources and roads, is an important factor in assessing the suitability of land for agricultural use. This criterion has a significant impact on the efficiency of land use, as proximity to key infrastructure elements is directly related to logistical costs and ease of resource management. Accessibility was considered one of the important components of the analysis, as it facilitates the process of land cultivation, transportation of products, and provision of water, which is critical for growing grain crops. Sites located closer to water sources received higher scores for suitability. Water is

one of the key elements for sustainable crop growth, and proximity to natural water sources or artificial irrigation systems reduces irrigation costs. Land that requires high costs for water delivery may be less suitable for intensive agricultural use, as this significantly affects its profitability. The distance to water sources also determines the possibility of prompt water supply during periods of drought, which ensures more stable yields and reduces the risks associated with moisture shortages. Thus, proximity to water sources contributes to the suitability of land for agricultural use, especially for crops that require regular irrigation, such as grain.

The availability of transport infrastructure, namely proximity to roads, is an equally important criterion for determining land suitability. Land located closer to roads receives higher scores because convenient access to transport routes reduces the logistical costs of delivering agricultural products to markets or storage facilities. Transportation is an important component of profitability, and distance from roads can significantly increase costs and delivery times, which is especially important for perishable products (Bulgakov *et al.*, 2019). In the context of cereals, which require significant volumes of transport after harvest, good transport links are a crucial factor for optimal land use. Thus, plots located close to roads are more attractive in terms of suitability, as they facilitate access to necessary services and resources.

In general, the accessibility criterion addresses key aspects that affect the profitability and convenience of land cultivation. Proximity to water sources reduces irrigation costs and ensures a stable water supply, which is important for agricultural production, especially in regions with changing climatic conditions (Yeraliyeva *et al.*, 2017). Proximity to roads reduces the cost of transporting products, making land more attractive for agricultural investment. Application of the AHP method to assess the suitability of land for agriculture in Albania and Ukraine. The application of the AHP method to assess the suitability of land for agriculture is of particular importance for countries such as Albania and Ukraine. Both countries have large agricultural areas, but face unique challenges, making the AHP method particularly valuable for comprehensive land valuation.

Albania due to its mountainous landscape, should efficiently use domestic resources (Shahini, 2024). For this country, every available plot, especially in the face of growing demand for food and the increased threat of environmental degradation, should be employed with maximum efficiency. The AHP method can be used to thoroughly assess various factors such as soil texture, depth, climatic conditions, access to water resources and flood risk. This allows for science-based decisions on land management and contributes to sustainable agricultural development, which is a priority for Albania. In addition, AHP is affordable and can be effectively integrated with GIS tools, enabling spatial analysis that addresses the geographical complexity of the country.

As one of the largest agricultural countries in Europe with fertile soils and a large volume of agricultural exports, effective land management is critical to the economy. However, due to the diversity of climatic zones and significant variations in soil quality across different regions, there is a need for methods that allow for a comprehensive assessment of land suitability. The AHP method accounts for both agroecological factors, such as soil moisture, acidity and temperature, as well as socio-economic aspects, such as access to infrastructure and logistics, which are important in the context of Ukraine's large territory. For crops such as cereals, which are strategically important for Ukraine, AHP can help identify the most productive areas and optimise resource allocation. The AHP method provides a structure for complex decisions by combining different criteria and allowing for the optimal use of land. This is especially relevant in the context of climate change and the threat of soil degradation. For both countries, the application of AHP can be the basis for developing effective agricultural policies aimed at increasing productivity with minimal environmental impact.

DISCUSSION

The study, based on the AHP, confirmed the importance of a comprehensive approach to soil assessment, which includes a detailed analysis of physical, chemical, biological and climatic characteristics. This approach was used to more accurately determine soil quality, fertility and ability to support different types of vegetation. Physical characteristics such as soil texture and structure affect water-holding capacity, while chemical properties, including pH and nutrient content, determine the ability of plants to grow. Biological characteristics, such as microbial activity, play a key role in the decomposition of organic materials and the supply of essential elements to the soil (Drobitko & Kachanova, 2023). Finally, climatic conditions, such as temperature and humidity, also have a significant impact on all other aspects, shaping the overall soil ecosystem. An integrated approach that addresses all these factors is therefore essential for effective land management and sustainable agricultural development.

Various studies have used AHP methods to assess land suitability in different agricultural and environmental conditions, confirming the effectiveness of these methods in multicriteria analysis. A study by A. Ezra *et al.* (2023) in Nigeria employed AHP to create maps of suitability for growing certain cereals, addressing climate and soil characteristics. This study emphasised the importance of spatial analysis for effective management of agricultural areas. C. Singha *et al.* (2023) in West Bengal employed the Fuzzy AHP method to determine the suitability of land for rice and potato cultivation. The focus was on climatic indicators, such as rainfall, which proved to be an important factor in ensuring optimal conditions for crops. These conclusions

were consistent with the results of studies where climate factors also played an important role in determining land suitability.

In Turkey, B. Sarçın and S. Karaca (2023) conducted a study to assess the suitability of land for wheat and barley in semi-arid conditions. In that study, drainage and soil physical characteristics were considered as the main criteria affecting productivity, which was slightly different from the focus of this study. Shaloo *et al.* (2022) employed the AHP method and geospatial techniques to analyse the suitability of land for cereals in North India. The study showed that factors such as climatic conditions, soil physical characteristics, and access to water resources have a decisive impact on crop productivity. The results highlighted the importance of multi-criteria analysis in land valuation to accurately identify the most productive areas, which is similar to the approach used in this study to the integrated land valuation for agriculture.

In Nigeria, M. Ahmed and D. Jeb (2014) conducted a study that also used the AHP method to assess the suitability of land for sorghum cultivation. This study demonstrated that the key factors affecting productivity include topography, climate conditions and access to water. The study demonstrates the similarity in the importance of multi-criteria methods for justifying agricultural decisions in different regions, in particular in conditions that require accurate analysis of water availability for crops. A study by D. Debalke *et al.* (2023) in Ethiopia addressed physical soil properties, such as depth and texture, to assess the suitability of land for crop production in a rainfed area. This study showed that these factors had a significant impact on productivity, especially for crops that depend on a stable water supply.

A study by F. Garbaba and B. Wolteji (2024) in the Guder sub-basin, Northwest Oromia, Ethiopia, also used geospatial technologies to assess the suitability of land for wheat and maize cultivation. The researchers studied how the combination of physical soil characteristics and climatic conditions can affect the efficiency of crop production. The results confirmed that GIS in combination with multi-criteria analysis (as in this study) provide accurate data to determine the optimal areas for agriculture. This makes it possible to assess the potential of land at the regional level, considering the specific climatic and soil conditions of each site. The study confirms the importance of adapting methodologies such as AHP and GIS for agricultural regions with different climatic conditions.

In China, L. Xue *et al.* (2023) assessed the suitability of land for integrated rice culture using AHP and GIS for detailed spatial analysis. The study showed that the AHP method was used to more accurately determine the optimal conditions for crops in specific climatic zones. Thus, the results of the study confirmed the importance of multi-criteria methods for analysing the suitability of land for different crops in different

climatic and geographical conditions. H. Abbasi and M. Zeeshan (2023) also used an integrated GIS and AHP approach to determine the suitability of sites for hybrid solar-biomass power plants. Although the scope is energy-related, the approach is consistent with the methodology used in this study of land suitability for crops. The study addressed a multi-criteria analysis that included environmental and infrastructural factors such as resource availability, which is similar to the analysis of accessibility to water sources and transport routes for determining the productivity of agricultural areas. Thus, the study showed the versatility of AHP and GIS that can be adapted to different sectors to assess the suitability of land, whether for agricultural purposes or energy projects.

According to a study by A. Wubalem (2023), using AHP to model land suitability in the semi-arid regions of Ethiopia, demonstrated that the method effectively assesses topographic and soil features. The study emphasised the importance of surface slope and soil structure for irrigated agriculture, which is consistent with the findings of this study on the importance of topographic characteristics for soil fertility and efficient drainage. F. Sadiq *et al.* (2023) assessed the suitability of land for soybean production in Nigeria using a multi-criteria GIS-based approach. Parameters such as soil quality and climatic conditions are significant in their modelling. This confirms the importance of climate factors, which were also included in this study. The values of average air temperature and total precipitation as the main climatic parameters were justified because they determine the moisture supply of the soil and affect the wheat development cycle.

Notably, M. Günal *et al.* (2022) also applied AHP in the semi-arid region of Central Anatolia to assess the suitability of land for wheat production. They found that soil texture, pH, and slope were the key parameters that determined land productivity. This is in line with the findings of this study, where soil texture was given the highest weight among physical factors (27%) and slope (22%) was also found to be highly relevant. Soil pH was also emphasised in this study as one of the most important chemical factors affecting plant nutrient availability. A. Pilevar *et al.* (2020) used the integration of fuzzy logic, AHP and GIS to assess land in semi-arid regions for wheat and maize production. This study confirmed that a combination of different analytical methods can address the complex relationships between climate and soil characteristics. The consideration of complex environmental conditions and the use of a multi-criteria approach ensured accuracy in determining land productivity, which is consistent with the findings of this study that multiple assessment methods should be integrated to increase the reliability of results.

M. Tadesse and A. Negese (2020) used GIS and AHP to assess land in the Agamsa sub-basin of Ethiopia and found that slope and soil texture were key factors for

sorghum production. This highlights the importance of topography and soil texture, which were also demonstrated in this study to be significant factors for wheat production. The similarity in the results indicates the universality of these factors in the agriculture of different crops. A. Al-Hanbali *et al.* (2022) studied the suitability of land for rice cultivation in Tanzania, with a focus on the use of GIS and AHP to address topographic and soil characteristics. The approach, which included an analysis of topography and soil structure, is consistent with the findings of this study, which also highlighted the importance of slope as a factor affecting erosion and water conservation.

S. Han *et al.* (2021) addressed climate change and its impact on land suitability in Jilin Province, China, using remote sensing techniques combined with AHP. The research highlighted the importance of climate change adaptation, which is a critical aspect of this study. The study confirmed that climate change can affect the long-term productivity of land and that considering seasonal fluctuations in temperature and precipitation is important to ensure sustainable agricultural production. V. Ramamurthy *et al.* (2020) focused on assessing land suitability for maize in the semi-arid conditions of South India using an integrated GIS and AHP approach. The authors concluded that such an approach allows for more accurate identification of productive land plots, which coincides with the results of this study on the benefits of multi-criteria land assessment.

K. Naima *et al.* (2022) developed a comprehensive model of land suitability for cereal production in the remote Sahara region of Algeria, considering the specific extreme climatic conditions that characterise this arid region, as well as the problems associated with soil salinity. The study highlighted the importance of soil chemistry, in particular parameters such as pH and CEC, which correlates with the findings of this study on the critical importance of soil chemistry for the successful cultivation of wheat and other cereals. The impact of soil salinity was also considered in detail as a potentially limiting factor for agronomic productivity in some parts of this project. This highlighted the need to address not only the physical but also the chemical characteristics of the soil when planning agricultural activities in regions with similar environmental conditions. B. Kalaiselvi *et al.* (2024) highlighted the importance of sustainable agricultural production in semi-arid regions of India, using GIS and AHP to promote crop diversification. The authors determined that the introduction of modern technology can improve the efficiency of land planning and management, which is consistent with the recommendations of this study on the use of remote sensing and GIS for monitoring and planning.

Lastly, a study conducted by G. Tesfaye *et al.* (2024), focuses on mixed cereal and legume cultivation in Ethiopia, which is a relevant aspect of modern agriculture. The authors emphasise the importance of a

balanced approach to the use of natural resources, which can have a significant impact on the sustainability of agricultural systems. Their findings, which emphasise the need to address the interactions between different crops, point to the importance of integrating agronomic practices to improve overall production efficiency. This is also of great importance in the context of land suitability assessments, as optimising the use of resources can not only increase yields but also help to maintain ecological balance in the region. Thus, the study highlights the importance of integrating physical, chemical and climatic factors for a comprehensive land use assessment, which is consistent with the results of many previous studies. Further research could focus on modelling climate change scenarios and improving land management practices to enhance adaptive strategies for food security.

CONCLUSIONS

This study applied the AHP before assessing the suitability of land for cereal production using wheat as an example. This approach made it possible to accurately determine the impact of various physical, chemical, biological and climatic factors on the potential yield of land. As a result, clear qualitative and quantitative indicators were obtained that were used to rank land plots according to their suitability. The analysis highlighted the critical factors influencing land suitability for grain crop production, emphasising the dominant role of soil and environmental characteristics. Flood and erosion hazard, with a weight of 32.2%, emerged as the most significant factor, reflecting its substantial impact on soil stability and long-term agricultural viability. Soil physical characteristics ranked second with a weight of 25.6%, underscoring the importance of texture, depth, and slope in water retention, aeration, and root development. Soil biological and chemical characteristics, with a weight of 22.3%, were ranked third, demonstrating the crucial influence of soil fertility parameters such as pH, organic matter, and CEC on nutrient availability and plant growth. Climate, accounting for 14.1%, was identified as the fourth most influential criterion, as precipitation and climatic conditions play an essential but less critical role compared to soil-related factors. Accessibility, with a weight of 5.8%, was the least significant factor, as logistical and infrastructural considerations are secondary to the biophysical attributes of the land. The consistency ratio of 4% validated the reliability of these weightings, ensuring a robust and systematic evaluation of land suitability for grain crop production. Climatic factors, including average temperature and total precipitation, determine the main conditions for wheat growth. The optimum temperature range (15-25°C) and adequate rainfall (350-1250 mm per year) provide the best conditions for the development of the crop. At the same time, the risk of flooding and erosion affects the long-term suit-

ability of land, as excess water and soil loss can cause substantial agronomic issues.

The AHP method is relevant for agricultural countries such as Albania and Ukraine, as it can be used to efficiently assess and plan land use, accounting for specific soil and climatic conditions. In Albania AHP can be used to optimise ground use, accounting for food growth demand and environmental risks. In Ukraine, which is a major exporter of agricultural products, AHP can be used to assess both natural and infrastructural factors that are critical for productive and sustainable agriculture. In this way, AHP contributes to the development of agricultural policies that increase productivity and minimise environmental impacts, ensuring the rational and sustainable use of land resources in both countries.

Practical recommendations include the use of appropriate agronomic measures to reduce the risk of erosion, such as terracing on slopes and the use of cover crops. In regions with a high risk of flooding, drainage systems and protective plantings are recommended. To improve fertility, organic fertilisers can be used to increase CEC levels and improve soil structure. Key areas for further research include a deeper analysis of the impact of seasonal climate change on wheat yields and modelling of climate change scenarios to assess

long-term risks to farmland. In addition, consideration should be given to integrating modern technologies, such as remote sensing and GIS, to better map land and monitor its suitability.

The limitations of the study include the dependence of the results on the accuracy of the data used for the analysis and the limitations of the AHP method, which may require additional verification in real-world conditions. Moreover, the impact of seasonal and long-term climate change has been partially considered, which may affect the conclusions on land suitability. Further research should address the impact of seasonal climate change and the use of modern technology to more accurately assess land resources.

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CONFLICT OF INTEREST

None.

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Застосування аналітичного ієрархічного процесу в оцінці придатності земель для вирощування зернових культур

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Анотація. Оцінка придатності земель для вирощування зернових культур є актуальним питанням для забезпечення сталого сільськогосподарського виробництва та підвищення продовольчої безпеки. Метод аналізу ієрархій (MAI) є ефективним методом багатокритеріальної оцінки, який систематично враховує всі параметри. Метою дослідження був аналіз використання методу аналізу ієрархій для визначення вагомості та пріоритетності різних ґрунтово-кліматичних характеристик для аналізу придатності земель для вирощування зернових культур на прикладі пшениці. В результаті дослідження було визначено ключові фактори, що впливають на врожайність, та розроблено рекомендації щодо ефективного управління земельними ресурсами. Для зважування різних критеріїв, включаючи фізичні, хімічні та кліматичні характеристики, було використано метод аналізу ієрархій. Дані були оброблені для визначення впливу кожного фактору на придатність землі з перевіркою на узгодженість для забезпечення надійності результатів. Дослідження показало, що найбільш важливими фізичними факторами є характеристики небезпеки повеней та ерозії (32,2 %) та фізичні характеристики ґрунту (25,6 %). Кислотність (pH) та ємність катіонного обміну (ЄКО) мають значний вплив на доступність поживних речовин, тоді як середня температура та кількість опадів визначають основні кліматичні умови для росту пшениці. Ризики повеней та ерозії також розглядаються для довгострокової оцінки придатності. Для оцінки придатності земель для вирощування пшениці було використано метод аналізу ієрархій, що дозволило визначити найважливіші фактори та їхню вагу. Практичні рекомендації включали застосування агротехнічних заходів для зменшення ерозійних ризиків та покращення родючості ґрунтів. Результати дослідження можуть бути використані агрономами, землевпорядниками та політиками для вдосконалення управління земельними ресурсами, що сприятиме підвищенню ефективності сільськогосподарського виробництва та продовольчої безпеки в умовах зміни клімату

Ключові слова: критерії оцінки; родючість ґрунтів; ерозійний ризик; кліматичні фактори; управління земельними ресурсами; агротехнічні заходи

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Effective methods of rational water resource use in the agrarian sector of Kazakhstan

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Abstract. The study aimed to determine effective methods of rational water resources use in the agricultural sector of Kazakhstan. The impact of modern irrigation technologies, such as drip and sprinkler irrigation, as well as automated monitoring systems on crop productivity, soil condition and adaptability of farms to climate change was analysed. Drip irrigation was noted to reduce water losses by up to 40%, while sprinkler systems provided uniform coverage of large areas, optimising water resources. Automated monitoring systems using soil moisture sensors and weather

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forecasting reduced water consumption by 25-50% and increased crop yields by 15-30%. The study also determined that introducing such systems improved soil quality, reducing depletion and ensuring long-term productivity. An analysis of the experience of farms in Kazakhstan, Israel, Spain and China confirmed the economic feasibility of such approaches by reducing operating costs as well as dependence on external financing and increasing resilience to climatic stresses. In particular, automation of water supplies reduced water, energy and system maintenance costs, which ensured long-term farm stability. The practical value of the work was the formation of scientifically based recommendations for the introduction of innovative irrigation technologies to improve the efficiency of the agricultural sector of Kazakhstan, reduce the impact of climate change and ensure sustainable development

Keywords: irrigation; soil productivity; automated systems; crop yield; optimisation

INTRODUCTION

Rational use of water resources in the agricultural sector is one of the key challenges for Kazakhstan, which is limited, whereas agriculture remains a central sector of the economy. In the context of climate change, deteriorating water bodies and the growing need for water for irrigation, optimisation of water use is not only a necessity to improve production efficiency but also an important factor in the sustainability of agricultural enterprises. The introduction of modern irrigation technologies, such as drip and sprinkler irrigation, as well as the use of water monitoring and automation systems, is a promising way to reduce water losses, cut costs and increase yields. These technologies contribute not only to economic benefits but also to the improvement of soil quality and the sustainability of agricultural production in the context of changing climatic and natural factors.

The issue of rational use of water resources in the agricultural sector of Kazakhstan is relevant due to the limited water resources and the need to improve efficiency. M. Li *et al.* (2022) determined that optimisation of water use in agricultural farms significantly reduced water costs, which improved the financial performance of agricultural enterprises. The authors also stressed that such measures improved the environment in regions with limited water resources, creating a sustainable basis for agricultural development. W. Loiskandl and R. Nolz (2021) demonstrated that the introduction of drip and sprinkler irrigation minimised water losses and increased yields, thus increasing farm profitability. The authors also highlighted that such irrigation systems ensure a more rational distribution of water resources and reduce excessive consumption. T. Maraseni *et al.* (2021) highlighted that the use of automated water consumption monitoring systems improved the accuracy of water distribution, which significantly reduced water overruns. These technologies also contribute to the improvement of the overall efficiency of the agricultural sector by increasing the efficiency of available water resources. L. Jin-Yan *et al.* (2021) determined that the introduction of sensors and intelligent systems not only saves water but also prevents its overuse, which positively affects soil quality. The authors also noted that such technologies have increased crop productivity, ensuring sustainable production growth.

E. Bwambale *et al.* (2022a) noted that modern irrigation technologies feature significantly reduced operating costs, which increases the profitability of agricultural enterprises. These technologies have also provided more stable financial results in the long term, contributing to the sustainability of agriculture.

D. Mengistu *et al.* (2021) studied the impact of climate change on water resources and recommended adapting water use methods to changing conditions to minimise risks to agriculture. The authors stressed that these measures increase the sustainability of agricultural production in the context of global climate change. J. Fito and S. W. Van Hulle (2021) argued that water use optimisation reduces land rehabilitation costs and the dependence of farms on external financing. This also improves the financial stability of farms and reduces their vulnerability to economic crises. A.L. Srivastav *et al.* (2021) demonstrated that rational water use reduced the need for additional investments, which improved the financial stability of agricultural enterprises. The authors also noted that this improves the long-term sustainability of enterprises and ensures more efficient use of available resources. M. Mallareddy *et al.* (2023) highlighted the importance of sustainable water management practices for increasing the resilience of agricultural farms to adverse natural factors such as droughts and overheating of the soil. They stressed that such methods also help improve the quality of agricultural products and increase their competitiveness. C. Ingraio *et al.* (2023) proved that the introduction of economically viable irrigation methods was a key factor in stabilising agricultural production in conditions of limited water resources. These methods have increased the efficiency of agricultural production and reduced the risks associated with climate change and water shortages. However, despite the wide range of studies, some gaps require further research, such as a more detailed study of the impact of new technologies on soil, an in-depth study of the economic impact on small and medium-sized farms, and more accurate models for predicting water consumption in light of climate change.

The study aimed to identify the most effective methods of water management in Kazakh agriculture.

MATERIALS AND METHODS

A comprehensive methodology, including several inter-related methods, was used to conduct a comprehensive assessment of the state of water resources and the efficiency of their use in the agricultural sector of Kazakhstan. For a more detailed analysis, a geographic information system (GIS) and mapping methods were used to conduct a spatial assessment of water availability for agriculture. This identified problem areas where water resources are scarce, creating risks to the sustainability of agricultural production.

A comparison was made to evaluate the efficiency of different irrigation methods such as drip and sprinkler irrigation. This analysis addressed the impact of each method on parameters such as yield, water use and water losses. The comparison established how each method affects water utilisation and production results. System analysis and modelling techniques were used to assess the impact of intelligent monitoring systems on water use. This approach was used to evaluate existing technologies such as soil moisture sensors and automated water use monitoring systems. These systems were studied to determine their role in optimising water allocation and improving water management in agricultural enterprises. Economic modelling and cost analysis techniques were used to estimate the economic benefits of implementing rational water use practices. Models were constructed from water expenditure and yield data to show that the introduction of more efficient irrigation methods and automation leads to lower costs and higher yields. These results were also used to assess the impact of water use optimisation on the resilience of agricultural farms to climate change, improving their adaptability to extreme weather conditions.

Water management practices in the agricultural sector were analysed, highlighting irrigation systems and water supply management. The experience of successful farms and international examples of efficient water use were also reviewed. Specific enterprises were reviewed, such as Baiserke-Agro (2024) in Kazakhstan and Netafim Company (2024) in Israel, as well as Citrus Valley (Valencia's Citrus Coast, 2024) in Spain and Shandong Green Agriculture (2024) in China. Experiences with technologies such as drip irrigation, automation of water supply and the use of sensors to monitor soil moisture, and their impact on reducing costs, increasing yields and improving resilience to climate change were analysed as part of the work. This approach highlighted how the introduction of innovative water management technologies has reduced costs, increased profitability and improved farm resilience to climate change.

The study analysed methods of rational use of water resources in the agricultural sector and assessed their impact on the economic efficiency of agricultural farms. Various irrigation and water automation technologies were considered, as well as their impact on cost reduction and yield increase. The method of strategic analysis was applied to develop recommendations for improving water use in the agricultural sector. Based on the findings, measures were proposed to introduce innovative technologies, improve water use monitoring and enhance the skills of specialists. These recommendations were designed to ensure sustainable agricultural development in the context of limited water resources and climate change.

RESULTS

In the Kazakhstan agricultural sector, water resources are essential for sustainable agricultural production, especially in the context of significant climatic changes and limited water sources. The economics of water use in this context includes a set of methods, technologies and strategies aimed at optimising the use of water resources and reducing the costs of their consumption. Kazakhstan, one of the largest countries in Central Asia, faces a water shortage challenge. This is determined not only by geographical peculiarities but also by the rapid growth of agriculture, especially in regions where irrigation is the main method of agricultural production. The state of water resources in Kazakhstan requires careful analysis, especially in the context of their regional distribution, accessibility for the agricultural sector and existing management problems. The volume of water resources in Kazakhstan is estimated at 100-120 cubic kilometres of water per year (Table 1). However, most of the water resources are concentrated in river basins such as the Irtysh, Syr Darya and Amu Darya, which flow through neighbouring countries, making them difficult to manage.

As a result, much of the water resources, especially in the southern and western regions, are subject to international agreements, limiting their availability for domestic consumption (Kenzhegulova *et al.*, 2023). For Kazakh agriculture, irrigation water is critical, accounting for approximately 80% of the national total water needs. In the southern and eastern regions, such as Zhambyl and Almaty regions, where the main agricultural areas are located, irrigation plays an important role in ensuring crop yields. However, these regions face water resource constraints, leading to increased competition for water among agriculture, industry and the population (Abraliyev *et al.*, 2024).

Table 1. Water use in the agricultural sector of Kazakhstan by years

Year	Total water use (billion cubic metres)	Water volume for irrigation (billion m ³)	Water volume for livestock production (million m ³)	Water volume for other needs (billion m ³)	Share of water for irrigation (%)
2020	100	60	30	10	60%
2021	105	63	33	9	60%

Table 1. Continued

Year	Total water use (billion cubic metres)	Water volume for irrigation (billion m ³)	Water volume for livestock production (million m ³)	Water volume for other needs (billion m ³)	Share of water for irrigation (%)
2022	110	65	35	10	59%
2023	108	62	34	12	57%
2024 (estimate)	112	67	36	9	60%

Source: compiled by the authors based on Bureau of National Statistics (2024)

One of the primary issues in Kazakhstan is outdated water supply and irrigation systems that not only do not ensure rational use of water but also cause significant water losses. Examples are canals and water supply networks that have a low degree of insulation, which favours evaporation and water leakage. In addition, due to the lack of coordination between different levels of government and the absence of a unified water management system, inefficient water distribution occurs. Local agricultural producers often face difficulties in accessing the necessary volumes of water, while other sectors such as industry or energy also require significant amounts of water. Ecosystems that suffer from water overload are especially notable. Environmental problems such as the shallowing of rivers and reservoirs,

degradation of aquifers, and pollution of water resources have a long-term impact on the health of ecosystems and agricultural development (Berezhniak *et al.*, 2022).

Irrigation is an integral part of agricultural production, especially in regions with limited water resources. In the context of Kazakhstan, where agriculture is highly dependent on water supply, the choice of irrigation methods is essential to improve the economic efficiency and sustainability of the agricultural sector. The development of irrigation technologies such as drip and sprinkler irrigation in recent decades was central to optimising water use and increasing crop yields. Each of these systems has unique features that can significantly affect the production results and financial sustainability of agricultural enterprises (Table 2).

Table 2. Water use optimisation methods

Optimisation method	Description	Advantages	Disadvantages
Drip irrigation	A technology in which water is supplied directly to the roots of plants through drippers, which minimises water loss.	Reduced water losses, increased yields, reduced soil erosion.	High initial investment, and difficulty in maintaining and repairing the system.
Sprinkler irrigation	Water is sprayed through special devices that simulate rain.	Uniform water distribution, increased yields over large areas.	Water losses due to evaporation, and high operating costs in strong winds.
Automated water consumption control systems	The use of sensors and humidity sensors to automatically adjust the water supply according to the needs of the plants.	Increased accuracy, water savings, and reduced labour costs.	High cost of implementation and maintenance, requires technical training of personnel.

Source: compiled by the authors based on H. Li *et al.* (2021)

Drip irrigation is one of the most efficient irrigation methods in water-limited environments (Manda *et al.*, 2021). This method involves the precise delivery of water directly to the root system of plants through special pipelines with drip elements. This reduces water consumption and plants receive moisture evenly, which significantly increases crop yields. With traditional irrigation methods, such as sprinkling, water is applied to the entire field area, which results in significant water losses due to evaporation, run-off and uneven distribution. For instance, irrigation of one hectare of wheat requires approximately 5,000 m³ of water, thus creating high water supply costs. This approach is not optimal as most of the water is used inefficiently, increasing water supply costs and reducing water use efficiency. Drip irrigation can significantly reduce the volume of water used for irrigation. By precisely metering water and delivering it directly to the root system, water

consumption per hectare is reduced by up to 3,000 m³. This saves 40% of water compared to traditional irrigation methods. At a water cost of 5 tenge per m³, the cost of water supply per hectare before the introduction of drip irrigation is 25,000 tenge (5000 m³×5 tenge). After the introduction of drip irrigation, the costs are reduced to 15,000 tenge (3000 m³×5 tenge), which gives a saving of 10,000 tenge per hectare.

Sprinkler irrigation is a method in which water is distributed through rotating sprayers that irrigate a large area (Chauhdary *et al.*, 2023). Although this method is less efficient compared to drip irrigation, it has low cost and is affordable for many farms. For traditional sprinkler irrigation methods or with low-efficiency systems, water consumption is high, often in unharvested areas. However, when sprinklers are used, approximately 6000 m³ of water is used per hectare of wheat, which is 20% more than drip irrigation. Compared to

conventional irrigation methods, sprinkler irrigation reduces water costs because water is applied uniformly, but still not as accurately as with drip irrigation. For 6000 m³ of water per hectare, the cost of water supply is 30,000 tenge (6000 m³×5 tenge). The use of sprinkler irrigation reduces water costs compared to traditional methods, but it is still less efficient than drip irrigation.

Automated water use control systems use soil moisture sensors, weather forecasts and other technologies to automatically adjust water inputs (Ray & Majumder, 2024). This enables efficient irrigation management, reducing water use in the event of rainfall or other natural factors affecting irrigation demand. Without automated systems, irrigation is usually done manually or based on standardised calculations that do not always match the actual needs of the plants. Therefore, water supply costs can be inflated due to unnecessary irrigation. With automation, water supply costs are reduced by 15-20%. Water consumption for irrigation of one hectare is reduced to 4000 m³. The cost of irrigation after the introduction of automated systems is reduced to 20,000 tenge (4000 m³×5 tenge). This provides savings of up to 5,000 tenge compared to traditional irrigation methods and ensures greater accuracy and efficiency of water inputs.

Every year, water scarcity is becoming an increasingly urgent problem for agriculture. Effective water management is critical for the sustainability of agricultural farms, especially in the face of climate change and increasing water demand. In recent years, modern technologies for monitoring and managing water use, such as sensors and intelligent control systems, are increasingly relevant to this process. These technologies not only improve the accuracy of water allocation but also significantly reduce water costs, which affects the economic efficiency of agriculture. One of the most important steps in improving water use has been the introduction of intelligent systems that allow real-time monitoring and regulation of irrigation (Palakshappa *et al.*, 2024). These systems use sensors to measure soil moisture levels, temperature, and other parameters necessary for optimal water distribution. For instance, moisture sensors detect changes in soil moisture levels, which allows the irrigation system to automatically switch the irrigation system on or off depending on the actual water demand of the plants. This eliminates water wastage and makes irrigation more precise. Intelligent systems not only make irrigation more efficient but also enable remote management. Using mobile

applications or computer systems, farmers can monitor water supply parameters, obtain data on soil conditions and forecast water requirements based on weather conditions. This approach reduces human error and increases the efficiency of water management.

Sensors used in modern irrigation systems are crucial to the accuracy of water distribution (Bwambale *et al.*, 2022b). For instance, sensors installed in the soil measure its moisture content and can transmit the data to the control system. This allows not only precise water dosing but also accommodates changes in plant demand due to weather conditions, growth phases or even time of day. As a result, irrigation is carried out according to the actual needs of the plants, which significantly reduces water wastage. The use of sensors also reduces the number of irrigations, which are traditionally carried out according to fixed schedules, regardless of actual conditions. This in turn minimises unnecessary evaporation and water loss, especially in hotter years. In regions where water resources are limited, this approach becomes particularly valuable as it maximises the use of every drop of water.

The use of water monitoring and management technologies has a direct impact on reducing water costs. Traditional irrigation systems often experience high water losses due to over-irrigation or improper water distribution. The introduction of modern technologies eliminates these issues. For instance, automated systems that respond to changes in soil moisture and weather conditions can adjust the amount of water based on current needs rather than on a predetermined schedule. In addition, such systems help reduce energy costs by eliminating the operation of pumps and other devices outside of normal business hours or when not needed. This also reduces equipment maintenance costs and contributes to the longevity of the system, as it is not subjected to excessive stress.

Rational use of water resources in agriculture is becoming not only an environmental necessity but also an economic benefit. Under conditions of limited water resources, climate change and increasing demand for agricultural products, efficient water use management is of key importance for improving the economic sustainability of rural households. The introduction of modern irrigation methods and water use control systems can significantly reduce water costs, increase crop yields and improve financial results, as well as strengthen farm resilience to changes in climatic conditions (Table 3).

Table 3. Economic benefits of using sensors and intelligent systems

Parameters	Before system implementation	After system implementation	Savings
Water consumption (m ³ /ha)	1,000	700	300
Cost of water supply (USD/ha)	500	350	150
Energy costs (USD/ha)	200	160	40
Total water supply costs (USD/ha)	700	510	190

Source: compiled by the authors based on K. Obaideen *et al.* (2022)

Optimisation of water use implies the introduction of technologies that accurately dose the amount of water required for irrigation and reduce losses. For instance, a shift from traditional irrigation methods such as open canal irrigation to more modern methods such as drip and sprinkler irrigation significantly reduces water losses. These methods deliver water directly to the plant roots or spray it evenly over the surface, minimising evaporation and wastage. Such technologies allow farmers to significantly reduce water supply costs, which is especially important for regions with limited water resources, such as Kazakhstan. Moreover, the automation of the irrigation process through sensors and intelligent control systems reduces energy costs, as pumps and control systems are only started when they are needed. This significantly reduces operating costs and makes water use more economical and efficient.

One of the main factors in increasing the economic efficiency of agricultural production is the increase in crop yields. The introduction of rational water management practices improves conditions for plant growth, reducing the risk of water shortages that can reduce crop yields. Modern irrigation systems, such as drip irrigation, ensure uniform water distribution, which enhances nutrient uptake and improves overall crop health (Yeraliyeva *et al.*, 2017). In addition, precise water management improves water efficiency for different crops depending on the needs. For instance, some crops, such as vegetables or fruits, require more intensive irrigation, while others, such as cereals, may need smaller quantities of water. This improves overall agricultural productivity and, as a result, increases the profitability of the enterprise.

Climate change has a significant impact on agricultural production by causing extreme weather conditions such as droughts and heavy rains (Habib-ur-Rahman *et al.*, 2022). Under such conditions, the resilience of agricultural enterprises to climate variability becomes a critical challenge. Rational use of water implementation of modern irrigation techniques and monitoring of water consumption are essential in this process. Automatic control systems and soil moisture sensors ensure a rapid response to changes in weather conditions, adjusting the amount of water needed to supply the plants according to current needs. This reduces crop losses during periods of drought and minimises damage from overwatering in the event of heavy rainfall. In this way, farmers can adapt water management practices more precisely to changing climatic conditions, increasing their resilience to extreme weather events.

Optimisation of long-term water use contributes to the sustainability of agricultural farms, both economically and environmentally. Lowering water and energy costs reduces the dependence of agricultural enterprises on external sources of financing, which is particularly relevant in an unstable economy. Effective water

management contributes to soil sustainability by reducing the risks of soil depletion and improving soil quality. In addition, efficient water management minimises negative environmental impacts by reducing waste and water losses, which also contributes to the long-term sustainability of agricultural production. Optimisation of water use in agriculture is an important factor in ensuring economic efficiency and sustainability of agricultural enterprises. With global climate change, water scarcity and increasing competition for water, the implementation of innovative water management practices is becoming a necessity. In this context, examples of successful agrarian enterprises in Kazakhstan and foreign countries can serve as a reference point for other farms seeking to improve their efficiency through the rational use of water resources.

A notable example of successful water use optimization in Kazakhstan is the Baiserke-Agro agricultural enterprise (2024), located in Central Kazakhstan. Specializing in the cultivation of grain and vegetable crops, this enterprise has significantly enhanced its economic efficiency by achieving a 15-20% increase in yields and a 30% reduction in water usage. These improvements were made possible through the implementation of advanced drip irrigation systems and the automation of water supply processes (Atakulov *et al.*, 2023). In 2023, companies made significant advancements in irrigation by introducing soil moisture sensors and automatic water flow control systems. Previously reliant on traditional irrigation methods that often resulted in substantial water losses, farmers achieved notable improvements by transitioning to drip irrigation (Farms in North Kazakhstan region are..., 2023). The introduction of these advanced technologies also led to a reduction in the energy consumption needed to operate pumping stations. Thus, this farm has demonstrated how modern irrigation techniques can not only reduce costs but also increase profitability.

Israel stands out as one of the global leaders in water management, with its innovative practices and technologies serving as a valuable example for other nations (Dai, 2021). In the face of freshwater scarcity and frequent droughts, Israel has developed advanced technologies in drip irrigation, which has significantly improved agricultural efficiency. Netafim (2024), a company based in Israel, has pioneered the development and implementation of drip irrigation systems, which are now widely used in agriculture worldwide (Israeli Climate Innovation for..., 2024). Drip irrigation systems developed by Netafim enable precise dosing of water, delivering it directly to the roots of plants, minimising water loss and increasing crop yields. This method is particularly effective in arid areas such as Southern California, Australia and the Middle East where water resources are limited. As a result of the introduction of drip irrigation, agricultural enterprises using this technology have achieved significant yield increases with

minimal water use, making them more economically sustainable and profitable.

Spain, one of the driest countries in Europe, has also made significant strides in optimising water use in agriculture. In the Valencia region, where citrus and other crops are grown, farmers are actively adopting irrigation control systems and automated technologies that help use water efficiently. In particular, the Citrus Valley agricultural complex (Valencia's Citrus Coast, 2024), an example of efficient water use, employs soil moisture sensors and systems that automatically adjust the amount of water applied based on the plant's needs (Poveda-Bautista *et al.*, 2021). The results showed that the adoption of such technologies enabled farmers to reduce water consumption by 20%, while yields increased by 20%. The water savings significantly reduced water purchase and transport costs, which is important in the context of limited water resources and high-water prices. It has also contributed to improved product quality, making Spanish farmers more competitive in international markets.

In China, where water problems have become more pronounced, agricultural enterprises are actively adopting water management technologies. One example is

an agricultural complex in Shandong Province specialising in fruit and vegetable production, known as Shandong Green Agriculture (2024). This complex has successfully applied innovative drip irrigation systems and remote monitoring systems for water use, which significantly reduced water losses and increased crop yields (Guo *et al.*, 2024). The complex also introduced water recycling and reuse systems to minimise water consumption and reduce water supply costs. The results of implementing these technologies were as follows: water costs were reduced and crop yields increased (Yang *et al.*, 2023). This experience shows how the use of innovative water use technologies not only helps to manage water resources efficiently but also to make agriculture more resilient to external economic and environmental challenges. It is worth noting that the introduction of modern irrigation systems has a significant impact on the efficiency of water use and the yield of agricultural enterprises. Various innovative methods, such as drip irrigation and water supply automation, significantly reduce water consumption while increasing agricultural productivity. Table 4 shows the impact of these technologies on water use and yields in agricultural enterprises.

Table 4. Impact of modern irrigation systems on water use and yields in agricultural enterprises

Company/Location	Irrigation technology	Impact on water usage	Impact on yield	Additional information
Baiserke-Agro (Kazakhstan)	Drip irrigation	Reduced water consumption by 30%, saving 500,000 cubic metres annually	Increase in grain and vegetable yields by 15-20%	Improving water use efficiency and yields, reducing water costs
Netafim (Israel)	Drip irrigation systems	Reduced water consumption by up to 50% in some regions	Increase yields by up to 30% for certain crops	Leader in irrigation technologies for water-limited areas
Citrus Valley (Spain)	Automated water supply management systems	Reduce water bills by 25%, saving 1 million litres annually	Increase in citrus yields by 20%	Automated irrigation improves yields and reduces operating costs
Shandong Green Agriculture (China)	Combined irrigation technologies	Reduction of water consumption by 40%	Increase in productivity by 25%	Focused on sustainable agriculture and high-technology irrigation

Source: compiled by the authors based on T. Atakulov *et al.* (2023), Israeli Climate Innovation for Energy and Water Security Solutions (2024), R. Poveda-Bautista *et al.* (2021), B. Guo *et al.* (2024)

Sustainable water use is an important element of the strategic development of the agricultural sector in Kazakhstan, which faces limited water resources and changing climatic conditions. Innovative methods and strategies need to be introduced to improve the efficiency of water resources utilisation and ensure the sustainability of agriculture. The study made the following recommendations:

Drip irrigation is one of the most effective methods of water use, which allows to significantly reduce water losses and increase crop yields. In Kazakhstan, especially in arid and semi-arid regions, such systems can be introduced in most agricultural enterprises specialising in growing cereals, vegetables and fruits. It is necessary to support farmers in the transition to drip irrigation

through state subsidies and tax incentives, as well as to provide training for farmers in new technologies and methods of water management.

Monitoring and automation systems for water management are instrumental in improving water use efficiency. The introduction of soil moisture sensors, as well as systems that regulate water supply according to the actual needs of plants, will optimise water resources, eliminating unnecessary expenditure. It is necessary to integrate such systems within the framework of the state project on the digitalisation of agriculture, which will provide farmers with access to up-to-date information and increase the accuracy of irrigation decisions. For effective implementation of innovative water use technologies, it is necessary to train highly qualified

specialists in agronomy, hydrology and engineering. It is important to develop educational programmes that will focus on the use of new irrigation methods and water management technologies. It is also necessary to establish a system of certification and advanced training for agrarians, which will enable them to keep abreast of the latest trends and effective practices in water use.

One of the promising directions for improving water use in the agricultural sector is the system of water reuse. The introduction of such technologies as filtration and wastewater treatment will reduce the consumption of fresh water for irrigation. The implementation of such solutions may be particularly relevant for regions with limited water resources. In addition, it is necessary to develop infrastructure for water recycling at the level of large agricultural complexes and processing plants, which will provide additional savings. To accelerate the introduction of innovative water-use technologies in the agricultural sector of Kazakhstan, it is necessary to attract more private investment and develop partnerships with international organisations working in the field of sustainable development. Mechanisms for attracting financial resources, such as green bonds and grants, can contribute to the development of environmentally sustainable technologies and the introduction of best practices in water use. Joint projects with international partners, such as the World Bank or the United States Agency for International Development, will allow Kazakhstan to benefit from the experience of other countries and implement best practices.

For the long-term development of the Kazakh agricultural sector, it is necessary to apply an agroecological approach, which includes methods of protecting water resources, improving soil quality and enhancing biodiversity. This will not only increase the resilience of agriculture to climate change but also ensure a balance between economic interests and ecosystem conservation. There is a need to adopt agroforestry practices that will help conserve water resources and use sustainability-oriented land and water management practices. To effectively manage water resources in the agricultural sector, a unified data and monitoring system needs to be established to track changes in water supplies, water use levels, and soil health and yields. Data from such systems will contribute to optimising irrigation scheduling and rational water allocation between different agricultural sectors. This will ensure more equitable and efficient use of water resources.

DISCUSSION

Key aspects affecting the efficiency of water resources use and the costs associated with their use were identified in the analysis of the economics of water use in the agricultural sector of Kazakhstan. The assessment of the status of water resources has shown that water supply in certain regions of the country is limited due to natural conditions and insufficient infrastructure for

efficient water distribution. As a result, many agricultural enterprises face a shortage of water resources, which requires careful consideration of irrigation methods and rational water use. This problem was also investigated by Y. Zhao *et al.* (2021), confirming that analysing the status of water resources in the agricultural sector is key to ensuring agricultural sustainability and efficient use of water resources. In the face of climate change and increasing water consumption, especially in arid regions, the availability of water sources for agricultural production needs to be carefully assessed. An important aspect is an analysis of seasonal variations, as well as geographical and infrastructural water availability, which directly affects agricultural development (Mustafayeva & Tagiyev, 2023).

X. Liu *et al.* (2022) also demonstrated that the assessment of water allocation in the agricultural sector requires consideration of various factors such as the spatial location of water bodies, the density of water withdrawals and the degree of utilisation. Uneven water distribution can cause deficits in some areas and surpluses in others, creating additional challenges for the agricultural sector. It is necessary to develop strategies aimed at optimising the distribution of water resources, including the improvement of infrastructure and the introduction of water-saving technologies. It is worth noting that effective management of water resources in the agricultural sector requires not only analysing their availability but also addressing various external factors such as climate change and demographic growth. These factors can significantly change the water needs of agricultural regions, which poses a challenge for public and private structures to adapt to new conditions. Therefore, it is necessary to develop monitoring and forecasting systems that will help to identify possible water problems on time and take measures to address them, such as the introduction of innovative irrigation and water conservation methods.

One of the main factors affecting the economic efficiency of the agricultural sector is the choice of irrigation methods. A study of different irrigation systems established those traditional methods, such as surface irrigation, cause substantial water losses. Modern technologies such as drip and sprinkler irrigation can significantly reduce water consumption and increase crop yields (Pichura *et al.*, 2023). The application of these technologies in Kazakhstan has already shown positive results, especially in water-scarce areas. S.Z. Safoevna and M.N. Juraevna (2021) concluded that modern irrigation methods, such as drip and sprinkler irrigation, significantly affect agricultural economics by increasing productivity and reducing water costs. Drip irrigation, for instance, minimises water loss by spot irrigating the root zone of plants, thereby improving crop growth and yield. This is particularly relevant in the context of limited water resources and increased concern for the resilience of agro-systems to climate change.

D. Bhavsar *et al.* (2023) highlighted that a comparison of the efficiency of drip and sprinkler irrigation with traditional methods shows that modern irrigation systems provide higher economic efficiency. Drip irrigation reduces water and energy consumption, leading to lower operating costs in the long term. Sprinkler systems, on the other hand, have greater versatility as they can be used on different soil types and for a wider range of crops, but they also require more water and energy compared to drip irrigation. These results support the above study as they show that modern irrigation systems, such as drip and sprinkler irrigation, significantly reduce overall water consumption and provide a more precise distribution of moisture flow based on plant needs. This not only improves crop yields but also reduces the operational costs of water management. In the face of climate change and uncertain water availability, the use of such technologies can be key to ensuring food security and agricultural sustainability in the long term. Data collected on the deployment of water use monitoring technologies has demonstrated the high efficiency of intelligent control systems, which allow farmers to monitor water consumption in real-time and optimise resource use. Sensor systems integrated with information technology provide more accurate water distribution depending on crop needs, which reduces water costs and minimises losses. The use of such solutions in Kazakhstan has already been implemented in some large agricultural enterprises, allowing them to improve their economic sustainability.

The study by M. Lowe *et al.* (2022), which also determined that monitoring technologies are significant in optimising water use by enabling more precise water management at all levels of agricultural production, is noteworthy. Modern intelligent systems such as moisture sensors, automated irrigation control systems and satellite technology can be used to monitor the condition of soil and vegetation in real time. These technologies make it possible not only to improve the efficiency of water use but also to minimise the risks associated with its excessive or insufficient application. X. Xiang *et al.* (2021) concluded that the use of intelligent systems to control and distribute water resources can improve the accuracy of water distribution between different sites and crops. Such systems can automatically adjust the amount of water supplied depending on soil moisture data, plant needs and weather forecasts. This significantly reduces water losses and improves crop quality, as well as lowering the financial costs of water and energy, making agriculture more sustainable and cost-effective. These findings are consistent with the thesis in the previous section, as they confirm that the use of intelligent monitoring systems significantly improves water use efficiency. Real-time technologies provide accurate information on water requirements, thus avoiding surpluses and shortages of water in agricultural processes. This, in turn, improves not only the

sustainability of agricultural systems but also contributes to long-term cost savings and environmental efficiency in agriculture.

Economic analysis demonstrated that optimisation of water use through the introduction of new technologies reduces irrigation costs and, in turn, increases the profitability of agriculture. While traditional irrigation methods require significant water costs, modern technologies significantly reduce these costs, while improving product quality and increasing yields (Zhovtonog *et al.*, 2022). The effectiveness of such methods was confirmed by several Kazakhstani farms, which managed to significantly improve their financial results. H. Quon and S. Jiang (2023) also conducted a study, the results of which confirmed that the introduction of new water-use technologies, such as drip irrigation and intelligent management systems, can significantly reduce irrigation costs. These technologies minimise water losses and provide a more accurate distribution of resources, which reduces the need for energy costs and equipment maintenance. As a result, agricultural businesses can significantly reduce operating costs, which sets the stage for improved economic performance. T. Zhang *et al.* (2021) also identified that reduction in irrigation costs directly affects yield and profitability improvements because it allows farmers to use water more efficiently, a resource that is often limited. Better management of water flows promotes optimal plant growth, increasing yields and product quality. This, in turn, improves financial performance, as agricultural enterprises can significantly reduce costs while increasing production and profits.

Comparing the data obtained during research, it is possible to assert that the introduction of modern water-use technologies leads to a significant reduction in irrigation costs. These technologies improve the precision of the amount of water required for different crops, which reduces unnecessary expenditure and improves overall resource efficiency. As a result, farmers can use the freed-up funds for other needs, such as improving soil conditions or purchasing more efficient technologies, which contributes to the overall profitability of farms.

The study also revealed the importance of external factors such as climate change and lack of investment in water supply infrastructures. For sustainable development of the agricultural sector in Kazakhstan, it is necessary not only to improve irrigation technologies but also to invest in the modernisation of water supply systems and water conservation developments. Without these changes, the long-term economic efficiency of water use in agriculture may be limited. S. Skendžić *et al.* (2021) concluded that climatic changes and external factors such as increased frequency of droughts or floods have a major impact on agricultural water use. These changes require continuous adaptation of irrigation and water supply systems, as traditional water supply systems often cannot effectively cope with the new

challenges. Therefore, there is a need to modernise infrastructure so that it can provide a more stable and reliable water supply despite unstable climatic conditions. A. Adeniran *et al.* (2021) revealed that modernisation of water supply systems and investment in infrastructure is becoming key to ensure the sustainability of water supply in agriculture. Modern water supply systems require flexibility, and resilience to climate change and are equipped with the latest monitoring and management technologies. Investing in such projects will not only improve the quality of water supply but also significantly reduce water losses, which in the context of global climate change is becoming particularly relevant for food security and agricultural sustainability.

Climate change is significantly increasing the pressure on existing water supply systems, requiring them to be modernised to respond effectively to new challenges (Kravchenko & Tkachenko, 2024). Water supply systems that were designed with more stable climatic conditions in mind cannot cope with increases in extreme weather events such as droughts and floods. As a result, to maintain sustainable water use, investments need to be directed towards infrastructure improvements as well as innovative technologies to optimise water flows and minimise losses. Thus, the results of the analysis confirm the importance of further implementation of technologies aimed at rational use of water resources, as well as the need to create government support for innovation in the agricultural sector. The application of modern water management practices can be a key factor in improving the sustainability of agricultural production and reducing costs, which will improve the economic situation in rural areas of Kazakhstan.

CONCLUSIONS

The study determined that water resources in Kazakhstan, especially in arid regions, are limited, which creates additional difficulties for farmers. Traditional irrigation methods, such as surface irrigation, lead to significant water losses, which increase the cost of water use and reduce overall economic efficiency. However, the introduction of more modern irrigation technologies, such as drip and sprinkler irrigation, can significantly reduce water consumption, improve the distribution of moisture across fields and, as a result, increase crop yields.

Drip irrigation is the most efficient method, reducing water consumption by up to 40% and saving 10,000 tenge per hectare. Sprinkler irrigation is less efficient, but still reduces water consumption compared to traditional methods. Automated water use control systems can achieve water savings of up to 20% and improve the accuracy of resource utilisation. To maximise savings and efficiency, it is recommended to use drip irrigation in combination with automated control systems. In addition, the introduction of modern drip irrigation technologies in agrarian farms in Kazakhstan, such as Baiserke-Agro, has reduced water consumption

by 30%, saving approximately 500,000 cubic metres of water per year, with grain and vegetable crop yields increasing by 15-20%. In Israel, Netafim has achieved a 50% reduction in water use in some regions, contributing to a 30% increase in yields for some crops. In Spain, automated water management systems implemented by Citrus Valley reduced water costs by 25% and saved 1 million litres of water annually, while increasing citrus yields by 20%. In China, Shandong Green Agriculture reduced water consumption by 40% and increased productivity by 25%, improving agricultural sustainability and water optimisation.

The introduction of monitoring technologies and intelligent systems to control water use has demonstrated its effectiveness. The use of sensors and automated control systems makes it possible to accurately monitor water consumption and promptly adjust it depending on plant needs. This minimises water losses and reduces overall irrigation costs, which contributes to the economic sustainability of farms. In addition, the study showed that the introduction of innovative technologies in the agricultural sector leads to lower costs and increased profitability. Such technologies allow farmers to use water resources more efficiently, which becomes especially important against the background of climate change and decreasing water availability. The implementation of such solutions also contributes to increasing the resilience of agriculture to unfavourable climatic changes.

The study concluded that additional consideration should be devoted to the modernisation of water supply infrastructure, as old systems are often unable to cope with the demands of modern technologies. Investments in modernisation of water supply networks, creation of efficient irrigation systems and water management will be key to the long-term sustainability of the agricultural sector. Thus, the optimisation of water use in the agricultural sector of Kazakhstan is the most important task for improving the economic efficiency of agriculture. The introduction of innovative technologies and improved water management can ensure sustainable development of the agricultural sector and increase its productivity and resilience in a changing climate. A limitation of the study is the lack of data on the long-term economic results of the introduction of innovative technologies in different regions of Kazakhstan, which impedes a more in-depth analysis. In addition, it is necessary to study the impact of various climatic factors on the efficiency of water-use technologies in the agricultural sector of Kazakhstan, as well as to assess the possibility of adapting irrigation methods to changes in weather conditions.

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CONFLICT OF INTEREST

None.

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Ефективні методи раціонального використання водних ресурсів в аграрному секторі Казахстану

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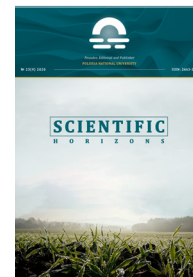
Анотація. Метою дослідження було визначення ефективних методів раціонального використання водних ресурсів в аграрному секторі Казахстану. Проаналізовано вплив сучасних технологій зрошення, таких як крапельне та дощувальне зрошення, а також автоматизованих систем моніторингу на продуктивність сільськогосподарських культур, стан ґрунтів та адаптивність господарств до зміни клімату. Було відзначено, що крапельне зрошення зменшує втрати води до 40%, тоді як дощувальні системи забезпечують рівномірне покриття великих площ, оптимізуючи використання водних ресурсів. Автоматизовані системи моніторингу з використанням датчиків вологості ґрунту та прогнозування погоди зменшили споживання води на 25-50% та підвищили врожайність на 15-30%. Дослідження також визначило, що впровадження таких систем покращило якість ґрунту, зменшивши його виснаження та забезпечивши довгострокову продуктивність. Аналіз досвіду фермерських господарств Казахстану, Ізраїлю, Іспанії та Китаю підтвердив економічну доцільність таких підходів за рахунок зменшення операційних витрат, а також залежності від зовнішнього фінансування та підвищення стійкості до кліматичних стресів. Зокрема, автоматизація водопостачання знизилася витрати на воду, енергію та обслуговування системи, що забезпечило довгострокову стабільність фермерських господарств. Практична цінність роботи полягає у формуванні науково обґрунтованих рекомендацій щодо впровадження інноваційних технологій зрошення для підвищення ефективності аграрного сектору Казахстану, зменшення впливу зміни клімату та забезпечення сталого розвитку

Ключові слова: зрошення; продуктивність ґрунту; автоматизовані системи; урожайність; оптимізація

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Green technologies of the agro-industrial complex as the main element of increasing the competitive innovative development of Central Asia

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Abstract. The purpose of this study was to analyse the advantages of using green technologies as an innovative means of increasing the market stability of agricultural companies in the Central Asian region. The essence of the methodological approach was a combination of theoretical methods of analysis and synthesis with an empirical

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study of the application of green technologies in the practice of farms in the agricultural sector of the Jalal-Abad region of Kyrgyzstan. The results obtained reflect the dynamics of changes in the yield of key crops during the time periods January–August 2023 and 2024. Data were obtained on green technologies in the field of agriculture, which are successfully used in the Kyrgyz Republic, and especially in the Jalal-Abad region, facilitating an increase in crop yields and production of livestock products. The role of green technologies used in agriculture as a key element of increasing the competitiveness of agricultural companies and innovative development of Central Asia as a whole is highlighted, since real prospects for the implementation of these technological solutions were presented on the example of agricultural farms in the Jalal-Abad region. These prospects, in particular, lie in the possibility of improving soil fertility parameters through the use of biological technologies for processing agricultural waste to develop better fertilisers, searching for soil sites for optimal planting of certain types of crops through the use of remote sensing methods, improving the soil layer treatment process through the use of anti-erosion tillage and many other opportunities that open up when using the technologies in question

Keywords: agriculture; industry; advanced solutions; ecology; regional production; implementation of improvements

INTRODUCTION

Over the past few decades, there has been a tendency in the Central Asian region and around the world to gradually abandon the old model of economic development of countries, which involves a relatively rapid accumulation of financial, human, and physical capital through the excessive depletion of natural resources (Segatto *et al.*, 2022). In such a situation, there is a rapid deterioration of ecosystems and natural resources to obtain short-term economic profit (Zhang *et al.*, 2024). The reason for introducing such an initiative lies in the detrimental effect of the outdated model of economic growth and development on the well-being of living generations, in addition, significant risks are being formed for future generations (Concept of Green..., 2018).

In the conditions formed by the beginning of 2024 in the economy of Kyrgyzstan and on a global scale as a whole, the green economy contains a solution to environmental safety problems (Anoraga *et al.*, 2024), since the use of technologies of this kind pursues the goal of maintaining a balance of interests and needs of the individual, society, and the environment. This is especially important in the agricultural complex, where there is direct human contact with nature to solve a complex of primary issues related to various aspects of providing society with necessary food (Rani *et al.*, 2023). In the current situation, the creation of conditions necessary for the competitive innovative development of the Kyrgyz Republic and Central Asia is impossible without the introduction of green technologies of the agro-industrial complex as a rational way to solve problems of food security and environmental conservation.

The issues of investigating the actual state of affairs in this sector of the economy of the Kyrgyz Republic, and the existing important problems and solutions to them were considered in the joint study by Zh.S. Baimova and A.S. Dzhambankulov (2024). The researchers note that since the beginning of 2024, there has been a tendency in agriculture in Kyrgyzstan to increase production by 1.4% compared to the corresponding period

of 2023. According to the researchers, this indicator may be significantly higher in the case of the systematic introduction of modern green technologies into the practice of agricultural companies seeking to obtain tangible market advantages, and to minimise harmful effects on the external environment.

For its part, A.B. Urazkeldiev *et al.* (2023) considered a number of important aspects of managing the salt regime of the soils of the Kyrgyz Republic in conditions of insufficient provision of agricultural areas with water for irrigation. Researchers note that the mechanism of salt accumulation in the groundwater aeration zone of soil layers is quite complex and cannot be reliably described by simple balances of substances, especially since excess salts cannot be effectively eliminated through the use of conventional technologies. According to the researchers, only the use of innovative green technologies will contribute to the effective elimination of salts from agricultural soils, without spoiling the soils themselves and the environment.

The role of green technologies in the agricultural sector in the context of the development of the “creative” economy of various countries was considered in a joint study by S.M. Mambetalieva and A.D. Osmonova (2023). Researchers note that green technologies of the agro-industrial complex are one of the components of the “creative” economy, which is based on the introduction of innovative solutions in various economic sectors. According to the researchers, in the context of agriculture in Kyrgyzstan, such technological innovations can include “smart” farming, remote sensing technologies, recycling of agricultural waste, and a number of others. In the study by I.J. Al-Baydani (2021), aimed at investigating a number of individual difficulties of using modern innovative technologies to solve the problems of strategic development of enterprises of the agro-industrial complex, it is noted that in today’s economic realities, the activities of these farms require finding optimal ways to solve problems of food and environmental

safety. According to the researcher, this can be implemented solely through the introduction of green technologies as the main element of increasing the competitive innovative development of agricultural enterprises.

B.A. Omran and K.-H. Baek (2022) in a joint study aimed at finding optimal opportunities to solve the problems of converting agro-industrial waste into green nanomaterials for wastewater treatment of enterprises in the agricultural sector, point to the fact that green technologies open up wide prospects for wastewater treatment, which is extremely important for modern agricultural companies. Researchers note that the use of such green technologies in the agricultural sector opens up additional opportunities to address key issues of sustainable development of agricultural companies in modern economic realities. Additional detailed study is required on the issues of increasing the competitiveness and innovativeness of green technologies used in the practice of agricultural farms in Central Asia, in the modern realities of technological development of agriculture on a global scale.

The purpose of this study was to analyse the real prospects for the use of green technologies in the agricultural sector of the economy to effectively solve the problems of increasing the competitive innovative development of Central Asia.

MATERIALS AND METHODS

The methodological approach in the presented study was a combination of empirical and theoretical methods of studying the problems of using modern advanced technologies in the daily activities of agricultural enterprises. Methods of analysis and synthesis were chosen as methods of theoretical research of the issues submitted for consideration. The theoretical basis of the conducted scientific research is the analysis of the results of the work of a number of researchers from the Kyrgyz Republic and other countries aimed at investigating a wide range of problematic aspects of the use of green technologies in the agro-industrial complex as the main element of increasing the actual level of innovative economic development in Central Asia.

The Jalal-Abad region of the Kyrgyz Republic was chosen as the region of scientific research. The issues of changes in the volume of harvesting of major crops in the region in the period January-August 2023 and a similar time period in 2024 were investigated, at a time when various types of environmentally friendly technologies were introduced in agricultural farms in various areas of the area under study, aimed at obtaining data on the optimal sowing site with certain crops, ensuring proper soil care, pest control of agriculture, and increasing yields. The use of the analysis method helped to obtain comparative data on the volume of harvesting of the main agricultural crops grown in various districts of the Jalal-Abad region in 2023-2024. This allowed tracking the dynamics of changes in the yield

of these crops in the context of the use of green technologies of the agro-industrial complex.

Through the implementation of the synthesis method, it was possible to summarise data on the practice of using green technologies of the agro-industrial complex in various farms of the Kyrgyz Republic and the results obtained, expressed in increasing crop yields and livestock production volumes. This helped to establish the final effect of using certain technological solutions in the practice of enterprises in the agricultural sector of the Jalal-Abad district, which, in turn, allows assessing their prospects for their subsequent use in terms of competitiveness of innovative development of the region as a whole.

The empirical study consisted in determining the green technologies of the agro-industrial complex that are effective in practical application in the activities of farms in the Jalal-Abad region of the Kyrgyz Republic. Through empirical research, it was possible to establish the real prospects for the application of this type of technology in the agricultural sector, and their importance in the context of increasing the competitiveness of innovative development in Central Asia. In addition, through the application of the empirical research method, specific types of green technologies have been identified that are effective in applying in the practice of agricultural farms in specific areas of the Jalal-Abad region of Kyrgyzstan, when growing specific types of agricultural and livestock products. This combination of scientific research methods helped to establish the main areas of practical application of green technologies in agriculture in Kyrgyzstan and Central Asia, which, in turn, gave grounds for assessing the role of these technological solutions in increasing the competitiveness of innovative development of agricultural farms in the Jalal-Abad region of the Kyrgyz Republic and Central Asia as a whole.

RESULTS

As of the beginning of 2024, the Kyrgyz Republic perceives the concept of a "green" economy as an economy that leads to an increase in the general level of well-being of the country's citizens, strengthening the equity of the social plan, subject to a significant reduction in risks to the environment, capable of preserving and multiplying available natural resources, rationally using natural resources and stimulating the conservation of natural environmental state systems (Green Economy Development..., 2019). In the realities of a "green" economy and the use of green technologies in the agro-industrial complex, an increase in the income level of citizens and an increase in their employment are ensured by attracting public and private investments designed to reduce carbon emissions into the environment (Hayajneh *et al.*, 2023). The creation of additional, environmentally friendly jobs for men and women, and an environment favourable for the lives of

citizens and their health, along with an increase in the efficiency of the use of energy, resources, and ecosystem services, is also an objective consequence of the introduction of green technologies in this area.

As of the beginning of 2024, Kyrgyzstan had a tendency towards an annual increase in the country's GDP (gross domestic product) by an average of 50-90% due to the introduction of technological innovations (Abulova *et al.*, 2023). In this context, the issues of determining the key areas of scientific and technical development of certain sectors of the economy, including agriculture, are becoming more relevant. In addition, it is especially important to identify the key sectors of the use of innovative "green" technologies that can not only provide a sustainable socio-economic effect, but also ensure stable economic growth in the agricultural sector, against the background of compliance with environmental protection measures. In particular, the use of "green" technologies, along with the digitalisation of agricultural machinery, can significantly adjust production costs and reduce the need for manual labour (Mukambaeva *et al.*, 2024; Srinivasan & Venkatachalam, 2024). For example, the use of information obtained through satellite reconnaissance of the area and field sensors in field work and in animal husbandry, crop production, will achieve more effective results, expressed in an increase in the volume of agricultural products produced. Satellite tracking and logistics systems through digi-

tal control systems help to optimise the scheme and sequence of deliveries of agri-food products, to ensure the most objective information for consumers (Sagar *et al.*, 2024). Other agricultural technologies, the characteristics of which allow them to be classified as "green", include: anti-erosion tillage, integrated pest control of crops, biological technologies, organic agriculture, vertical farming, and irrigation.

The Kyrgyz Republic is a predominantly mountainous country, in which about 85% of the territory is occupied by mountains, 1,500 metres high and above (Jalilova *et al.*, 2024). The country's population is concentrated mainly in rural areas – about 65% of the total population in the country. Due to the compactness of Kyrgyzstan's territory, regional urban centres (40 in total) can be fully supplied by pendular migration. The consistent development and improvement of the principles of the organisation of the green economy in the medium- and long-term time prospects presupposes the concentration of agricultural production in regional centres. The specialisation of industrial processing of agricultural products will depend on the location of one or another of the cities in a particular altitude zone (PAGE, 2020). Table 1 shows data on the volume of output of certain types of agricultural products (livestock products) in the Jalal-Abad region of the Kyrgyz Republic for the period January-August 2023 and 2024.

Table 1. Volume of production of livestock products in the Jalal-Abad region of the Kyrgyz Republic for the period January-August 2023-2024

Year	Meat (live weight, tonne)	Raw milk (tonne)	Egg (thous. units)	Wool (physical weight, tonne)
2023	44,389	259,875.5	60,874	2,395.8
2024	44,975	266,086.4	61,878	2,415.9

Source: I.A. Masabirov *et al.* (2024)

According to the information provided in Table 1, during the period January-August 2024, 44,975 tonnes of meat (in live weight) were produced in the region under study, which is 586 (1.3%) tonnes more than in the corresponding period of the previous year, 2023. Toguz-Torou district produced 82 tonnes more (3.6%), Bazar-Korgon district produced 171 tonnes more (2.8%), and Chatkal district produced 56 tonnes more (2.4%). In general, 266,086.4 tonnes of milk were produced in the region during the period January-August 2024, which is 6,210.9 tonnes (2.4%) more than in the same time period of 2023. Bazar-Korgon district produced 3,061 tonnes more (7.6%), Toguz-Torou district produced 681 tonnes more (5.5%), and Ala-Buka district produced 1,242 tonnes more (3.7%) milk.

However, as follows from the data shown in Table 1, during 2024, 61,878 thousand eggs were produced in the region, which is an increase of 1,004 thousand (1.7%) compared to the same time period in 2023. 361 thousand more eggs (4.5%) were produced

in Bazar-Korgon district, 126 thousand more eggs (3.9%) in Toktogul district, and 224 thousand more eggs (2%) were produced in Ala-Buka district. In addition, due to a decrease in the total number of chickens by the beginning of 2024, egg production in Jalal-Abad decreased by 61 thousand units (2.4%) from the previous year's figures.

In its physical weight for the study period 2024, 2,415.9 tonnes of wool was sheared, an increase of 20.1 tonnes (0.8%) compared to 2023. In Chatkal district, wool was sheared in its physical weight by 5 tonnes more (3.9%), in Toguz-Torou district by 1 tonne more (1.3%) and in Toktogul district by 2.5 tonnes more (1%). In addition, due to a decrease in the total number of sheep and goats, by the beginning of 2024, 2.2 tonnes (12.8%) less wool was sheared in Kara-Kul than a year earlier (Masabirov *et al.*, 2024). Table 2 shows data on the volume of harvest by all categories of farms in the Jalal-Abad region of the Kyrgyz Republic for the period January-August 2023-2024.

Table 2. Harvest volumes by all categories of farms in the Jalal-Abad region of the Kyrgyz Republic for the period January-August 2023-2024

Year	2023	2024
Seed	133,599.8	161,597.2
Wheat	481,599	638,973
Legumes	1,490	884
Oilseeds	23,779	12,311
Potatoes	578,340	608,731
Vegetables	211,571.3	235,471.8
Cucurbits	825,274	102,338.6
Fruits and berries	96,882	120,832
Grape	4,463	4,125

Source: I.A. Masabirov et al. (2024)

According to the data in Table 2, during the period January-August 2024, 161,597.2 quintals of grain were harvested and threshed in Jalal-Abad region from a total area of 43,731 hectares, which is 27,997.4 (21%) quintals more than in the same time period last year, 2023. In particular, in the Chatkal district of the region, more than 2,747 quintals (0.3%) were harvested and threshed, in the Toktogul district more by 14,576 (1.3%) quintals of grain, and in the Suzak district by 139,976 (10.2%) quintals of grain. It should also be considered that in the Toguz-Torou district, the volume of grain production decreased by 5,679 (8.7%) quintals. During the specified period of time in 2024, 884 quintals of leguminous crops were harvested from 42 hectares of acreage, which is 606 (58%) quintals less than in the period taken for the study in 2023. The reason lies in the reduction of acreage for planting legumes compared to the previous year. Moreover, in the Ala-Buka district of Jalal-Abad region, a decrease in the volume of harvested crops by 553 (46.4%) quintals was noted.

During the period from January to August 2024, 12,311 quintals were harvested from a total sown area of 1,182 hectares, which is almost half the same time period of 2023. The reason lies in the reduction in the amount of acreage compared to the previous year. The volume of harvesting of this crop by districts decreased as follows: 5,590 (45%) quintals less were collected in the Suzak district, 190 (1.3%) quintals less in the Bazar-Korgon district of the region, and 366 (3.7%) quintals of oilseeds in the Aksy district. Potato harvesting in Jalal-Abad region was carried out from an area of 3,726 hectares. During the time period taken for the study in 2024, 608,731 quintals were excavated, which is 20,291 (5.3%) quintals more than in this period in 2023. In the Ala-Buka district, an increase in the volume of collection was noted by 31,266 (2.8%) quintals, in the Bazar-Korgon district by 25,497 (2.4%) quintals, and in the Toguz-Torou district by 4,003 quintals. On the territory of Toktogul district, there was a decrease in the volume of potato harvesting by 26,379 (11.8%) quintals, in Aksy district by 8,700 (5.6%) quintals, compared with the period January-August 2023.

During January-August 2024, 235,471.8 vegetables were harvested in the region, which is 239,005 (11.3%) quintals more than in the same period of 2023. In the Nooken district, an increase in the volume of harvesting of vegetables was noted by 223,014 quintals (15.8%), in the Bazar-Korgon district by 53,682 (44.5%) quintals. In the Suzak district, a decrease in this indicator was noted by 17,808 (31.8%) quintals, compared with the same period of 2023. The yield of cucurbits for the study period 2024 from a total sown area of 1,066 hectares was harvested at 102,338.6 quintals, an increase of 198,112 quintals (24%) compared to 2023. In the Bazar-Korgon district, an increase in the volume of collection was recorded by 37,298 (8.5%) quintals compared to 2023, in the Nooken district by 59,527 (15.2%) quintals, and in the Aksy district by 100,610 (21.5%) quintals. In the Suzak district of the region, the volume of cucurbits harvesting decreased by 165 quintals (18.6%), in the Toktogul district by 1,407 (16.8%) quintals.

In 2024, 120,832 quintals of fruit and berry crops were harvested in the region, which is 23,950 (24.7%) quintals more than in the study period of 2023. In the Ala-Buka district, an increase in the volume of crop data collection was recorded by 16,870 (19.8%) quintals, and in the Aksy district by 1,060 (1.9%) quintals. In 2024, 4,125 quintals of grapes were harvested in Jalal-Abad region, which is 338 (8.6%) quintals less than in the previous year, 2023. In the regional centre itself, the city of Jalal-Abad, a decrease in the volume of grape harvest by 392 quintals (10.1%) was recorded (Masabirov et al., 2024).

The yield of grain types of agricultural products was increased in 2024 compared to 2023, mainly due to the implementation of remote sensing techniques, integrated pest control measures, and vertical farming technologies. The intensification of production in the agro-industrial complex of Kyrgyzstan, Jalal-Abad district and Central Asia as a whole, achieved through the use of green technologies in the agricultural sector, can develop and ensure sustainability in a number of industrial sectors in a short time, in particular, in the light and processing industries (PAGE, 2020).

During the time period indicated in Tables 1 and 2, significantly more fruit and berry crops, cucurbits, vegetables, and potatoes were harvested in 2024 compared to 2023. It is very important that in 2024, anti-erosion soil treatment technologies, biotechnology and vertical farming technologies were actively used in rural farms of the Jalal-Abad region. The adoption of measures to develop a green economy in this region involved the introduction of a set of measures to increase livestock while preserving the ecosystem of the area. Measures of this kind include the development of concentrate feed production and

the transition to the fattening of livestock by the stall method, which is the initial stage of preserving the soil structure of the land (Investment opportunities for the green economy in the Kyrgyz Republic, 2020). A positive consequence of the implementation of these measures was an increase in the production of meat (in "live" weight), milk and wool (in physical weight) in the region in 2024, compared with 2023. Table 3 shows the main types of green technologies of the agro-industrial complex, effective in use in the agricultural sector of Central Asia in general and the Jalal-Abad region in particular.

Table 3. Green technologies of the agro-industrial complex, effective when applied in the agricultural complex of Central Asia and the Jalal-Abad region

Technology	Essence	Advantages of the application	Prospect of implementation in the region
Remote sensing of the area	Use of unmanned aerial vehicles to monitor the condition of the soil in a given area of agricultural work	Ability to calculate various soil and vegetation indices based on the light reflected by plants and soils, which significantly expands the possibilities of determining quantitative and qualitative indicators of various agroecosystems	Conducting scientific research to determine the dynamics of changes in soil conditions in the region and the feasibility of planting certain types of crops and monitoring environmental processes
Comprehensive pest control	Control of agricultural pests through natural methods, provided that minimal damage is caused to the environment	It allows effectively resisting pests of agricultural crops, without harming agricultural ecosystems	In the agro-industrial sector of the Jalal-Abad region and in Central Asia as a whole, a comprehensive strategy for improving the quality of crop protection and harvest has been developed
Vertical farming	Technological process in the agricultural industry in which the cultivation and production of food takes place on surfaces with a vertical slope	It helps to make much better use of space, with an increase in the number of cultivated crops that can be placed on a unit area	Expanding the possibilities of farming in the region and reducing the amount of soil and irrigation water used for crops. Year-round harvesting provides an increase in the yield of traditional crops by several dozen times
Anti-erosion tillage	Tillage by means of general (ploughing, harrowing, cultivation) and special (slitting, grooving, furrowing) techniques, to provide protection against erosion	Provides the maximum possible absorption of moisture from precipitation into the soil, prevents moisture loss by evaporation, promotes safe drainage of water in areas with excessive moisture in the soil layer	Improvement of the quality of soil treatment, which ensures the preservation of their fertile properties for as long as possible. This is especially true for meadow-steppe soils of the Jalal-Abad region, characterised by increased salinity and carbonate content, and a developed humus horizon
Organic farming	Technology for maintaining soil and ecosystem health based on ecological processes, diversity of biological species and cycles specific to the realities of a particular region and area, rather than on the involvement of resources that cannot be renewed	The possibility of providing medium- and long-term effects on the agro- and ecosystem, food production in a balanced ecological situation, preventing depletion of soil fertility, eliminating problems with pests of agricultural crops	It attracts additional attention of investors due to the discovery of opportunities for the rational use of soils, in conditions of their premature depletion and loss of fertile properties
Biological technologies	Technologies of cryopreservation of seeds, their artificial production, somatic embryogenesis, and other forms of tissue or cell cultures	The possibility of obtaining plant varieties with increased resistance to pests, increasing the productivity of agricultural crops and their feed value	Development and implementation of additional sources of raw materials for secondary and reproducible resources, including agricultural waste, their subsequent use as feed preparations, organic fertilisers. Significant increase in crop yields

Source: compiled by the authors based on T. de Ponti et al. (2022) and E. Bottani et al. (2022)

According to the analytical data presented in Table 3, the use of green technologies in the agro-industrial

complex of the Jalal-Abad district and the Central Asian region as a whole carries numerous advantage

that determine the prospects for their subsequent use in the practice of agricultural enterprises. In particular, the prospects for the introduction of vertical farming technologies lie in the possibility of reducing the area of soil used for crops and water for irrigation. In addition, the use of this kind of technology allows harvesting crops all year round, which helps to increase the yield of traditional crops by several dozen times (Rodrigues *et al.*, 2024). The use of organic farming technologies and biotechnologies for the safe processing of industrial waste allows creating effective fertilisers, which significantly increases soil fertility and their useful life for harvesting (Mandal *et al.*, 2021).

In the Kyrgyz Republic, as in the whole world, there are a number of problematic situations that need to be addressed related to population growth, the influence of climatic factors and the negative impact of the pandemic, which generally leads to increased interest in ensuring healthy nutrition, and environmental protection. In this context, the use of a wide range of green technologies, in particular: organic farming, biotechnologies, etc., provides agricultural enterprises implementing them with competitive environmental advantages compared to other methods of agricultural production (Strapchuk & Mykolenko, 2022;

Dimitrijević *et al.*, 2024). This is especially important in the situation that has developed by mid-2024, when the development of efficient agriculture in terms of resource consumption has become one of the key areas of development even for a number of leading world powers with significant reserves of natural resources (Honcharuk *et al.*, 2024). The efficiency of using natural resources should be considered one of the main priorities of a large number of UN member countries, while green environmental technologies can become the most important means of implementing new innovative solutions designed to effectively solve the tasks of increasing resource efficiency, dematerialising production and consumption, and attracting a number of auxiliary sources of value formation (Burdina & Priss, 2016; Dong *et al.*, 2022).

The role of green technologies in the context of increasing the competitiveness of innovative development also lies in the prospects for solving a wide range of problems of agro-industrial enterprises through the use of these technological solutions in combination with digital technologies (Saparova, 2024). Table 4 presents the main problems of the agro-industrial complex of Central Asia, successfully solved by the practical application of this complex of technological solutions.

Table 4. Problems of the agro-industrial complex of Central Asia, successfully solved through the use of green and digital technologies

Problems	Effect of the introduction of technological solutions
Climate risks	Reduction of climate risks through the use of digital sensors to monitor the response to climate change in the soil structure, along with the use of vertical farming technologies, monitoring and control of the movement and condition of pets, and the use of other, more advanced technologies and systems
The use of outdated machinery in agricultural work	Use of digital systems and equipment with a digital interface that provide full control of the entire cycle of the process of using green technologies, with timely detection of equipment malfunctions, reduction of repair time and replacement of necessary parts, while processing significant amounts of data in a short time
Insufficient diversification of agricultural products	Expanding economic activity and increasing its contribution to the social and economic development of rural areas based on equal opportunities for all participants in the agricultural production process, through the effective use of innovative green and digital technologies
Lack of qualified personnel in agro-industrial enterprises	Use of digital databases and integrated training systems to reduce the training time of specialists in the field of digital and green technologies in agriculture
Problems of supply of manufactured goods to domestic and foreign markets	Use of a digital online portal will facilitate the timely provision of information needed by rural producers to reduce transaction costs and activate the supply chains of agricultural products to the end consumer
Low productivity of manual labour with the practical implementation of green technologies	Introduction of digital technologies in all production processes involving the introduction of green technologies will generally lead to an increase in the productivity of employees of agricultural enterprises, facilitate mechanical processes with their replacement by automatic processes, which in the future will enable reporting on the results of these processes

Source: compiled by the authors based on Z. Abulova *et al.* (2023)

As follows from the information provided in Table 4, the combination of green and digital technologies in the practice of agro-industrial enterprises in Central Asia causes these enterprises to have significant competitive advantages. This should be explained by the fact that such a model of interaction involves providing agricultural enterprises with the basic principles

of sustainable development for a considerable time, by attracting investment funds necessary for the introduction of a combination of these technologies. In addition, it provides support for the implementation of sustainable development objectives related to environmental protection, conservation, and enhancement of natural resources, a low-carbon economy, and social

responsibility (Du, 2024). This is especially relevant in the 21st century, in conditions of constantly increasing use of natural resources, and anthropogenic pollution of the area, which together necessitated the search for alternative technological solutions that allow maintaining the production of agricultural products at the proper level and preserving the ecological diversity of the environment (Gupte *et al.*, 2023). The final effect of the implementation of green technologies in the practice of agricultural farms in Central Asia largely determines the prospects for the establishment of these farms on the principles of an innovative economy as a whole, and the availability of opportunities to increase the competitiveness of the entire agricultural sector in the long term.

DISCUSSION

During this scientific study, the results were obtained, indicating the presence of significant advantages of using green technologies in the practice of agricultural farms in the Jalal-Abad region in January-August 2024. Their use contributes to an increase in crop yields, soil fertility and, in general, has a positive impact on the prospects for innovative development of modern agricultural enterprises of the Kyrgyz Republic. R.D. Raut *et al.* (2019) in a joint study aimed at investigating parameters for tracking the effectiveness of the implementation of green management practices for agricultural companies, note that the use of green technologies in the management of enterprises in the agricultural sector of the economy minimises the impact of the supply chain on the external environment, while increasing its economic efficiency. According to the researchers, various aspects of the productivity of agricultural enterprises are important from the standpoint of optimising resource consumption, and the practical implementation of the concepts of sustainable development of a single organisation. The opinion of researchers is fully confirmed by the results that were revealed during this study due to the fact that the issues of optimising the consumption of resources of a single agricultural company are essential from the standpoint of increasing its productivity, provided that the technologies in question are introduced into its activities.

The topic of the introduction of green technologies into the activities of agricultural producers to increase the bioconversion of agricultural waste was considered by B. Singh and A.S. Jana (2023). Researchers pointed to the fact that the cultivation of agricultural crops is inevitably accompanied by a large amount of solid waste, the dumping of which in landfills causes numerous environmental problems. To manage this process, a special approach is needed, based on the use of green technologies aimed at solving issues of waste disposal and recycling, without harming the environment (Myronycheva *et al.*, 2017). According to the researchers, this will help to increase the competitiveness of innovative development of rural agricultural regions in which

technologies of this kind have found their application. The opinion expressed coincides with the results obtained in this study, since the methods of applying biological technologies and organic farming (including the use of fertilisers obtained during the processing of industrial waste) in the agricultural sector allow farms to obtain a higher yield per unit area, which distinguishes them from farms that do not use such technologies.

T. Marinchenko (2020) considered a number of issues related to the construction of a methodology for expert assessment and selection of innovative projects in the agricultural business and the organisation of agricultural enterprises. According to the researcher, an integral part of innovation activity in the field of application of green technologies of the agro-industrial complex is the selection of innovative projects and the system of evaluation of the innovativeness of the proposed solutions based on it. However, there are difficulties in measuring the quality indicators of innovative projects being implemented and their true effectiveness when used in the activities of modern agricultural companies (Stepanenko *et al.*, 2023). The opinion expressed is controversial on the grounds that the innovativeness of the proposed solutions can often be fully assessed only after a certain time after a practical result has been obtained from the application of a particular project.

The topic of the introduction of green technologies for the production of environmentally friendly products in agriculture has been considered by S. Bhadra *et al.* (2022). The researchers note that the use of green technologies in agriculture, such as plant-microbial fuel cells to produce environmentally friendly bioelectricity and wastewater treatment, helps to reduce the amount of waste and allows them to be effectively disposed of. According to researchers, the use of such technological innovations is necessary to increase the competitiveness of agricultural enterprises using them in their daily activities. The opinion expressed is confirmed by the results obtained in this study, since the effective disposal of industrial waste through organic farming methods and biological technologies increases soil fertility, which, in combination with vertical farming methods, allows increasing the volume of harvesting per unit area, which, in turn, increases the competitive stability and investment attractiveness of farms using these technologies.

A similar topic is raised in the paper by R. Sharma (2024), aimed at studying the problems of converting agro-industrial waste into energy. The researcher makes a statement that the use of innovative green technologies to ensure environmentally friendly recycling of waste from agricultural enterprises has an effective social and economic impact. This allows forming a closed-loop model for the entire agricultural industry, in which waste products, passing through an intermediate phase, are again converted into material for subsequent use. The researcher's conclusions are confirmed by the results obtained in this study due to the fact that

the use of green waste recycling technologies in the practice of agricultural enterprises contributes to increasing soil fertility and productivity.

The issues of practical application of green technologies in solving problematic issues of enterprises in the agricultural sector of the economy for the production of composite materials from waste were discussed by D. Zindani *et al.* (2021). Researchers pointed to the fact that numerous environmental problems associated with the incineration of agricultural waste can be successfully solved through the use of innovative green technologies based on the production of green composites from agricultural waste. They are produced specifically for the development of environmentally friendly products, which allows solving a number of problems in this sector and increasing the competitiveness of enterprises that introduce such production. The conclusions of the researchers generally correspond to the results that were obtained in this study, while it should be noted that the issues of increasing the competitiveness of agricultural enterprises implementing green technologies require more detailed consideration, since competitiveness in the context of the development of the modern agricultural sector depends on a number of additional factors.

D. De *et al.* (2021) in a joint study aimed at investigating a number of problematic aspects of creating a strategic platform for the environmentally friendly processing of agricultural waste, note that the production of biologically based composite materials reinforced with cellulose has become an effective biologically sustainable alternative to high-quality functional polymer materials to replace the currently dominant plastics based on oil. However, according to researchers, the development of an inexpensive carbon-neutral strategy for the separation of cellulose particles from lignocellulose waste residues to simultaneously reduce the amount of solid waste is an innovative solution that in the future can provide opportunities for innovative development of agricultural companies applying this kind of technological innovations. The opinion expressed corresponds to the results obtained in this study, since the use of a number of biological technologies in the practice of agricultural producers contributes to increasing the stability and yield of crops, due to higher quality of soil treatment due to effective waste processing.

U. Sarma *et al.* (2024) examined a wide range of issues related to the use of green technologies to produce relatively clean wastewater. The researchers express the opinion that the practical implementation of technological solutions of this kind will contribute to solving the problems of the water crisis in cities and industrial enterprises. After the conducted research, the conclusion is presented that the prospects for using green technologies to increase the level of environmental sustainability of agricultural enterprises and entire cities are quite wide, while their use contributes to an increase

in the overall level of environmental protection, which is of fundamental importance from the standpoint of the development of a green economy. This conclusion needs additional verification, since studies using statistical data are needed to confirm the effectiveness of green technologies in environmental protection

A. Jahan *et al.* (2023) discussed the use of innovative green technologies for the manufacture of coatings obtained from secondary products of agricultural enterprises. A team of researchers expresses the opinion that such green technologies are very effective for combating metal corrosion of agricultural machinery, while extending the life of its trouble-free operation. On this basis, it is concluded that the use of green technologies in the sector under consideration has significant prospects, since it allows optimising the activities of agricultural companies using them, providing them with additional prospects for innovative development and tangible competitive advantages. The presented conclusion is confirmed by the results of the conducted research, since they clearly demonstrate the fact of the effectiveness of the use of the technologies in question in the practice of a number of farms in the Jalal-Abad region.

CONCLUSIONS

As a result of the conducted research, it was found that the practical application of green technologies of the agricultural sector in the activities of farms in the Jalal-Abad region of Kyrgyzstan contributed to a significant increase in the volume of production of these farms in 2024 compared with 2023. In the agro-industrial farms of the region in question, in 2024, a number of green technologies aimed at increasing soil fertility and yield, producing fertilisers from agricultural waste, increasing the effectiveness of pest control in agriculture, and finding more optimal ways to sow suitable areas of the area and year-round harvesting from the chosen crop for this purpose showed significant practical effectiveness the terrain.

Improving the competitiveness of the innovative development of the Jalal-Abad region of Kyrgyzstan and Central Asia as a whole through the introduction of green technologies in the sector of the economy taken for research lies in the availability of practical experience for agricultural enterprises using these technologies to effectively address issues of agricultural production. Thus, the increase in the volume of harvesting of cereals, potatoes, vegetables, melons, and fruit and berry crops in a number of districts of the Jalal-Abad region in 2024 compared to 2023 due to the use of a number of green technologies in the practice of agricultural farms emphasises the innovation and effectiveness of these technologies, and opens up significant prospects for their further use. This is especially relevant in the conditions of the Kyrgyz Republic, given the significant role of the agro-industrial sector in the

country's economy, due to the predominance of mountainous terrain and the concentration of a significant part of the population in rural areas.

The limitations of this study are caused by difficulties in assessing the final effect of the use of green technologies in the practice of individual agricultural farms and related problems of assessing their real innovativeness on the scale of individual regions and Central Asia as a whole. The practical importance and the need for further research in the framework of the

subject matter are conditioned by the increasing role and importance of green technologies in improving the competitiveness of innovative development in Central Asia and the Kyrgyz Republic, as an integral part of it.

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CONFLICT OF INTEREST

None.

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Анотація. Метою даної науково-дослідницької статті виступав аналіз переваг застосування зелених технологій, як інноваційного засобу підвищення ринкової стійкості сільськогосподарських компаній центрально-азійського регіону. Суть методологічного підходу в представленому дослідженні становило поєднання теоретичних методів аналізу і синтезу з емпіричним дослідженням питань застосування зелених технологій у практиці господарств аграрного сектора Джалал-Абадської області Киргизстану. Під час виконання наукового дослідження було отримано результати, що відображають динаміку зміни обсягів урожайності ключових сільськогосподарських культур протягом часових проміжків січень-серпень 2023-го та 2024-го років. Були отримані дані про зелені технології сфери сільського господарства, які успішно застосовуються в Киргизькій Республіці, і особливо в Джалал-Абадській області, що дають змогу підвищити врожайність сільськогосподарських культур, збільшити обсяги виробництва продуктом тваринництва. Висвітлено роль застосовуваних у сільському господарстві зелених технологій, як ключового елемента підвищення конкурентоспроможності аграрних компаній та інноваційного розвитку Центральної Азії загалом, оскільки було представлено реальні перспективи впровадження цих технологічних рішень на прикладі аграрних господарств Джалал-Абадської області. Ці перспективи, зокрема, полягають у можливості поліпшення параметрів родючості ґрунтів за рахунок застосування біологічних технологій перероблення відходів сільськогосподарського виробництва для розроблення більш якісних добрив, пошуку ділянок ґрунтів для оптимального висаджування тих чи інших видів сільськогосподарських культур за рахунок застосування методів дистанційного зондування місцевості, удосконалення процесу обробітку ґрунтового шару за рахунок застосування методу протиерозійного обробітку ґрунту, а також багатьох інших аспектів

Ключові слова: сільське господарство; промисловість; передові рішення; екологія; регіональне виробництво; впровадження удосконалень

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Application of environmental, social and governance practices in agriculture

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Abstract. The purpose of the study was to conduct a comparative analysis of the features of applying Environmental, Social, Governance practices to ensure sustainable development of the agricultural sector in Sweden, the Netherlands, Germany, and the Kyrgyz Republic. The comparison was conducted using the metrics of the International Financial Reporting Standards and the Sustainability Accounting Standards Board. It was found that Sweden has the highest standards in the European Union for the use of renewable energy and social equity, the Netherlands leads the sector in the use of circular economy, and Germany is a model of efficient use of renewable energy in various sectors of the economy. These achievements have been made possible by the countries' engagement in cross-border cooperation aimed at equitable and fair distribution of funds, attracting young professionals and promoting innovation in the agricultural sector. These initiatives contribute to the gradual transition to organic agriculture, the share of which in the member countries of the Union will be increased to 30% by 2030. In contrast to the above countries, the Kyrgyz Republic is at the very beginning of the path to managing the agricultural sector taking into account Environmental, Social, Governance-standards. The country's development on this path is hampered by insufficient economic, human, and information resources necessary for the transition from extensive to intensive agriculture. Development will be facilitated by the country's participation in international projects aimed at introducing Environmental, Social and Governance practices in the agricultural sector, attracting young specialists and supporting innovation processes at the national and regional levels. Wide implementation of Environmental, Social, Governance-principles can be used for the development of the agricultural sector of the Kyrgyz Republic, which is the subject of this study

Keywords: sustainable development; economic development; social development; environmental development; transboundary cooperation; innovations

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INTRODUCTION

As the world population increases and consumption grows, there is a need for sustainable development of the agricultural industry. The definition of “sustainable” is used to describe development that takes into account the needs of present and future generations. In other words, sustainable development implies a shift from extensive to intensive farming. Transition to a new stage of industry management means the introduction of innovative approaches, including the principles of ESG practices. This concept implies that the following components are considered when planning and implementing agricultural activities: economic, environmental and social. Implementing ESG practices is not an easy process, involving a change in philosophy and key approaches to farming. It also requires significant financial, economic and time resources, making the implementation of ESG practices a challenge in countries around the world, especially those in developing or transitional phases of development (Chen & Li, 2024). The academic literature tends to focus on isolated cases of ESG-philosophy implementation in the agricultural sector; however, comparative analyses that include economically developed countries and countries in transition are not well covered.

ESG practices emerged from the paradigm of sustainable development, which has received wide coverage in academic research (Shumka *et al.*, 2021). According to S. Soretz *et al.* (2023), one of the difficulties in implementing the principles of sustainable development is the lack of a unified interpretation of such development. Supporting this assertion is a study by M. Ogryzek (2022), in which five most commonly used theoretical models of sustainable development were proposed. In order to avoid controversy, I. Ziaul and W. Shuwei (2023) suggested that the term sustainable should be applied to define development aimed at improving and maintaining a healthy economic, environmental and social system of human development. Thus, in this study, the concepts of sustainable development and ESG practices are interchangeable. D.M. Hossain (2023) defined ESG practices as a wide range of environmental, social and governance factors that can be used to assess how companies manage their sustainability performance. Using a partial least squares structural equation modelling framework, F.E. Hazbi and Y. Mounir (2023) concluded that the use of ESG criteria allows companies to highlight and implement sustainability strategies. The researchers particularly observed that technological innovation is significant in creating environmentally friendly products and processes, improving energy efficiency and improving waste management practices. The research confirms that the implementation of ESG criteria and practices is key to effective management in different sectors of the economy, including agriculture.

Analysing the benefits of implementing ESG practices is also one of the frequently researched topics in the academic literature. G. Lew *et al.* (2024) concluded that the short- and long-term benefits of ESG practices include increasing the value of the business to its owners, helping to improve the image of the business, and reducing operational and financial risks. Similar conclusions were drawn by W. Shen (2024), who used a big data index system in his work to assess the benefits of implementing ESG practices in Chinese companies. According to the researcher, investing in such practices is beneficial because it improves the efficiency and competitiveness of companies.

Experts do not deny the fact that implementing ESG practices involves overcoming various barriers. According to R.R. Bezerra *et al.* (2024), who studied the implementation of ESG practices in the construction sector, the main barriers are lack of standardized performance indicators; insufficient regulatory guidelines related to ESG practices; lack of transparency of non-financial indicators and organizational resistance. Lack of support from the management body and resulting organizational resistance were also identified among the main barriers to the adoption of ESG practices by J. J.H. Liou *et al.* (2023) and I. Shabir *et al.* (2023). According to the researchers, those responsible for strategic planning may hinder the implementation of ESG practices by being insufficiently aware of their benefits.

This resistance may be particularly evident in developing or transition economies whose resources are insufficient to implement ESG practices. The studies analysed above do not provide sufficient understanding of how practices based on the principles of economic, environmental and social development can be introduced into the agricultural sector of developing and transition economies. The answer to this question can be obtained through a comparative analysis of the development characteristics of the agricultural sector of countries around the world. Thus, the aim of this study was to analyse the use of ESG practices in agriculture in Sweden, the Netherlands, Germany, and the Kyrgyz Republic. The objectives of the study were to examine the barriers to the implementation of ESG practices in the management of the agricultural sector in developing and transition economies, and to develop strategies to effectively overcome the existing barriers. The fulfilment of these objectives will contribute to the sustainable development of the agricultural sector in order to meet the growing needs of the current generation without harming future generations.

MATERIALS AND METHODS

The agricultural sector of the sample countries was analysed in terms of the implementation, or inability to implement ESG strategies in the period from 2020 to 2024. The conclusions were drawn based on data

collected through a SWOT analysis, which aimed to identify internal and external factors affecting the effectiveness of ESG practices in agriculture in the sample countries. The analysis examined the strengths and weaknesses of ESG strategies in each country of the world and explored opportunities and threats for further expansion of these practices. The analysis was also based on benchmarking results, i.e., comparisons based on benchmarks proposed in the European Commission reports, which use a uniform method of statistics in the EU member states, including the sample countries. Such a method, however, could not be applied to the Kyrgyz Republic, which is at the beginning of its journey to implement sustainable development practices in the agricultural sector and has limited involvement in cross-border co-operation on this issue. The comparative analysis of ESG practices in the sample countries was based on the following criteria: the share of arable land used for organic farming; the amount of sectoral support, including that aimed at the development of the rural sector; and funding for initiatives aimed at attracting young professionals and introducing innovative methods of agricultural sector management.

The analysis also takes into account the fact that the countries included in the sample may have scored high on one aspect of their ESG strategy and lower on others. According to the European Commission (Germany – CAP strategic plan, 2024; Netherlands – CAP strategic plan, 2024; Sweden – CAP strategic plan, 2024), Sweden was included in the sample as having the highest renewable energy and social equity standards in Europe. The Netherlands was added to the sample as a European Union (EU) leader country in utilizing the circular economy. Germany was selected as a country with record investments in farming and green energy. The Kyrgyz Republic was analysed as a country declaring readiness to introduce ESG practices in the agricultural sector, but still at the beginning of the road to achieving this goal.

The comparative analysis took into account the challenges faced by the sample countries regardless of their level of economic development: the share of arable land in the total land area, geographical and climatic conditions for farming, urbanization and the outflow of young professionals from rural areas, the gap between the average income of farmers and other professions, the monopoly of agricultural holdings and the sustainable development of small and medium-sized farms in the face of growing competition. The approaches used by countries to find solutions to these challenges at the national, regional and international levels were also analysed. The large-scale initiatives applied in the EU member states, including the LEADER programme, the European initiative aimed at creating Local Action Groups (LAGs) to attract young professionals to the agricultural sector, the introduction of innovative solutions and sustainable development

planning, were reviewed. To analyse the dependence of the transition to organic farming on the geographical location of the German states, we used data from the work by H. Kuhnert (2024), reflecting the share of organic agriculture in different federal states as of 2023. The analyses were based on sectoral reports, including the following sectoral reports from the European Commission (Germany – CAP strategic plan, 2024; Netherlands – CAP strategic plan, 2024; Sweden – CAP strategic plan, 2024), OECD Environmental Performance Reviews (2023) and Eurostat (2024). The study also used academic sources published no later than 2020, including K. Hakelius and J. Nilsson (2020), Global Finance (2024) and T.S. Sonu *et al.* (2024).

RESULTS

ESG practices in agriculture in the selected EU countries. Using the SWOT analysis method, it can be argued that the development of Sweden's agricultural sector takes place in a northern climate, which influences the choice of priority activities. According to the European Commission report (Sweden – CAP strategic plan, 2024), about 70% of Sweden is covered by forests and less than 10% of its territory is suitable for agriculture. There are also significant differences in the geographical, climatic and other conditions for farming in the north and south of the country. Agricultural products grown in the south contribute no more than 1% of the total national budget. Another difficulty is the long logistical chains due to the uneven distribution of the population. European Commission experts note that 60% of the country's population lives in rural or semi-rural areas. Based on these statistics, it can be said that farming in Sweden is not an easy task, but one that involves finding answers to many challenges. One of these challenges is the fact that agricultural activities are a source of environmental pollution. The data presented by I. Fetzer and M. Hall (2024) indicate that 22.7% of the carbon dioxide produced in the country, one of the main air pollutants, is emitted from agricultural activities. Increasing consumption of dairy and meat products, expansion of agricultural land and drainage of peatlands are factors that determine farming strategies and lead to pollution. Thus, Sweden's geographical and climatic conditions are among the factors that have a potentially negative impact on the development of the agricultural sector according to ESG standards. The country's involvement in regional and cross-border cooperation can minimize the impact of these factors, thus meeting the growing demand of the population and increasing agricultural imports.

The use of SWOT analysis to assess the development of the agricultural sector in the Netherlands suggests that the country has one of the most developed and innovative export-oriented agricultural sectors in the world. In conformity with a European Commission report (Netherlands – CAP strategic plan, 2024),

agricultural exports generate around 100 billion in annual profits for the country. There are 51,000 farms in the Netherlands, with an average size of 32 hectares. About 2% of the country's working population work on 66% of the land used for agriculture. These figures indicate not only the dynamics of Dutch agriculture, but also the potential of the sector for sustainable development. The Dutch strategy for the agricultural sector is based on the Global Reporting Initiative, which endeavours to cover all the main elements of the ESG strategy. Within this initiative, transformation is taking place at all levels of planning, conducting and evaluating agricultural activities.

Using the SWOT approach to analyse the development of the German agricultural sector, it can be argued that the country has better conditions for the development of the agricultural sector than Sweden or the Netherlands. For example, unlike Sweden, where only 10% of the territory is used for agriculture, Germany is a predominantly flat country with 57% of its territory suitable for agriculture. The latter takes many forms,

ranging from family farms in the mountainous parts of the country to highly specialized farms and agricultural holdings. According to the European Commission (Sweden – CAP strategic plan, 2024), there are 276,000 farms in the country, which is significantly larger than in Sweden or the Netherlands. Thus, the average farm size in Germany is comparable to that of Sweden and significantly larger than the average farm size in the Netherlands. Despite these differences, the German agricultural sector faces similar challenges to those documented in Sweden and the Netherlands, including economic difficulties, difficulties in attracting and retaining young professionals and the transition to organic farming. The sector management model adopted in the country is similar to the model used in the Netherlands and Sweden, and implies equal attention to key components of the ESG philosophy. Based on this analysis, it is possible to identify universal factors that influence the development of the agricultural sector and the adoption of ESG practices by individual EU member states. These universal factors are summarized in Table 1.

Table 1. Factors influencing the adoption of ESG practices in the agricultural sector in Sweden, the Netherlands, and Germany

Strengths	Weaknesses
<ul style="list-style-type: none"> ■ State policy of social justice aimed at equal distribution of income in support of small and medium-sized farms ■ Regional and cross-border co-operation, including economic co-operation ■ Various initiatives aimed at attracting young professionals and promoting innovation in the agricultural sector ■ A system of guarantees has been developed to ensure sustainable development of farms 	<ul style="list-style-type: none"> ■ In the sample countries, on average, only 2% of the working-age population is employed in agriculture ■ Outflow of able-bodied population due to lower incomes in the agricultural sector compared to the national average income ■ Transitioning to ESG practices is costly and not fully funded
Opportunities	Threats
<ul style="list-style-type: none"> ■ Attracting young professionals contributes to the development of the agricultural sector and enhances its prestige ■ Growing consumption of products produced by the agricultural sector ■ Increasing public support for sustainable development practices, including those in the agricultural sector ■ Cross-border co-operation that promotes ESG practices and supports sustainable development 	<ul style="list-style-type: none"> ■ Transition to a less costly, extensive way of managing the agricultural sector ■ Winding down of individual funding programmes for ESG initiatives ■ Declining profitability and stagnation of the agricultural sector ■ Natural disasters causing losses in the agricultural sector

Source: created by the authors

The Table 1 shows that despite the weaknesses and threats, the sample countries have developed a number of strategies that help to capitalize on the adoption of ESG philosophy in the management of the agricultural sector. One such practice is to increase the share of arable land used for organic farming. The most tangible results in this direction have been achieved by Sweden, which, according to Eurostat data from January 2024, ranks third among EU countries in terms of the total area of land partially or fully used for organic farming. According to Eurostat (2024), about 20% of the country's arable land is devoted to organic farming. In the Netherlands and Germany, the

share of land partially or fully converted to organic is significantly lower, as can be seen in Figure 1.

It is important, however, to interpret the data presented in the figure above in light of the unique realities of the individual countries in the sample. In the Netherlands, which ranks last in the ranking presented, there has been a steady increase in arable land: as of 2023, land used for organic farming represented 4.4% of all agricultural land (585 additional organic farms since 2015, 2022). In Germany, the transition to organic farming is highly dependent on the geographical location of the individual lands, as can be seen in Figure 2.

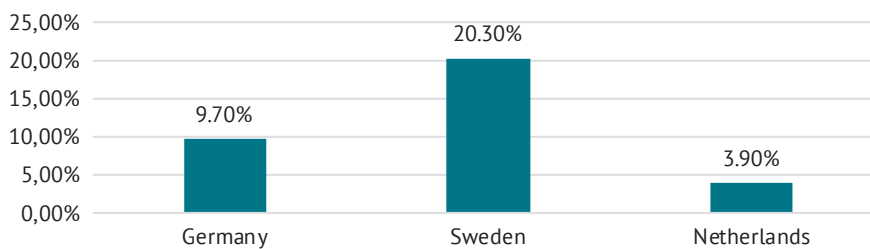


Figure 1. Share of agricultural land partially or fully converted to organic farming in Sweden, the Netherlands, and Germany as of 2023

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

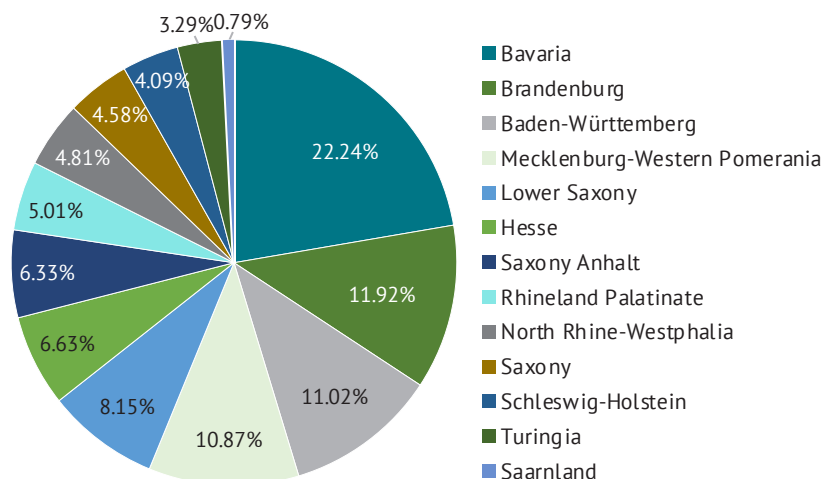


Figure 2. Proportion of organic farming in different German states as of 2023

Source: created by the authors based on H. Kuhnert (2024)

In Sweden, in turn, the transition to organic farming has a lot to do with the functioning of co-operatives, which provide their members with more opportunities and tools for sustainable development. Research conducted by K. Hakelius and J. Nilsson (2020), J. Nilsson (2020) indicates that state support motivates farms to join cooperatives that embody not only the economic but also the social aspect of the ESG strategy, as farmers' associations promote interdisciplinary co-operation and are a source of innovation processes in the agricultural sector. As part of the development of such cooperation, 9,000 farmers participated in an initiative of the European Commission (Sweden – CAP strategic plan, 2024) aimed at selecting and implementing digital tools to help calculate the exact dose of nutrients for crops, thus reducing chemical spillage and groundwater pollution by up to 1.4 million hectares annually. This example illustrates the social aspect of the ESG

strategy through the lens of supporting the farming community to ensure the sustainable development of the agricultural sector.

In addition to the environmental component, the sample countries pay attention to the social aspect, including the outflow of the working population from the sector, the lack of young professionals and the resulting stagnation of the agricultural sector. In the Netherlands, for example, the income in the agricultural sector is 40% below the national average, which significantly reduces the motivation of professionals, leads to a shortage of human resources and discourages innovation (Netherlands – CAP strategic plan, 2024). At EU level, the LEADER initiative has been developed with the aim of involving young professionals in decision-making and developing strategies for sustainable development of the country's agricultural sector. The table below provides data on the funding of this programme in the sample countries.

Table 2. Funding of the LEADER programme in Germany, the Netherlands, and Sweden

	Annual funding (€)	% of total sector funding
Germany	1,246,106,365	15
Netherlands	54,150,012	5
Sweden	92,204,301	9

Source: created by the authors

The Table 2 shows that the countries in the sample pay uneven attention to the development of the LEADER initiative: as a percentage of total funding for the sector, the largest contribution is made in Sweden and the smallest in the Netherlands. Management decisions in planning and implementing the transition to ESG strategies in the agricultural sector are also important.

The governance component in particular manifests itself in the amount of funding for individual components of the agricultural sector allocated by the national government as well as funding agreed with international partners. A comparative analysis of the amount of funding for the agricultural sector of the sample countries is presented in Table 3.

Table 3. Financing of selected components of the agricultural sector with ESG-philosophy of Germany, the Netherlands, and Sweden as of 2023

	Germany			Netherlands			Sweden		
	EU budget (€)	National funding (€)	Total (€)	EU budget (€)	National funding (€)	Total (€)	EU budget (€)	National funding (€)	Total (€)
Direct payments	22,194,364,998	-	22,194,364,998	2,977,971,465	-	2,977,971,465	432,713,183	-	3,432,713,183
Sectoral support	294,064,735	10,857,950	304,922,685	633,350,860	1,350,860	634,701,720	28,803,098	2,942,725	31,745,823
Rural development	8,239,166,987	3,634,979,151	11,874,146,138	1,082,970,984	414,381,162	1,497,352,146	1,059,448,705	1,541,365,536	2,600,814,241
Total	30,727,596,720	3,645,837,101	34,373,433,821	4,694,293,309	415,732,022	5,110,025,331	4,520,964,986	1,544,308,261	6,065,273,247

Source: created by the authors

The Table 3 shows that the largest amount of funding, both at the national and cross-border level, is allocated to the German agricultural sector, indicating the government's involvement in improving liquidity and sustainable development of the agricultural sector. In addition to pan-European ESG strategies, the EU countries in the sample have developed their own strategies for sustainable development of the agricultural sector. A distinctive feature of Germany's ESG strategy is a gradual shift towards alternative energy sources that reduce carbon emissions and increase the sustainability of the agricultural sector. As of 2024, 54% of the energy produced in the country is "clean", i.e., derived from renewable sources (Germany – CAP strategic plan, 2024). One of Sweden's priority strategies, which can be effectively adapted by other countries, is to improve groundwater quality by reducing the amount of chemicals used in agriculture. As of 2024, the country has established a network of 9,000 farmers using digital tools to accurately calculate the nutrients needed for crops. Such counting facilitates the transition to organic farming, which reduces emissions and improves water quality. Data from the European Commission (Netherlands – CAP strategic plan, 2024) confirms that preserving natural water bodies and improving their water quality is a priority environmental issue also for the Dutch government, which together with the EU has allocated EUR 174 million to address this issue. The funding supports the conservation of biodiversity, including several species of grassland birds, which will be attracted by 36,000 hectares of new grassland to reduce ammonia deposition and improve water availability. The Dutch government plans to increase the quality of the latter by 58% in the medium term. An important component of the ESG strategy, which distinguishes the Netherlands from other EU countries, is the care for animal welfare,

including the provision of appropriate conditions for animal welfare. The initiative, developed in co-operation with European Union experts, involves phasing out antimicrobials in animal breeding and care. According to a European Commission report (Netherlands – CAP strategic plan, 2024), Dutch farmers will also be given funding to improve animal welfare, which will initially affect 3% of all livestock raised in the country.

Implementation of ESG-strategies in agriculture of the Kyrgyz Republic taking into account the experience of the EU member states. A significant difference between agriculture in the Kyrgyz Republic and agriculture in the EU member states is the unpreparedness of state bodies and national infrastructure to implement ESG-philosophy. Pursuant to the World Bank (2024), agriculture is one of the most important sectors of the economy, given its 15% share of gross domestic product (GDP) and 30% of all jobs in the country. It is also a positive factor that about 54% of the country's total land is suitable for agriculture. According to the assessment of experts from the World Bank Group, Climate Change, Agriculture and Food Security, CIAT (2018), the Kyrgyz Republic has prerequisites for the introduction of climate-smart agriculture, which is one of the indicators of effective implementation of the ESG strategy. The process of implementation of this way of farming, however, is slowed down by a number of internal and external factors.

The unstable economic environment in the country and the region is one of the reasons hampering the sustainable development of agriculture in the Kyrgyz Republic (Kadyraliev *et al.*, 2024). According to Global Finance: Kyrgyz Republic (2024), the country experienced a severe economic crisis in 2020 due to the coronavirus pandemic and related constraints. After a minor recovery, the country experienced a new round of recession from 2023, and 2024 growth was relatively small.

GDP growth is currently at 4.28%, which is insufficient to overcome the country's financial difficulties. The economic recession is closely related to inflation and growing unemployment, which also have a negative impact on the economic development of the Kyrgyz Republic. The economic downturn implies a decrease in state funding for the agricultural sector, as well as the withdrawal of capital from the country, i.e., the inability to receive support for the development of projects in the field of sustainable agriculture. According to Global Finance: Kyrgyz Republic, a record capital outflow from the country was recorded in 2024. Unlike their German, Dutch and Swedish counterparts, Kyrgyz farmers cannot count on comprehensive state support, and the risk insurance system is not well-developed. As a result, the implementation of ESG strategies slows down or stops altogether. An example illustrating this statement is the statistics on agricultural land in the country, partially or fully converted to organic. According to M. Sagynalieva (2024), the share of land

used for organic farming does not exceed 0.21% of all irrigated land.

Without sufficient support from the state and international partners, stakeholders are forced to choose extensive agricultural practices that lead to various environmental problems. World Bank Group data (2024) indicate a gradual decline in the share of arable land as a result of intensive use of pesticides and other pollutants. Overgrazing is also a factor in the decline in the proportion of land suitable for agriculture. According to data provided by World Bank Group, Climate Change, Agriculture and Food Security, CIAT (2018), 70% of the country's winter pastures have been destroyed by overgrazing. The declining share of arable land and its declining quality are also affecting the country's natural diversity and the extinction of many plant and animal species. Based on the above data, a comparative analysis of the features of ESG practices adoption in the agricultural sector of the sample countries was carried out, presented in Table 4.

Table 4. Comparative analysis of ESG practices in the agricultural sector of the sample countries

Country	ESG strategy element		
	Environmental	Social	Managerial
Sweden	Restoration of arable land; transition to organic agriculture; care for biodiversity	Support of young specialists and beginning farmers; reduction of the gap between the level of farmers' income and the average income level in the country; insurance of farming activities; cross-border cooperation in the introduction of LEADER and other programmes aimed at raising the prestige of farming activities	The state seeks social justice by redistributing income from agrohholdings to support medium and small farms; cross-border co-operation is encouraged, including at EU level; the state encourages the establishment of co-operatives without interfering in their activities
Netherlands	The majority of land is used for agriculture; restoration of natural biodiversity, including by increasing the area of grasslands; gradual transition to organic farming	Reducing the gap between farmers' income level and the average income level in the country; attracting young specialists and developing innovative farming; participating in the European LEADER initiative; creating new jobs and raising the prestige of working in the agricultural sector.	The state provides grants for the development of innovative projects in agriculture, green energy and conservation of natural biodiversity; supports cross-border cooperation, including the European LEADER initiative; provides loans and other support to farmers, especially start-ups; and seeks to liberalize the agricultural sector.
Germany	Increasing the amount of agricultural land allocated for organic farming; preserving and multiplying natural biodiversity, increasing grasslands, avoiding synthetic fertilizers and so on; developing green energy.	Financial support of farmers, especially beginners; insurance of farms against unfavourable weather conditions; creation of equal competitive conditions for farms, regardless of their size.	Encouraging participation in regional and international initiatives, including LEADER, aimed at developing the agricultural sector; respecting the principle of social justice by redistributing income from agrohholdings to small and medium-sized farms; liberalizing the agricultural sector.
Kyrgyz Republic	An extensive approach to agriculture, leading to a decrease in arable land; a decline in biodiversity, including due to overgrazing; contamination of soil and water bodies with chemicals; and the lack of a clear strategy for transitioning to sustainable development practices in the sector.	The majority of farmers are middle-aged or elderly, there is an outflow of young specialists to the city or abroad; there is an obvious gap between the income level in the agricultural sector and the average income level in the country; there are few examples of farmers coming together to plan sustainable development of the sector and the community.	The state declares its aspiration to transition to sustainable development and readiness for cross-border co-operation to achieve this goal; state support of farms in the form of grants and affordable loans is insignificant; participation in international projects is hampered by insufficient awareness of the target audience.

Source: created by the authors

The Table 4 above shows that the challenges facing the EU member states and the Kyrgyz Republic are universal and include environmental problems, such as the decline in natural biodiversity; the reduction of areas suitable for agriculture and the pollution of soil and water bodies. Regardless of the level of economic development, the countries also face social challenges such as low involvement of young professionals, urbanization, and the gap between incomes in the agricultural sector and the national average. A significant difference between the EU member states and the Kyrgyz Republic is the level of government involvement in addressing these challenges (Omurgazieva *et al.*, 2024). In contrast to the Kyrgyz Republic government, the governments of Sweden, the Netherlands, and Germany have developed extensive support systems for farms, making them more resilient to various types of crises, including environmental, economic and social crises. In their strategic planning, the governments of the EU member states also adhere to the principle of social justice, which provides for redistribution of income to support small and medium-sized farms. Compliance with this principle is less evident in the Kyrgyz Republic, where the chances of development are much higher for large agricultural holdings seeking to monopolize the market. This monopoly is made possible, in particular, because the Kyrgyz government has not initiated programmes to increase farmer involvement in community and sectoral issues, such as the LEADER initiative operating in the EU. It follows from the above comparison that the Kyrgyz Republic can benefit from the positive experience of the EU member states to implement ESG-philosophy and support sustainable development of the national agricultural sector.

Part of the environmental problems of the Kyrgyz Republic can be solved by focusing on the social aspect of the ESG strategy, e.g., creating new jobs in the industry, attracting young specialists and training stakeholders. Data collected by G. Saparova *et al.* (2024), supports the idea that the vast majority of farmers in the country are middle-aged and elderly, which makes them less receptive to innovations that contribute to the sustainable development of the agricultural sector. In turn, the attraction of young professionals is possible due to comprehensive support from the state, involvement in international projects and promotion of the idea of sustainable development among the local population. Thus, the comparative analysis shows that despite the declared national and regional commitment to sustainable agricultural development, the Kyrgyz Republic is far from implementing ESG-strategy norms. The existing discrepancy can be explained by the unstable economic situation of the country, which entails environmental and social challenges. An effective ESG solution to these challenges is possible by analysing ESG practices of other countries, including EU members.

DISCUSSION

This study suggests that in the 21st century, there is a growing global demand for sustainable agriculture. Support for this idea was found in an article by G.M. Robinson (2024) analysing the results of the International Geographical Union (IGU) congress held in Paris in 2022. According to the authors of the study, the result of this congress was the emergence and validation of the concept of Agriculture 4.0, emphasising the importance of innovations such as precision farming, digital technologies and genetic modifications to increase agricultural production per unit area. According to experts, including M.H. Islam *et al.* (2024) and E.M. Pechlivani *et al.* (2023) who studied Agriculture 4.0, this concept implies a gradual shift from extensive to intensive farming method. A.K. Sahoo *et al.* (2021) attributed this transition to the emergence of the idea of sustainable development, i.e., the belief that the needs of the present generation should not be met by sacrificing the needs of future generations. Thus, Agriculture 4.0 implies the sustainable use of natural resources, including arable land, water bodies and natural diversity, with a medium- and long-term perspective.

The growing popularity of the concept of Agriculture 4.0 motivates experts to analyse emerging trends. According to A.A. Koç *et al.* (2024) and S. Zaika *et al.* (2023), such trends include the introduction of advanced technologies and improvement of production processes. A similar opinion was also expressed by J. Xu *et al.* (2024), who concluded that in the 21st century, effective agricultural development depends largely on geospatial analysis and the use of digital strategies in planning management strategies. Thus, the accumulated evidence points to the need to rethink conventional approaches to the management of the agricultural sector and move towards innovative technologies that facilitate more efficient allocation and utilization of available resources.

The study also presented the idea that the introduction of ESG practices as a way of transition to sustainable agriculture is not an easy task, the implementation of which is hindered by various barriers. In the Kyrgyz Republic, the transition to ESG practices has been slowed down by the economic crisis, implying a lack of necessary resources. In countries with more favourable economic conditions, such as Sweden, the Netherlands, and Germany, the full transition to sustainable agriculture may be hindered by the outflow of population from rural areas and the reluctance of young professionals to stay in the sector due to relatively low incomes. In other words, the integration of ESG practices can be a challenge for any country in the world, regardless of its geographical location, climatic conditions, arable land area or level of economic development (De La Llave *et al.*, 2022).

Support for this thought was found in earlier studies, particularly the work of J. Cao & Y.A. Solangi (2023), who used Analytical Hierarchical Process (AHP) and

Simple Additive Weighting (SAW) methodologies to identify the main obstacles to the adoption of ESG practices in China's agricultural sector. The researchers concluded that the main obstacle is financial constraints; and this idea is confirmed in the presented work, highlighting that no country in the sample has been able to implement a completely equitable resource allocation that supports sustainable development of farms, regardless of their size. Financial constraints limit access to the resources needed to make the transition to sustainable agriculture, including tools and technologies (Mukambaeva *et al.*, 2024). The impact of this constraint is most evident in countries with low levels of economic development, including countries in Africa and Pakistan, studied by M. Bilal and J.T. Tinoush (2024). For the Kyrgyz Republic the experience of these countries is particularly important, as they are in similar economic, political and socio-cultural conditions, and therefore face similar barriers to the introduction of ESG-philosophy in the agricultural sector.

The comparative analysis of the development of the agricultural sector in Kyrgyzstan and selected EU countries suggested that the most effective strategy in overcoming the analysed barriers is thematic cooperation not only at the national, but also at the regional and international levels. The analysis of the experience of Sweden, the Netherlands, and Germany confirmed the importance of cross-border cooperation, which resulted in the implementation of LEADER and other projects aimed at transition to agricultural activities in accordance with ESG criteria. Being at the very beginning of this journey, the Kyrgyz Republic can learn valuable lessons from regional and international co-operation, the effectiveness of which has been confirmed by academic studies, including S. Kalogiannidis *et al.* (2024) and R. Khoerunnisa and Z. Maulana (2023). According to the statement of S. Kalogiannidis *et al.* (2024) who interviewed 400 farmers and agricultural experts in Greece, the best results in the transition to sustainable agriculture were achieved by farms that joined a co-operative, i.e., became part of the professional community and had access to its resources. Thus, the results of this study confirm the previously presented idea that the co-operative system is one of the factors of sustainable development of the Swedish agricultural sector. The importance of international co-operation was also confirmed by R. Khoerunnisa and Z. Maulana (2023), who studied the impact of transnational arrangements for food security. Thus, the conclusions drawn by the authors of the earlier studies are in line with the results of the analysis and emphasize the importance of cooperation in overcoming barriers to the implementation of ESG standards.

Cross-border cooperation should be considered not only as a source of financial resources necessary for farming in accordance with ESG requirements, but also as a source of innovative ideas, the implementation

of which contributes to the sustainable development of the analysed sector. The confirmation of this idea can be found in the works of A.G. Malau *et al.* (2024), P. Vrabcova and H. Urbancova (2023). The former in their study relied on qualitative analyses of interviews and focus groups conducted with farmers and agricultural experts. According to A.G. Malau *et al.* (2023), the interviewees showed interest in technological innovations, which they perceived as a prerequisite for effective agribusiness management. Such innovations were viewed by participants through the lens of interdisciplinary collaboration, emphasizing the importance of interaction between stakeholders at national, transboundary and international levels. According to P. Vrabcova and H. Urbancova (2023), information and knowledge underpinning innovation processes are as important for sustainable agriculture as financial resources. On this basis, the researchers proposed an extensive system of protection of such information and knowledge, including through patenting, trademarks and copyright.

Thus, there were no significant contradictions between the data of the presented comparative analysis and the conclusions proposed in earlier studies. Striving for sustainable development, the countries of the world are planning the transition of their agricultural sector to development in the ESG-paradigm. Implementation of such a transition is a long and resource-intensive process, especially in countries with unsustainable economic development. Analyses of the experience of EU member states, as well as African and Asian countries, suggest that the key to sustainable development of the agricultural sector is regional and cross-border co-operation aimed, *inter alia*, at information exchange and innovation development.

CONCLUSIONS

A comparative analysis of the capacity of individual EU countries (Germany, the Netherlands, Sweden) and the Kyrgyz Republic for sustainable development of the agricultural sector, taking into account environmental, economic and governance aspects, was carried out. As EU member states, Sweden, the Netherlands, and Germany can benefit from cross-border cooperation in the development of their agricultural sector: access to favourable loans and support programmes for beginning farmers, insurance of farms against the effects of adverse climatic conditions and the creation of a common professional network to access innovative technologies, share experience and jointly solve emerging problems. From the point of view of SWOT-analysis, the long and resource-intensive transition to ESG-standards can be compensated by the benefits of sustainable development of the agricultural sector: environmental management, development of innovative technologies, creation of a professional network and increased competitiveness of farms. Further comparison of the agricultural sector of the EU member states with the

agricultural sector of the Kyrgyz Republic revealed that the introduction of ESG practices is hampered by the existence of economic, technological and other barriers. The national agricultural sector in its current form is unattractive for young professionals who could become the driving force of innovation processes. There is a direct link between the outflow of young professionals, lack of innovation and stagnation of the agricultural sector. The country's participation in regional and cross-border projects aimed at equitable distribution of resources and equal access to information and knowledge that would contribute to the development of the sector could help attract such specialists.

The results obtained can be used in the development of national strategies in transition countries, in-

cluding the adaptation of successful EU practices in the Kyrgyz Republic. A promising direction for further research could be a comparative analysis of strategies for the introduction of ESG-philosophy in the development of the agricultural sector in Kazakhstan, Tajikistan, Uzbekistan, Turkmenistan and other countries in the region that have similar geographical, climatic, economic and socio-cultural conditions of development with the Kyrgyz Republic.

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CONFLICT OF INTEREST

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Застосування екологічних, соціальних та управлінських практик у сільському господарстві

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Анотація. Метою дослідження було проведення порівняльного аналізу особливостей застосування Environmental, Social, Governance-практики для забезпечення сталого розвитку сільськогосподарського сектора Швеції, Нідерландів, Німеччини та Киргизької Республіки. Порівняння було проведено з використанням метрик Міжнародних стандартів фінансової звітності та Ради зі стандартів обліку в галузі сталого розвитку. Було виявлено, що Швеція має найвищі в Європейському Союзі стандарти з використання відновлюваної енергії та забезпечення соціальної справедливості, Нідерланди лідирують у секторі використання кругової економіки, а Німеччина є зразком ефективного використання відновлюваної енергії в різних секторах економіки. Перелічені досягнення країн стали можливими завдяки їхній залученості до транскордонного співробітництва, спрямованого на рівномірний і справедливий розподіл коштів, залучення молодих фахівців і розвиток інновацій у сільськогосподарському секторі. Зазначені ініціативи сприяють поступовому переходу до органічного сільського господарства, частка якого в країнах-членах союзу буде збільшена до 30 % до 2030 року. На відміну від перерахованих країн, Киргизька Республіка перебуває на самому початку шляху до управління сільськогосподарським сектором з урахуванням Environmental, Social, Governance-стандартів. Розвиток країни на цьому шляху гальмується недостатністю економічних, людських та інформаційних ресурсів, необхідних для переходу від екстенсивного методу ведення сільського господарства до інтенсивного. Розвитку ж сприятиме участь країни в міжнародних проєктах, спрямованих на впровадження Environmental, Social, Governance-практик у сільськогосподарському секторі, залучення молодих спеціалістів та підтримка інноваційних процесів на національному та регіональному рівнях. Широке впровадження Environmental, Social, Governance-принципів може бути використане для розвитку сільськогосподарського сектору Киргизької Республіки, що є предметом цього дослідження

Ключові слова: сталий розвиток; економічний розвиток; соціальний розвиток; екологічний розвиток; транскордонне співробітництво; інновації; екологічний розвиток; інновації

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The impact of state policy on the development of organic agriculture in Azerbaijan

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Abstract. The purpose of this study was to analyse the impact of government policy on the development of organic agriculture in Azerbaijan and to assess the effectiveness of support programmes for organic farmers. The methodology included an analysis of legislative documents, government support programmes for farmers, and reports of state and international organizations. The study found that organic agriculture in Azerbaijan is actively supported through legislative initiatives, such as the Law of the Republic of Azerbaijan No. 650-IIIQ "On Ecologically Clean Agriculture", adopted in 2008, and government support programmes. The law prohibits the use of genetically

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modified organisms and chemicals, and sets standards for the certification of organic products. As of 2020, the area of certified organic land was 40,779 hectares, indicating significant potential for the sector. The Azerbaijan 2020: Looking to the Future programme provides financial support to farmers by providing subsidies for fertilizers, seeds and other inputs that contribute to the development of organic production. In 2021-2022, AZN 61.8 million was paid to support agriculture. The study also identified significant challenges, including high certification costs, limited access to modern technologies and low demand for organic products in the domestic market, where only 15% of organic goods are sold. According to forecasts, with increased government support, the area of organic land could reach 500,000 hectares by 2030, which would help increase exports and improve the competitiveness of organic products in international markets. Further development also requires improving infrastructure and creating new sales channels for organic products

Keywords: government programmes; agricultural sector; subsidies; environmentally friendly production methods; certification

INTRODUCTION

Organic agriculture, which is characterized by environmentally friendly production methods, is an important component of sustainable development, contributing to the conservation of biodiversity, improving soil quality and reducing the use of chemical fertilizers and pesticides. In the context of global climate change and increased interest in environmentally responsible production methods, the development of organic agriculture is becoming particularly relevant for Azerbaijan. In a country with rich natural resources and agricultural traditions, organic farming can not only become a new vector of development, but also contribute to economic diversification. However, the adoption of organic methods faces numerous barriers, which are mainly economic and institutional in nature. These include high costs of product certification, limited markets, and a lack of adequate infrastructure for the production and distribution of organic products. In view of this, the government plays a key role in facilitating the transition to organic agriculture through subsidies, grants, tax breaks and legislative regulation.

The development of organic agriculture is becoming increasingly important around the world, including Azerbaijan, where the environmental and economic benefits of this approach are particularly relevant. According to a study by A. Guliyeva and M. Lis (2020), organic agricultural organizations in Azerbaijan face a number of challenges, including high certification costs, insufficient government support, and limited domestic demand for organic products. At the same time, the authors emphasize that the transition to organic methods can improve product quality, expand export potential and contribute to the country's economic growth. This study demonstrates the need for a more structured approach to supporting the organic sector in Azerbaijan, taking into account the experience of other countries that have successfully integrated organic practices into national development strategies.

Forecasts and prospects for the development of the organic products market were studied by A. Proshchalykina et al. (2019), who point to the increased interest of

consumers in environmentally friendly products in response to global environmental threats. The study by K. Todorova and D. Nikolov (2023) analyses the challenges and opportunities for Bulgaria in the context of the sustainable intensification approach to agriculture, which is part of the EU's Common Agricultural Policy. The author considers the potential benefits that Bulgaria can gain by adhering to the principles of sustainable intensification agriculture, including environmental support, increased resource efficiency and rural development, and provides information on how one of the EU countries is adapting to the requirements of sustainable agriculture, which are similar to those implemented in Azerbaijan for organic production.

Organic agriculture is becoming increasingly popular globally due to its environmental and socio-economic benefits (Stepanenko et al., 2023). Research by G. Ondrasek et al. (2023) highlights that organic agriculture is an effective response to the challenges of the modern agricultural sector, including soil degradation, biodiversity loss and dependence on synthetic chemicals. The authors emphasize that environmentally friendly production methods can help restore soil and maintain a stable ecosystem, while ensuring food security. The experience of different countries, including Poland, shows that organic farming can stimulate local economies and attract investment, but its development requires significant government support, in particular through subsidies and tax breaks (Antczak, 2024). At the same time, the issues of food security and the environmental impact of organic farming remain the subject of active research. N.P. George and J.G. Ray (2023) note that although organic methods often require more resources, they can have a positive impact on ecosystem conservation and contribute to long-term food security. A.M.K. Ghanem et al. (2024) also point out that organic agriculture has several environmental benefits, such as reduced greenhouse gas emissions and increased organic carbon content in the soil.

In Azerbaijan, the development of the organic sector can help solve a number of environmental prob-

lems and increase the competitiveness of local producers on international markets. However, to achieve sustainable development, broad government support is needed, including through subsidies, grants, and tax breaks (Huseynov *et al.*, 2023). Given the environmental and economic benefits of organic farming, some studies show that it could be an effective solution to overcome the current problems of agriculture in Azerbaijan. A. Hashimova (2023) notes that the main challenges are limited infrastructure, high certification costs, and lack of awareness of modern technologies among farmers. Similar problems arise in neighbouring countries, such as Kazakhstan, where organic agriculture is considered a key element of food security, as emphasized by A. Duisenbekuly *et al.* (2024). In Azerbaijan, the transition to organic production methods can increase food security and stability of the agricultural sector, but only if a targeted state policy is implemented to overcome these challenges.

The importance of organic agriculture is growing in the scientific discourse, but most studies focus on economic benefits and environmental aspects, while farmers' needs for support at the local level are often overlooked. This study fills the gap in the existing literature by focusing on the analysis of local policies and support instruments that can serve as a model for other countries with similar conditions for the development of organic farming. The aim of this study is to assess the effectiveness of political and economic support instruments aimed at developing organic agriculture in Azerbaijan, and to identify key factors that facilitate or constrain the development of this sector.

MATERIALS AND METHODS

The research methodology involved a comprehensive approach to studying the impact of state policy on the development of organic agriculture in Azerbaijan. The study covered the period from 2019 to 2023 and included a detailed analysis of official regulations and reports of governmental and international organizations, such as legislative documents of the official website of the Food and Agriculture Organization of the United Nations (2024), Organization for Economic Co-operation and Development (n.d.), and the World Bank (2024).

In particular, the legal documents governing agricultural policy were examined, such as the Law of the Republic of Azerbaijan No. 650-IIIQ (2008), which prohibits the use of genetically modified organisms and chemical fertilizers in the production of organic products. To study financial mechanisms to support farmers, authors used official data from the Agribusiness Association (A new sustainable..., 2011). The study examined subsidy programmes that provide payments to farmers based on the area of land under cultivation, as well as special subsidies for the development of perennial plantations and intensive horticulture. The analysis also covered subsidies for product certification, including

support for farms certified to international standards. In addition, grants for the purchase of organic fertilizers and seed were considered. In particular, the Enhancing Resilience in Agriculture programme supports small and medium-sized farmers by providing grants for organic certification and the purchase of organic fertilizers, as well as guidance on certification standards that ensure compliance with environmental standards in production (Food and Agriculture..., 2024). The main governing document regulating organic certification standards is the Law of the Republic of Azerbaijan No. 650-IIIQ (2008).

In the course of the study, a comparative analysis of policies and programmes supporting organic agriculture in the EU was carried out, in particular, in Germany – the German Organic Act (Bio-Siegel) (Federal Ministry of Food and Agriculture, n.d.), France – the national Ambition Bio programme (Ministry of Agriculture and Food Sovereignty, 2024) and Poland – the Rural Development Programme (Agency for Restructuring..., 2014). These programmes provide comprehensive support for organic agriculture in the form of subsidies, tax benefits, training programmes and certification services, which contributes to their effective development and creates conditions for the implementation of successful models in Azerbaijan.

To ensure a representative analysis, various sources of information were used, covering both the regulatory and practical framework. Data processing was carried out using electronic databases and information systematization tools such as Microsoft Excel. The tools helped to structure data on certified organic land, exports and retail sales.

RESULTS AND DISCUSSION

State support mechanisms: subsidies, tax benefits, training programmes

In Azerbaijan, the development of organic agriculture is actively supported by government initiatives and international projects aimed at increasing the sustainability of the agricultural sector. The main legislative act, the Law of the Republic of Azerbaijan No. 650-IIIQ (2008), defines the legal framework for organic production and covers standards for growing plants and keeping environmentally friendly livestock. The law prohibits the use of genetically modified organisms and chemicals for product processing, and sets requirements for certification and environmental labelling of products.

Some programmes provide financial assistance for product certification and the purchase of organic fertilizers, as well as scientific support for organic production, which promotes research and the adoption of environmental practices. Organizations such as the Ganja Agribusiness Association are actively involved in training farmers (A new sustainable..., 2011). Ganja Agribusiness Association has also established a certification body, AZEKOSERT, which promotes organic production

standards. In addition, government-supported courses in organic agriculture management have been introduced at the Azerbaijan State Agrarian University (Aliyev et al., 2022). Development strategies are supported by international organizations, including Food and Agriculture Organization of the United Nations, which helps to harmonize national standards with international norms. These initiatives contribute to environmental protection, food security and the development of rural communities. Thanks to the implementation of these policy decisions, organic agriculture in Azerbaijan is developing, although the sector still needs to overcome barriers related to education and infrastructure modernization.

The programme Azerbaijan 2020 provides for subsidies to support the agricultural sector (Food and Agriculture..., 2019). They include subsidies for the purchase of seeds, fertilizers, agricultural machinery and direct payments for the area under cultivation. These measures are aimed at increasing agricultural productivity and encouraging the adoption of environmentally friendly practices. The Azerbaijani government provides significant subsidies to farmers, which plays a critical role in encouraging agricultural production, including organic production. Farmers receive direct financial support based on the area they cultivate. For example,

farmers are paid AZN 40 per hectare per year, with additional payments for specific crops such as wheat and rice. These subsidies are intended to reduce the financial burden on farmers and encourage the adoption of more sustainable agricultural practices.

According to recent data, particularly in 2022-2023, several types of subsidies were introduced to support farmers in establishing new perennial plantations, developing intensive horticulture, and installing irrigation systems. According to the Agricultural Credit and Development Agency, approximately AZN 61.8 million was paid to farmers in the 2021/2022 season (Fig. 1). The subsidies covered almost 300,000 hectares of land, and the main costs included fertilizers, seeds, and plant protection products. A subsidy of AZN 200 manats/ha was also provided for sowing (for some crops such as corn, sunflower, soybeans, potatoes, etc.). Farmers who plant intensive orchards with drip irrigation also receive significant subsidies: for intensive and semi-intensive orchards such as nuts, a subsidy of 700 manats/ha is provided for the first 4 years, then this amount is reduced to 240 manats/ha; a one-time subsidy for planting fruit orchards ranging from 4,400 to 11,000 manats/ha depending on the type of crop (e.g., zeytuns, citrus, nut plantations).

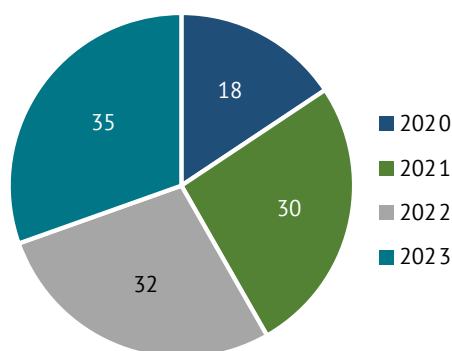


Figure 1. Subsidies for organic agriculture in Azerbaijan (2020-2023), mln

Source: compiled by the authors based on the Food and Agriculture Organisation of the United Nations (2024)

Such subsidies are intended to reduce the cost of new plantings and help farmers avoid additional costs for water and crop care. For example, in 2023, payments to support autumn agriculture were increased, including additional incentives for farmers who cultivate land for organic farming. These measures help to increase the competitiveness of Azerbaijani agriculture both domestically and internationally, as new plantations, especially those using intensive technologies, require significant initial investment.

Tax incentives for agricultural producers further stimulate investment in organic agriculture. The main benefits include: exemption from value-added tax for agricultural producers on major products, including organic products. This eases the financial burden on farmers and allows them to invest more in improving

production. Preferential income tax rates applied to agricultural enterprises, encouraging investment in the development of organic farming and sustainable agriculture. Incentives for farmers who adopt organic production methods, including special rates for property and land used for organic farming. These incentives help to create an enabling environment for farmers, easing their financial situation in an environment where investments in organic practices can be costly but bring long-term benefits. Table 1 provides a structured overview of the state support and key aspects of organic agriculture in Azerbaijan. It illustrates the main measures, including legislative initiatives, subsidies provided, area of certified land, exports, and other important indicators that demonstrate the impact of government policy on sustainable agriculture in the country.

Table 1. State support for organic agriculture

Year	Type of support	Amount or volume	Description
2008	Legal framework	N/A	Law of the Republic of Azerbaijan No. 650-IIIQ (2008) was introduced to regulate organic practices
2015	Training centre in Qakh	N/A	The Regional Centre for Experimental Agriculture was established to support organic farming in the region
2020	Certified organic land	40,779 ha	The total area of organically certified land, including agriculture and wild collection
2021	Export of organic products	Around 60,000 tonnes of hazelnuts	Hazelnuts are one of the main organic export crops, exported to 25 countries
2022	Subsidies and grants for agriculture	587 million USD	Support, including subsidies for food security and support for organic farming
2022	Retail sales of organic products	3 million euros	Retail sales of organic products, which indicates the potential of the domestic market and the need for exports

Source: compiled by the authors based on H. Gengenbach et al. (2020)

The information presented here highlights the government's efforts to strengthen the organic sector through subsidies, legal frameworks and training programmes for farmers. Law of the Republic of Azerbaijan No. 650-IIIQ (2008), laid down the legal framework for organic production, providing basic requirements and standards for the development of this sector. The legislation aims to regulate organic practices that reduce harmful environmental impacts and promote the production of high-quality organic products. In 2020, about 40,779 hectares of land were certified for organic production in Azerbaijan. This area includes both agricultural land and areas for the collection of wild plants. This indicates a significant potential for the development of organic production, although the area remains limited across the country. In 2022, the Azerbaijani government has allocated approximately USD 587 million to support agriculture, including subsidies for food security, irrigation system development, and other measures to promote sustainable organic production. This funding aims to improve farmers' access to inputs and help them adapt to environmentally friendly practices. Exports of organic products, in particular hazelnuts, play an important role in Azerbaijan's agriculture. In 2021, about 60,000 tonnes of hazelnuts were exported to 25 countries, highlighting the international demand for organic products and the importance of government support for exports. In 2022, retail sales of organic products in the domestic market of Azerbaijan reached 3 million euros. This demonstrates the demand for organic products among local consumers, but also points to the need to develop exports due to the limited domestic market. In 2015, the Regional Centre for Experimental Agriculture was established in the Qakh region. This centre supports farmers in adopting organic practices by providing them with access to training programmes and advice on environmentally friendly technologies. Legislation, subsidies, educational programmes and export incentives create the conditions for the expansion of the organic sector, providing long-term economic and environmental benefits for the country.

Grants. The Enhancing Resilience in Agriculture programme in Azerbaijan aims to support small and medium-sized farmers by providing grants for the purchase of organic fertilizers and certification for organic production (Organisation for Economic..., n.d.). This initiative is designed to strengthen the climate resilience of the country's agriculture in response to the challenges of climate change. The main objectives of the programme include reducing dependence on chemical fertilizers and promoting sustainable farming practices. In line with the World Bank (2024) policy framework, the programme supports so-called Climate-Smart Agriculture by providing farmers with resources to improve soil quality and increase yields using environmentally friendly technologies. The programme aligns with national sustainable agriculture goals by providing financial assistance for the purchase of organic fertilizers and certification, allowing farmers to officially label their products as organic. In addition, the programme works with international and local partners to implement sustainable agricultural practices in vulnerable regions of Azerbaijan.

A joint grant project of Food and Agriculture Organization of the United Nations (2024) and Turkey. This initiative is aimed at developing organic agriculture and institutional capacity in Azerbaijan. The project is aimed at strengthening the legal framework, conducting training programmes for farmers and organizing study tours to Turkey for Azerbaijani specialists. An Organic Agriculture Documentation Centre has also been established, providing access to international databases and materials for the development of farmers' knowledge. This project is funded by Turkey and implemented by Food and Agriculture Organization of the United Nations with a budget of USD 300,000, and has been operating since 2015.

Training and research programmes. Organic agriculture in Azerbaijan is actively supported by training programmes organized in cooperation with international organizations such as Food and Agriculture Organization of the United Nations. These programmes contribute

to raising awareness among farmers and expanding their knowledge of organic farming practices, including sustainable tillage, resource management and product certification. The Ganja Agribusiness Association (A new sustainable, 2011), together with Food and Agriculture Organization of the United Nations (2024), organized practical trainings for farmers focused on the application of organic standards and preparation for international markets, in particular the EU.

These programmes educated farmers about the value of organic certification, natural resource management and reducing dependence on chemical fertilizers. In addition, attention was paid to preparing for compliance with European standards for organic products, which increases export opportunities for local producers. The organic agriculture development projects have attracted resources to support scientific research to help farmers adapt international standards to local conditions. For example, research covers topics such as restoring soil fertility and increasing yields, which allows for the integration of environmentally friendly methods into the country's conventional agricultural practices. These research enhancement and support programmes are creating favourable conditions for the development of the organic sector in Azerbaijan, contributing to food security and strengthening the economic potential of the agricultural sector.

Problems and challenges of organic agriculture in Azerbaijan

Despite the support mechanisms in place, organic agriculture in Azerbaijan faces a number of serious problems and challenges. The main barriers for farmers seeking to adopt organic methods include high certification costs, lack of access to innovative technologies and knowledge, and limited markets for organic products. It is worth having a closer look at these challenges.

Certification is a key step for farmers who want to enter the organic market. However, the cost of this process can be significant. According to Food and Agriculture Organisation of the United Nations (2024), the cost of certification of an organic farm in Azerbaijan can range from AZN 2,000 to AZN 5,000 depending on the volume of production and the requirements of certification bodies: farmers can spend up to 10% of their annual income on the certification process alone, which is a significant financial burden, especially for small farms.

Main provisions of certification standards. Ban on the use of genetically modified organisms: Law of the Republic of Azerbaijan No. 650-IIIQ (2008), which defines the basic standards for organic production and certification, clearly prohibits the use of genetically modified organisms in the production of organic products. Control over the use of chemicals. The use of synthetic fertilizers and pesticides is prohibited: products must be grown using natural plant protection products and fertilizers. Certification and labelling: products

that meet organic standards must be certified and labelled. This ensures that products meet environmental requirements and allows consumers to choose organic products with confidence.

The certification of organic products in Azerbaijan is carried out by certification bodies such as AZEKOS-ERT, which was established on the initiative of the Ganja Agribusiness Association (A new sustainable..., 2011). AZEKOSERT is guided by international standards, such as those of the International Federation of Organic Agriculture, to ensure that products meet national and international requirements. The main stages of certification are: application by the farmer for product certification; assessment and verification of production for compliance with environmental standards, including soil, plant protection system and animal welfare; and issuance of the certificate. Products receive a certificate if they meet the established standards and can be labelled as organic.

The problem of access to modern technologies and knowledge in the field of organic agriculture is a serious barrier for farmers in Azerbaijan (Maharramova & Maharramov, 2023). Local producers face limited opportunities to learn the latest organic methods due to several reasons, including a lack of educational programmes and a lack of technical support for training farmers. This significantly hinders the development of organic production in the country. Limited state support for training and access to information: according to the 2022 national survey, about 65% of farmers said they did not receive adequate support from the state in terms of training in the latest agricultural technologies and access to information on innovative methods. In particular, farmers note insufficient funding for seminars, lack of advisory centres, and limited access to international resources on organic farming.

Insufficient number of research and extension centres. In Azerbaijan, agricultural research institutions are still only partially integrated with local farmers. This results in limited access to new knowledge for farmers, who are not always able to engage in practical research or receive advice on the implementation of modern organic farming methods. The government should invest in research and advisory centres that would provide farmers with new knowledge and raise their awareness of organic farming methods. Information also remains inaccessible to many farmers due to the lack of digital learning platforms that could provide ongoing access to modern technologies and practices. Digital tools such as mobile applications, online courses and experience-sharing platforms can greatly simplify the learning process and improve the efficiency of organic farming (Abdullayev *et al.*, 2024a). According to the Food and Agriculture Organization of the United Nations (2024), such platforms can increase productivity by up to 20% by providing access to information on fertilizers, crop optimization and water management.

Thus, investments in the development of educational programmes, the establishment of advisory centres, the integration of research and the introduction of digital learning platforms are critical to improving farmers' access to innovative methods in organic farming. Limited markets for organic products in Azerbaijan. One of the biggest challenges for organic agriculture in Azerbaijan is the limited opportunities for marketing. This is due to both infrastructure barriers and weak demand for organic products among the local population. Due to the lack of efficient distribution channels and underdeveloped infrastructure, many farmers face difficulties in selling their organic products. Demand for organic products in the domestic market remains low, which creates constraints for farmers seeking to sell their products domestically. Only 15% of organic products produced in Azerbaijan are sold on the domestic market. This is due to the relatively high price of organic products compared to conventional products, which makes them less affordable for many consumers.

Infrastructure is one of the main barriers to the development of organic markets (Guliyeva, 2023). The lack of logistics centres, limited availability of cold storage and specialized storage facilities for organic products significantly complicates the transportation and storage of goods. A study conducted by the Food and Agriculture Organization of the United Nations (2024) shows that about 30% of all agricultural products are lost due to insufficient infrastructure. This increases the risks for farmers and hinders their potential to expand production. Azerbaijani farmers also face problems accessing international markets. Although the country has the potential to export organic products to the EU and other regions with high demand for organic products, the process of entering these markets remains difficult. The main barriers include high requirements for certification and standardization, which require significant investments from producers. According to experts, only about 10% of farmers in the country have sufficient resources to certify their products in accordance with European standards, which limits export opportunities (Organisation for Economic..., n.d.).

Efficient distribution channels that could facilitate the distribution of organic products are also limited. The absence of cooperatives or distribution companies specializing in organic products reduces farmers' ability to organize stable sales. The Azerbaijani government should consider establishing public or private distribution centres to provide logistical and marketing support to farmers. In order to overcome these barriers, it is recommended to increase state support for the creation of new marketing channels and to increase investments in the development of infrastructure for transport and storage. Investments in the creation of specialized cooperatives for organic farmers could significantly facilitate access to markets and improve sales (Lopatynskiy *et al.*, 2023). Another important step would be to promote

certification of products in accordance with international standards, which would provide access to European markets and open up new export opportunities.

The need for infrastructure development. The poor state of roads and transport infrastructure affects the competitiveness of farmers. A study by the Food and Agriculture Organization of the United Nations (2024) highlights that improved transport routes can reduce the cost of transporting agricultural products by up to 30%. In Azerbaijan, a large proportion of agricultural producers are located in remote areas where transport costs are high, making it difficult to market products, especially organic ones. This limits access to major trading centres and export markets, making products more expensive and less competitive. Investments in these areas will not only help reduce costs for farmers, but also open up new opportunities to expand markets, improve product quality and increase farmers' incomes.

Comparison of support programmes in Azerbaijan, Germany, France, and Poland and prospects for the development of organic agriculture in Azerbaijan

A comparison of state support programmes for organic agriculture in Azerbaijan and leading programmes in other countries, such as Germany, France and Poland, shows different approaches to stimulating sustainable agricultural development. The Azerbaijani government actively supports the development of organic agriculture, including through subsidies, tax breaks and grants. Law of the Republic of Azerbaijan No. 650-IIIQ (2008) regulates organic production standards, including certification and environmental labelling of products. The state also provides subsidies for farmers who cultivate land using organic methods and finances training programmes in cooperation with international organizations such as the Food and Agriculture Organization of the United Nations (2024). However, the main challenges for Azerbaijan remain the limited domestic market for organic products and the underdeveloped infrastructure.

Germany has one of the strongest support systems for organic agriculture in the EU. The Bio-Siegel Organic Agriculture and Labelling Act has been in force since 2001 and provides for strict standards for organic products (Federal Ministry of Food and Agriculture, n.d.). The support programme includes direct payments to organic farmers and additional payments for the implementation of environmentally friendly practices, and finances research and promotion of organic products on the market, in particular through large support programmes. In contrast to Azerbaijan, where the market is still developing, Germany has a strong culture of organic consumption, which stimulates demand and provides additional opportunities for farmers (Poyoi *et al.*, 2022).

The national programme Ambition Bio, established in France, aims to achieve 15% of organic land and increase the share of organic products in public

procurement (Ministry of Agriculture and Food Sovereignty, 2024). The programme includes comprehensive financial support for farmers through subsidies, tax breaks and loans for the development of infrastructure for organic production. The government also supports the promotion of French organic products on the domestic and international markets. Ambition Bio provides both infrastructure and marketing support for farmers, which increases the competitiveness of French organic products. Compared to Azerbaijan, France has a developed network of domestic distributors and significant public investment in exports.

The Polish Rural Development Programme covers the period until 2027 and is part of the EU's Common

Agricultural Policy (Agency for Restructuring..., 2014). It encompasses support for the transition to organic agriculture, subsidies for organic producers, and training programmes for farmers. Special attention is paid to developing market opportunities and promoting Polish organic products abroad. Unlike Azerbaijan, Poland has access to EU funds, which significantly increases investment in the sector and allows it to create favourable conditions for producers, in particular through subsidies for agricultural modernisation. A comparative analysis shows that while Azerbaijan actively supports the development of the organic sector, it lacks the level of infrastructure and financial support available in the EU (Table 2).

Table 2. Comparative analysis of support programmes

Country	Main support measures	Features	Problems and challenges
Azerbaijan	Subsidies, tax breaks, training programmes	Support programmes through Food and Agriculture Organization of the United Nations, underdeveloped infrastructure	Limited markets, high cost of certification
Germany	Bio-Siegel, direct payments	Developed domestic market, high culture of organic food consumption	High cost for small farmers
France	Ambition Bio, subsidies, loans	Export promotion, support through public procurement	Market expansion, international competition
Poland	Rural Development Programme, subsidies, training programmes	Access to EU funds, stimulating modernization	Dependence on EU funding

Source: compiled by the authors

The use of international experience, in particular the French Ambition Bio programme (Ministry of Agriculture and Food Sovereignty, 2024) and the Polish Rural Development Programme (Agency for Restructuring..., 2014), can help modernise the organic sector in Azerbaijan and ensure its sustainable development. The organic agricultural sector in Azerbaijan has significant prospects for development, especially if there is stable government support, integration with international markets and compliance with quality standards that meet the requirements of the EU and other countries with high demand for organic products. Based on assessments and forecasts of the organic sector, and taking into account the international context, the key trends and opportunities for its expansion are presented.

Growth forecasts under stable government support. The conditions for the development of organic agriculture are improving due to increased government support and funding for farmers seeking to work according to organic standards (Smolii & Mostoviak, 2024). According to the Ministry of Agriculture of Azerbaijan, in 2021-2023, government spending on organic agriculture increased by 18%, allowing farmers to cover the costs of certification and environmentally friendly technologies (Food and Agriculture..., 2024). If government support grows by 15-20% annually, the total area of land used for organic farming could increase to 500,000 hectares by 2030, which would be about 5% of the country's total agricultural land. This trend will

have a positive impact on the production of organic products and will allow Azerbaijan to increase its exports to the EU, where demand for organic products is growing by 10-12% annually.

The impact of international standards and integration with international markets. Azerbaijan is actively working to bring its organic production standards in line with international norms. This is especially important for EU markets, where consumers prefer certified organic products. According to a report by the European Commission, the organic market in the EU is estimated at around 45 billion euros per year, and this figure is growing, which opens up significant prospects for Azerbaijani exporters (Organisation for Economic..., n.d.). To access EU markets, Azerbaijani farmers can use certification in accordance with EU standards. For example, in 2023, more than 200 Azerbaijani farms were registered as having received certification that met international requirements, allowing them to enter new export markets. In addition, Azerbaijan is interested in cooperating with the EU in the field of organic agriculture. As part of the Eastern Partnership programme, the EU provides advice and financial support to local farmers who adopt organic practices. In addition to EU markets, there is a growing demand for organic products in Asian countries such as China, Japan, and South Korea. For example, in China, the organic market is estimated to be worth approximately USD 10 billion, and is growing at 15% annually (World Bank, 2024). This demand creates

potential opportunities for the export of Azerbaijani organic products to Asian countries, especially given their geographical proximity and Azerbaijan's participation in transport corridors connecting Europe and Asia.

Additional perspectives. Investing in improving the infrastructure needed to store and transport organic products will also have a positive impact on export potential. The World Bank estimates that proper infrastructure for the organic sector could increase exports by 20-30% in the next 5-7 years. In addition, the development of modern logistics centres at the country's borders will significantly reduce the time for delivery of products to the EU and Asian markets, which is important for the competitiveness of Azerbaijani organic products (Abdullayev *et al.*, 2024b). The findings of the study confirm that support for organic agriculture through government subsidies, grants, and tax breaks is a significant factor in encouraging farmers to switch to organic production methods. This is consistent with the findings of A. Agasalim (2020), who believes that direct government support is the basis for agricultural development, but only if it is complemented by access to innovation and modern technology. This study also emphasizes the importance of combining financial assistance with educational programmes to enable farmers to adopt more efficiently, environmentally sustainable production methods.

The results also indicate that expanding educational programmes for farmers is a critical step in overcoming barriers to organic production. This is in line with the position of M. Gulaliyev *et al.* (2019), who emphasize the importance of educational initiatives as a means of raising farmers' awareness and adapting them to new methods. In this context, the lack of access to knowledge and infrastructure makes it difficult for farmers to adapt to organic standards, which was also noted by M. Huseynov (2023), who points out the weak institutional support for innovation in the agricultural sector of Azerbaijan.

This study also found that successful implementation of organic farming requires cooperation among farmers, as high certification costs can limit individual farms from achieving organic production standards. The experience described by M. Galstyan *et al.* (2024) on the example of Armenia shows that the creation of cooperatives helps to reduce financial and administrative burdens for farmers. This opens up prospects for further research on the possibility of adapting cooperative models in Azerbaijan, which will allow small farmers to overcome financial barriers more easily. In addition, I. Khalilov and F. Jafarova (2022) highlight the importance of infrastructure to support organic agriculture in the regions of Karabakh and East Zangezur, where transport and storage issues are becoming barriers to the development of the agricultural sector. This study notes that similar infrastructure constraints may reduce the competitiveness of organic products on international markets.

The findings of this study highlight the importance of a comprehensive approach for the development of organic agriculture in Azerbaijan, where government support, access to finance and farmer education play a key role. It emphasizes the importance of financial instruments, such as subsidies and tax incentives, to facilitate the transition to organic production. This correlates with the findings of M. Agnoletti and Santoro (2022), who point out the importance of international cooperation and value chain analysis. They note that in Azerbaijan, the lack of efficient logistics and infrastructure for organic products is one of the main obstacles to agricultural development. These findings are consistent with the present study, which highlights the need to develop infrastructure, in particular for certification and transportation of organic products, to ensure their competitiveness on international markets.

At the same time, the results of the study by A. Ukalska-Jaruga *et al.* (2020) on soil contamination by persistent organic pollutants point to serious environmental barriers to organic farming in Azerbaijan. It is noted that contaminated soils can significantly limit the potential for organic production, as organic products have strict requirements for environmental standards. This issue is also mentioned in the study, which states that one of the main obstacles to the development of organic agriculture in the country is soil contamination and insufficient attention to environmental aspects of production. This highlights the importance of preserving natural resources and monitoring soil conditions as a prerequisite for the development of the organic sector.

In terms of general trends, studies by L. Cei *et al.* (2024) and H. Willer *et al.* (2023) show a steady increase in demand for organic products at the global level. In particular, the reports by L. Cei *et al.* and H. Willer *et al.* state that organic agriculture is showing positive dynamics in global markets, and organic products are becoming increasingly essential for food security. These trends are also consistent with the results of this study, which notes the importance of developing the organic sector to improve Azerbaijan's export potential: expanding markets for organic products can contribute to economic growth and increase the country's competitiveness at the global level.

Similarly, R. McGuire *et al.* (2022) emphasize that organic farming is an important tool for combating climate change, as this approach allows reducing greenhouse gas emissions and contributes to the restoration of biodiversity. This is also supported by this study, which states that the development of organic agriculture can have a positive impact on the environmental situation in the country, in particular by reducing the use of chemical fertilizers and pesticides. At the same time, the results of the study by S. Mirloo *et al.* (2021), which analyses the problems of organic agriculture in Western Azerbaijan, confirm the need to improve educational initiatives for farmers. They point to the

importance of improving farmers' skills and raising their awareness of organic methods. This is in line with the study, which emphasizes the importance of training programmes and increasing farmers' knowledge for a successful transition to organic production methods; more educational initiatives are needed to help farmers not only learn organic methods, but also to learn how to properly certify their products to enter international markets.

The findings of this study confirm the importance of developing organic agriculture in Azerbaijan as one of the priority areas for ensuring sustainable development of the agricultural sector. In the work by N. Okruashvili et al. (2023), the authors discuss the role of organic farming as part of the strategy for sustainable agricultural development in Georgia. Similar to the results obtained, the authors point to the need to integrate organic farming into national strategies, as it contributes to food security and economic stability. In the context of Azerbaijan, these findings are also relevant, as organic agriculture can significantly increase the country's export potential and ensure the sustainable development of rural communities. The study by B.L. Lakaria et al. (2022) discusses the prospects of organic farming in terms of reducing the impact of pesticides and chemical fertilizers. This is in line with the results of the study, which emphasizes the importance of the environmental benefits of organic agriculture, in particular in reducing soil and water pollution. However, on the way to implementing organic practices, it remains important to address the problem of soil pollution and ensure proper monitoring of soil quality, which was also noted in the study by K. Ukalska-Jaruga et al. (2020).

The work of N. Sirenko et al. (2019) points out the importance of adapting organic production to market conditions and competitiveness in global markets. This issue is also critical for Azerbaijan, where the development of the organic sector requires improving farmers' access to certification and creating effective sales channels for organic products. The results confirm that one of the main constraints for the development of organic agriculture in Azerbaijan is the limited access to international markets and the need to raise awareness among farmers about the requirements for organic products. The study of R. Al-Obaidy (2019) focuses on the challenges faced by organic agriculture, in particular, the problems of certification and standardization of products. This correlates with the results obtained, which indicate that high certification costs are one of the main obstacles to the development of the organic sector in Azerbaijan. Solving this problem requires both government support and the development of international partnerships to ensure access to technologies and knowledge that can reduce certification costs.

In general, the results of this study are consistent with the findings of R. Abbasov et al. (2019) about the need to expand educational programmes for farmers. The results of M. Navidi et al. (2024) support authors'

conclusion that it is important to develop management skills and strategic planning for organic agriculture to compete successfully with conventional methods. Finally, the environmental data of A. Behnami et al. (2023) confirm the need for government programmes that would eliminate residual pollution and help restore ecological balance, which is key to maintaining environmental sustainability in the region.

CONCLUSIONS

The study found that organic agriculture in Azerbaijan is actively supported through legislative initiatives, subsidies, grants and farmer training programmes, which provides potential for further development of the sector. Law of the Republic of Azerbaijan No. 650-IIIQ, adopted in 2008, establishes the legal framework for organic production and regulates certification requirements. The certification procedure for organic products in Azerbaijan is carried out by AZEKOSERT, which was established on the initiative of Ganja Agribusiness Association; the main provisions of the certification are: prohibition of the use of genetically modified organisms, control over the use of chemicals and labelling of products that meet organic standards.

As of 2020, the area of certified organic land in Azerbaijan is 40,779 hectares, which is a significant, albeit limited, result for the country. Since 2016, subsidies have been introduced with the support of national strategies such as the National Strategy for the Development of Agriculture, including support for certification, purchase of organic fertilizers and investment in research to develop environmentally friendly practices. It is important to note that since 2021, USD 587 million has been allocated to support the agricultural sector under the Azerbaijan 2020: Looking to the Future programme, which has helped cover the cost of fertilizers, seeds and crop protection products, including for organic production. According to the Agrarian Credit and Development Agency, in the 2021/2022 season alone, farmers were paid AZN 61.8 million, which covered almost 300,000 hectares of land. Subsidies for intensive orchards and irrigation significantly reduce costs for farmers, facilitating the adoption of modern organic methods.

Support programmes, such as Enhancing Resilience in Agriculture in Azerbaijan, provide support to small and medium-sized farmers through grants for the purchase of organic fertilizers and certification for organic production. The joint support programme of Turkey and Food and Agriculture Organization of the United Nations for Azerbaijan aims not only to develop organic agriculture, but also the country's institutional capacity. Quantitative data, including volumes of exported organic products, indicate a growing potential for exports, particularly of hazelnuts, with a volume of 60,000 tonnes in 2021, opening up new markets, especially in the EU. Despite this, however, there are serious barriers to the development of organic agriculture,

including high certification costs (up to AZN 5,000 per farm), limited access to innovative technologies, lack of digital training platforms, and insufficient infrastructure for storage and transportation. Given these constraints, only 15% of organic products are sold on the domestic market, suggesting that additional measures are needed to develop marketing and improve market infrastructure.

Comparison of state programmes to support organic agriculture in Azerbaijan with those of Germany, France, and Poland shows that, even with active support for the development of the organic sector in Azerbaijan, it lacks the level of infrastructure and financial support available in the EU. The study shows that in order to overcome these barriers, it is necessary to continue investing in infrastructure, establishing cooperatives to facilitate access to markets, and increasing subsidies for organic farmers. Given the existing demand for organic products in the EU and Asia, the potential for export expansion is significant, but requires improved certification and the development of export channels. Further growth of the organic market in Azerbaijan is possible through integration with international standards and active participation in global supply chains.

One of the main limitations of this study is the limited amount of information available on specific support programmes for organic agriculture in Azerbaijan, in particular on their effectiveness and practical implementation at the farm level. While much general data on policy and economic initiatives were available,

specific data on the impact of these measures on organic farmers were often not presented in sufficient detail in public reports. In addition, the study does not cover a wide range of regional differences, which may have a significant impact on the adaptation of organic farming in different parts of the country. Another limitation is the lack of specific data on the long-term economic impact of organic agriculture on farmers' incomes, which could help assess the effectiveness of state support and identify potential policy gaps.

A promising area for further work is to compare the results of organic farming in different regions of Azerbaijan, as the level of infrastructure development and access to resources can vary significantly depending on the area. This will allow to more accurately identify the needs and barriers for farmers in different parts of the country. Also, taking into account the positive experience of other countries such as Georgia or Poland, further research could focus on adapting organic farming models that have been successful in these countries to the conditions of Azerbaijan. This would help to develop specific recommendations for integrating the organic sector into the country's overall agricultural policy.

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CONFLICT OF INTEREST

None.

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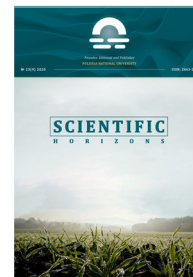
Анотація. Метою цього дослідження було проаналізувати вплив державної політики на розвиток органічного сільського господарства в Азербайджані та оцінити ефективність програм підтримки органічних фермерів. Методологія дослідження включала аналіз законодавчих документів, державних програм підтримки фермерів, а також звітів державних і міжнародних організацій. Дослідження показало, що органічне сільське господарство в Азербайджані активно підтримується за допомогою законодавчих ініціатив, таких як Закон Азербайджанської Республіки № 650-IIIQ «Про екологічно чисте сільське господарство», прийнятий у 2008 році, та державних програм підтримки. Закон забороняє використання генетично модифікованих організмів і хімікатів, а також встановлює стандарти для сертифікації органічної продукції. Станом на 2020 рік площа сертифікованих органічних земель становила 40 779 га, що свідчить про значний потенціал сектору. Програма «Азербайджан 2020: Погляд у майбутнє» надає фінансову підтримку фермерам шляхом надання субсидій на добрива, насіння та інші засоби виробництва, що сприяють розвитку органічного виробництва. У 2021-2022 роках на підтримку сільського господарства було виплачено 61,8 млн манатів. Дослідження також виявило значні виклики, серед яких високі витрати на сертифікацію, обмежений доступ до сучасних технологій та низький попит на органічну продукцію на внутрішньому ринку, де продається лише 15 % органічних товарів. За прогнозами, за умови посилення державної підтримки площа органічних земель може досягти 500 000 га до 2030 року, що сприятиме збільшенню експорту та підвищенню конкурентоспроможності органічної продукції на міжнародних ринках. Подальший розвиток також потребує покращення інфраструктури та створення нових каналів збуту органічної продукції

Ключові слова: державні програми; аграрний сектор; субсидії; екологічно чисті методи виробництва; сертифікація

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Integration of digital technologies to improve the efficiency of small and medium-sized agricultural enterprises

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Abstract. The purpose of the study was to assess the impact of the introduction of digital technologies on improving the efficiency of small and medium-sized agricultural enterprises in Kazakhstan. To achieve this goal, a set of methods was used, including statistical analysis, a comparative method, and content analysis of respondents' answers through questionnaires. The study results showed that the integration of digital solutions has significantly reduced management and production costs, reducing

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them by 12%. The introduction of digital technologies has helped to increase crop yields by 15% and improve the efficiency of agricultural production. In addition, digitalisation has reduced the time required to make managerial decisions by 20%, which has increased the efficiency of management processes. The use of ERP/CRM systems, agrotechnological platforms and business process automation positively correlated with increased profitability, with correlation coefficients of 0.45, 0.38 and 0.52, respectively, which is statistically significant (significance levels 0.01, 0.05, and 0.02). The ERP system ($r = 0.62$, p -value = 0.01) showed a particularly high correlation with energy efficiency, while automation ($r = 0.55$, p -value = 0.02) and agroanalysis ($r = 0.47$, p -value = 0.03) also made a significant contribution. Analysis of variance showed a statistically significant difference in profitability between enterprises that implement digital technologies (F-statistics 5.62, p -value 0.01) and those that do not use them (F-statistics 2.34, p -value 0.05). This confirmed the importance of digital transformation for improving business financial results. Thus, digital technologies significantly increase the efficiency and competitiveness of agricultural enterprises, which is confirmed by both quantitative and qualitative findings

Keywords: competitiveness; costs; yield; management processes; agrotechnological platforms; automation

INTRODUCTION

The modern agricultural sector is undergoing significant changes under the influence of digitalisation and the introduction of intelligent technologies, which significantly change approaches to managing production processes. The development of data monitoring and analysis technologies opens up new opportunities to increase productivity, reduce costs, and minimise risks associated with natural factors and market uncertainty (Martín & de la Fuente, 2022; Ammann *et al.*, 2022).

In the agricultural sector, the issue of improving the efficiency of small and medium-sized agricultural enterprises is relevant, especially given the global challenges of economic instability, climate change, and growing competition in international markets. Given limited resources and insufficient access to modern technologies, small and medium-sized farms often face difficulties in increasing productivity and ensuring sustainable growth. In response to these challenges, numerous studies highlight the importance of integrating digital technologies such as the Internet of Things (IoT), big data, cloud services, and automated management systems. Thus, P. Katsikouli *et al.* (2020) and R. Finger (2023) demonstrate that implementation of digital solutions can help to optimise production processes, increase yields, and minimise resource costs.

Research by P.V. Méndez-Zambrano *et al.* (2023) points to the successful experience of using intelligent sensors and data analytics to track soil condition, humidity levels, and weather forecasting, which contributes to timely management decision-making. However, most research focuses on large agricultural corporations that have significant financial capabilities, while the capabilities of small businesses remain poorly understood. Research conducted by A. Upadhyaya *et al.* (2021) draws attention to the fact that successful digitalisation of small agricultural farms requires state support that would contribute to the development of appropriate infrastructure, and the financing of technological solutions. In addition, it is particularly important for small businesses to have training programmes

that help to develop employees' digital skills. In particular, J. Trenkle (2020) notes that without proper training of personnel, effective implementation of modern digital tools in small farms is unlikely. In addition to these researchers, other studies also reveal important aspects of digitalisation in agriculture. In particular, the study by F. Saruchera and S. Mpunzi (2023) highlights the importance of precision farming based on innovative approaches to collecting and analysing plant health data. The researchers note that precision farming can significantly reduce the cost of fertilisers and water, and optimise agrotechnical processes, which directly increases the profitability of farms (Rehman *et al.*, 2018; Tandon *et al.*, 2020).

E. Ndhlovu and K. Dube (2023) also focus on the impact of climate monitoring technologies and weather forecasting systems. They found that due to the use of these systems, agricultural enterprises can more effectively plan the periods of sowing, harvesting, and carrying out protective treatments. However, the researchers note that such systems require stable access to the Internet and state support to ensure their distribution in remote areas. S. Rolandi *et al.* (2021) highlights the need to integrate digital solutions with sustainability strategies. The researcher notes that digital technologies can become an effective tool for reducing the impact of agriculture on the environment, for example, by reducing greenhouse gas emissions and saving natural resources. D.C. Rose *et al.* (2020) points out the lack of sufficient research on the impact of digitalisation on small producers, especially in developing countries. There are papers that emphasise the importance of an interdisciplinary approach to digitalisation of agriculture. Thus, V. Saiz-Rubio and F. Rovira-Más (2020) note that the involvement of specialists from various fields, such as agronomy, ecology, information technology and economics, is important for the integrated implementation of technologies. The researchers suggest that such interdisciplinary teams can help to develop digital solutions tailored to the

needs of different types of agricultural enterprises, regardless of their size.

A review of modern sources showed that although digitalisation of the agricultural sector as a whole is a promising area for improving production efficiency, there are significant gaps in the coverage of small and medium-sized agricultural enterprises. The purpose of this study was to determine the impact of the introduction of digital technologies on the efficiency and productivity of small and medium-sized agricultural enterprises in Kazakhstan. The research was aimed at filling existing gaps in the scientific substantiation of digital solutions for small agricultural farms and can serve as a basis for developing practical recommendations that will help small and medium-sized enterprises to gain access to modern technologies and increase their competitiveness in the market.

MATERIALS AND METHODS

The study was conducted in the period from 2021 to 2023 in Kazakhstan at 50 small and medium-sized agricultural enterprises engaged in the cultivation of agricultural crops. To conduct the study, a sample consisting of entrepreneurs and managers of small and medium-sized selected agricultural enterprises in Kazakhstan was formed based on criteria that provide experience in using digital technologies in production processes and business management. Respondents were selected from different regions of Kazakhstan to ensure representativeness. Since the study involved the use of mobile applications to collect information, respondents were selected from among those who actively use platforms such as Facebook Messenger, Telegram, Viber, and WhatsApp. 1000 invitations were sent, of which 870 people confirmed their participation in the study. All study participants were warned about the purpose of the study, its methods, and the possibility of refusing to participate at any time. Before participating in the survey, respondents confirmed their consent to the processing of the information provided. Anonymity and confidentiality of participants' data were preserved. All personal data was used only in the framework of this study and will not be disclosed without the consent of respondents.

Data was collected using a structured questionnaire developed through the Google Forms platform. The questionnaire contained closed and open questions related to such aspects as types of digital technologies, results achieved (reducing costs, increasing crop yields and enterprise efficiency, reducing time for making managerial decisions, etc.), and difficulties faced by enterprises. The questionnaires were sent via mobile applications (Facebook Messenger, Telegram, Viber, WhatsApp), which provides access to a wide audience. First of all, economic indicators before and after the introduction of digital technologies were compared, which allowed assessing changes in such aspects as

productivity, production costs, revenues and other important performance indicators. Additionally, the economic feasibility of introducing digital technologies at small and medium-sized agricultural enterprises was assessed. The assessment was carried out by analysing respondents' responses to questions related to cost reduction, improving management processes, and optimising resource use. An important aspect of the analysis was to identify factors that contribute to or hinder the effective implementation of digital solutions in small and medium-sized businesses. A separate content analysis of respondents' responses to open-ended questions was carried out, which allowed investigating their attitude to digital technologies in more detail.

To assess the relationship between the use of digital technologies and the financial performance of enterprises, a t-test was used to compare the average values between two groups of enterprises: those that use digital technologies and those that do not use them. Variance analysis (ANOVA) was used to determine statistically significant differences between groups of enterprises depending on the level of digital integration (low, medium, high). The significance level (p -value) reflects the probability that the results obtained may be random, and determines their statistical significance. This study used significance levels of 0.01, 0.02, and 0.05, which correspond to varying degrees of confidence in the reliability of the results. In particular, a value of $p < 0.01$ indicated a very low probability of randomness of the result, $p < 0.02$ confirmed a sufficiently high confidence, and $p < 0.05$ was the standard threshold indicating an acceptable probability of significance. All the analysed results in this study corresponded to the specified levels, which allowed considering them reliable. The authors adhered to the principles of the American Sociological Association's Code of Ethic (1997).

RESULTS

As a result of the study of the trend in the use of digital technologies among selected small and medium-sized agricultural enterprises, which are important for achieving greater efficiency and competitiveness in the agricultural sector, it was determined that enterprise resource planning (ERP) and customer relationship management (CRM) systems are used in 35% of enterprises. These are the most common digital technologies among respondents, which indicates the need for agricultural enterprises to increase the efficiency of resource management and improve customer interaction. Such systems help to centralise information, improve operations management, and facilitate informed decision-making, which is important for small businesses with limited resources.

Digital solutions for automating business processes are used by 26% of enterprises, which is an important step to optimise daily operations. Automation allows reducing the time required to complete routine tasks,

increasing productivity, and reducing the human factor in business processes (Gulaliyev *et al.*, 2023). Enterprises that use automation can improve internal processes, which is especially important for small agricultural enterprises with a limited staff. Agrotechnological platforms are used by 23% of enterprises and help farmers to plan sowing and harvesting operations, optimise the use of resources, and monitor the state of crops in real time (Potryvaieva *et al.*, 2024). This indicates that agrotechnological platforms are gradually being integrated into the agricultural sector, although they are not yet widespread, due to a lack of access to high-tech equipment or a lack of understanding of the benefits of digitalisation. Only 15% of the selected enterprises actively use platforms for agricultural analytics, which involves analysing data on yield, weather conditions, soil condition, and other factors that affect agricultural production. This indicates limited access of small and medium-sized enterprises to such analytical tools, or a lack of awareness of their capabilities. Analytics in the agricultural sector helps to optimise the use of resources and make informed decisions, which is key to increasing yields and reducing costs (Fig. 1).

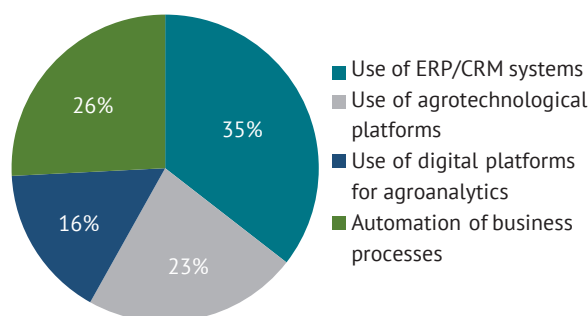


Figure 1. Use of digital technologies in small and medium-sized agricultural enterprises

Source: compiled by the authors

In general, the data show that ERP/CRM systems and business process automation are the most common among the selected small and medium-sized agricultural enterprises. This indicates the priority of such areas of digitalisation, which are aimed at improving the management and efficiency of enterprises. However, the use of agrotechnological platforms and agroanalytics remains less widespread, which may require additional efforts on the part of the state or private investors to improve access to these technologies. The assessment of the achieved results from the introduction of digital technologies in small and medium-sized agricultural enterprises shows significant improvements in key business indicators. First, the cost reduction after the introduction of digital technologies was 12%, which indicates the ability of these technologies to optimise enterprise costs for operational processes. This can be the result of automating certain processes, reducing the need for manual labour, and optimising resources. A 15% increase in crop yields indicates that digital solutions have a positive impact on the productivity of the agricultural sector. Intelligent platforms for agricultural analytics and automation help businesses better manage crops, control resources, and respond in time to changes in growing conditions.

The efficiency of management decision-making has increased by 20%, which is a sign of an improvement in the efficiency and accuracy of decision-making processes due to the use of ERP/CRM systems and agricultural technology platforms. Such systems provide businesses with up-to-date information for better planning and monitoring. A 20% reduction in decision-making time confirms the effectiveness of digital tools in speeding up operational processes. Appropriate platforms allow businesses to access the necessary information faster, which minimises delays in decision-making and improves the overall reactivity of companies to change (Table 1).

Table 1. Results achieved from the introduction of digital technologies

Indicator	Before implementation	After implementation	Change (%)
Cost reduction	100%	88%	-12
Increase in yields	100%	115%	+15
Improvement of the effectiveness of management decisions	100%	120%	+20
Reduction in decision-making time	100%	80%	-20

Source: compiled by the authors

In general, the results of the introduction of digital technologies demonstrate a significant positive effect on the productivity and efficiency of small and medium-sized agricultural enterprises, confirming that these innovations help to optimise resources, increase yields, and reduce operating costs. It is worth noting that the introduction of digital technologies faces several significant problems that may limit the effectiveness of their application. The main problem, according to the survey

results, is the high cost of implementing technologies, which is noted by 60% of respondents. This suggests that the cost of launching and integrating new technologies can be significant for entrepreneurs, which is often a barrier to initial investment. 55% of respondents report a lack of investment to scale technologies, which highlights the difficulties in expanding and distributing implemented solutions, even if they are successful at the initial stage.

An equally important problem is the lack of qualification of personnel, which is indicated by 45% of entrepreneurs. This reflects the need to educate and retrain employees to effectively use new digital and environmental technologies. Admittedly, for the successful implementation of such innovations, it is important that the staff has a sufficient level of knowledge and skills. Another problem is the low level of access to technology, which was reported by 50% of respondents. This may be conditioned by technical limitations, lack of infrastructure, or high costs for licenses and equipment. Therefore, enterprises face difficulties in gaining access to the latest technologies, which limits their ability to modernise and improve efficiency (Fig. 2).

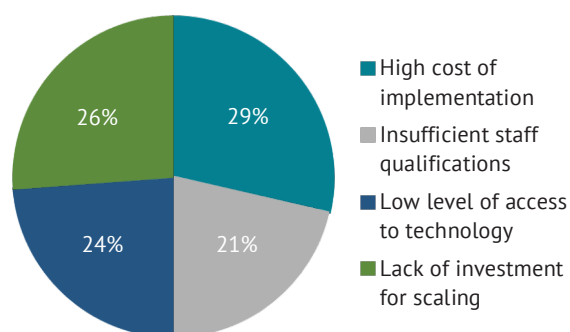


Figure 2. Main problems of implementing digital technologies

Source: compiled by the authors

To overcome the challenges that arise when implementing digital technologies, businesses can implement several strategies that will help to reduce financial barriers and ensure the effective use of new technologies. One of the most important ways is to attract state support, in particular, through subsidies, grants or tax incentives that reduce the initial costs of implementing new technologies. This allows enterprises to reduce the financial burden at the project launch stage. In addition, it is possible to use a step-by-step implementation strategy to reduce the cost of launching innovations. Enterprises should start with small, less costly projects and then gradually expand the use of technology.

Another important strategy is to find strategic investors to scale innovative solutions. Businesses can turn to private investors or venture capitalists who are interested in supporting new technologies. However, the creation of joint ventures with other companies allows attracting additional resources for faster development of technologies that have already been successfully tested. However, in order for innovation to have a real impact, it is necessary to consider the problem of insufficient skills of personnel. To do this, it is necessary to organise training and advanced training programmes for employees. Cooperation with educational institutions and the creation of specialised training courses would allow employees to quickly master new

technologies and apply them in their work. In addition, mentoring programmes and exchange of experience with experts can significantly speed up the adaptation of staff to new conditions. To overcome the problem of limited access to advanced technologies, which is associated with high costs for licenses and equipment, it is important to invest in the development of digital infrastructure, in particular, in broadband Internet coverage and the availability of necessary equipment for small and medium-sized enterprises. Technological hubs or innovation centres can also be created where companies can access the latest developments and test them in their processes.

The correlation analysis performed to assess the relationship between the level of use of digital technologies and the financial performance of enterprises showed a significant positive correlation between the implementation of ERP/CRM systems and profitability. The results show that technologies that have a positive correlation with the effectiveness of business processes can significantly improve them; in particular, ERP/CRM systems, agrotechnological platforms, and business process automation. The implementation of ERP systems has a correlation of $r = 0.45$, which is statistically significant at the level of $p\text{-value} = 0.01$, indicating their significant impact on business processes. Agrotechnological platforms show a weaker relationship with efficiency, but their impact also has statistical significance ($r = 0.38$, $p\text{-value} = 0.05$). Business process automation shows a strong positive impact ($r = 0.52$, $p\text{-value} = 0.02$), which confirms its effectiveness in improving management processes.

As for the impact of digital technologies on energy efficiency, the results show that the introduction of ERP systems and agricultural analytics has a significant positive effect. The correlation between ERP uses and energy efficiency is $r = 0.62$, which indicates a high level of impact on the energy consumption of the enterprise, while $p\text{-value} = 0.01$ confirms the statistical significance of this result. Similarly, agroanalysis has a correlation of $r = 0.47$ with energy efficiency, which is also statistically significant ($p\text{-value} = 0.03$). Process automation provides a correlation of $r = 0.55$ with energy efficiency, which once again highlights the importance of automation to reduce energy consumption. In addition, environmental innovations also have a significant impact on the financial results of enterprises. In particular, energy efficiency has a positive correlation ($r = 0.48$, $p\text{-value} = 0.01$) with financial indicators, which indicates the importance of energy saving for increasing profitability. The use of renewable energy also appears to be correlated with financial results ($r = 0.41$, $p\text{-value} = 0.04$), and recycling of organic waste has the least impact, but is still statistically significant ($r = 0.35$, $p\text{-value} = 0.05$).

Regarding the impact of technology on the financial performance of enterprises, profitability is one of the main indicators that positively correlates with the

introduction of digital and environmental innovations ($r = 0.58$, p -value = 0.01). However, energy efficiency has a correlation of $r = 0.47$, which also indicates the importance of energy saving for financial results (Table 2).

Thus, the analysis shows that digital technologies have a significant impact on improving the efficiency of small and medium-sized agricultural enterprises, reducing energy consumption and increasing profitability.

Table 2. Correlation coefficients between digital technology adoption and enterprise performance

Technology/Innovation	Correlation coefficient (r)	p-value
Impact on business process efficiency		
ERP/CRM systems	0.45	0.01
Agrotechnological platforms	0.38	0.05
Business process automation	0.52	0.02
Impact on energy efficiency		
Use of ERP	0.62	0.01
Use of agroanalytics	0.47	0.03
Automation	0.55	0.02
Impact of environmental innovations on financial results		
Energy efficiency	0.48	0.01
Renewable energy sources	0.41	0.04
Recycling of organic waste	0.35	0.05
Impact on financial performance		
Profitability	0.58	0.01
Energy efficiency	0.47	0.03

Source: compiled by the authors

As a result of the analysis of variance (ANOVA), statistically significant differences in profitability were identified between enterprises that actively implement digital technologies and those that do not use them. For a group of companies using digital technologies, the F-statistic is 5.62, and the p-value is 0.01, which indicates a significant difference in profitability. While for the group of enterprises that do not use

technologies, the F-statistic is 2.34, and the p-value is 0.05, which also indicates statistical significance, although at a slightly lower level (Table 3). These results confirm that the introduction of digital technologies has an important impact on the financial performance of enterprises, in particular, on profitability. This highlights the importance of digital transformation to improve business efficiency.

Table 3. Results of variance analysis (ANOVA)

Groups of enterprises	F-statistics	p-value
Using digital technologies	5.62	0.01
Without using digital technologies	2.34	0.05

Source: compiled by the authors

In general, the results of the study show that the introduction of digital technologies significantly improves not only the operational efficiency of small and medium-sized agricultural enterprises, but also their financial results. These innovations help businesses to reduce costs, increase crop yields, improve management decision-making efficiency, and speed up decision-making, which has a significant positive impact on their financial condition.

DISCUSSION

The study results demonstrate a significant impact of digital technologies on the efficiency of small and medium-sized agricultural enterprises in Kazakhstan. Automation systems, such as ERP and CRM, significantly reduce costs and improve management efficiency in agricultural enterprises. The results showed that after the introduction of digital solutions, costs for management

and production processes decreased by 12%, which is a significant indicator for small and medium-sized enterprises in the agricultural sector. This effect was achieved by reducing manual labour, automating routine processes, and facilitating access to information, which allowed businesses to respond faster to changes in market conditions and make more effective management decisions.

According to the results of the study, it was also revealed that investments in digital technologies can reduce the cost of management and production functions from 100% to 88%, which indicates the successful integration of these technologies into the business processes of agricultural enterprises. It is important that these changes not only reduce costs, but also significantly increase the level of managerial transparency and allow enterprises to use their resources more efficiently. With the introduction of modern information technologies, such as platforms for agricultural

analytics, enterprises are able to automate planning and control of production processes, reduce decision-making time, and thereby increase overall production efficiency (Kyfyak *et al.*, 2021). In Kazakhstan, where there is a high level of spending on management functions, the implementation of such solutions can be an important step towards reducing costs and increasing the competitiveness of the agricultural sector.

The study also highlights that the use of digital solutions can lead to an increase in crop yields by 15% by optimising their cultivation processes and improving the use of resources. In particular, the use of precision farming technologies allows precise regulation of the use of water, fertilisers, and other resources, which reduces costs and increases overall production efficiency (Askaraliev *et al.*, 2024). This was also confirmed in the study by R. Abiri *et al.* (2023), who notes that digital technologies in agriculture reduce the number of resources spent on the production of a unit of production, and this is an important factor in improving the economic efficiency of enterprises. One of the important features of digitalisation in the agricultural sector is also the improvement of environmental efficiency of production (Zadorozhniuk, 2023). Ultimately, the use of precision farming technologies helps to reduce the environmental burden on the environment. In particular, such technologies can significantly reduce water pollution and improve soil structure, which is important for the sustainability of agricultural ecosystems (Bibi & Rahman, 2023).

Analysis of the effectiveness of digital technologies in the agricultural sector using the example of small businesses also confirms the importance of investing in these technologies. According to R.A.A. Madushanki *et al.* (2019), digital solutions such as farm management platforms and big data analytics systems, enable farmers to optimise production processes and significantly reduce resource costs. Thus, automated systems allow controlling each stage of production and quickly adjusting strategies depending on changes in the market or weather conditions. As a result, businesses can increase their productivity and reduce management decision-making time by 20% (Bocean, 2024). M. Amarasiri *et al.* (2019), who analysed the impact of digital solutions on small and medium-sized agribusiness in conditions of limited access to investment, also notes that technologies such as big data analysis and intelligent decision-making systems can significantly improve the efficiency of agricultural enterprises, even in conditions of limited resources. This is confirmed by the results obtained, as even businesses with disabilities have been able to achieve improvements through the introduction of digital technologies.

The results of the study are also confirmed in the practice of other countries. Thus, B.B. Hojnik and I. Huđek (2023) argue that the introduction of ERP systems in US agribusiness has helped to significantly reduce production costs and improve enterprise financial

performance. In particular, it was noted that these systems helped to increase profitability by 10%, which allows enterprises to become more resilient to economic crises and competitive challenges. This shows that digitalisation is a powerful tool for ensuring the economic sustainability of agricultural enterprises, since automation of processes not only reduces costs, but also allows responding more quickly to changes in the market and adapting to new economic conditions. In addition, it is worth noting that one of the main factors for the successful introduction of digital technologies in agriculture is the level of access to these technologies for small and medium-sized enterprises (Lopatynskiy *et al.*, 2023). In Kazakhstan, many agricultural enterprises, especially at the initial stages of development, face difficulties in implementing innovations due to limited access to financial resources and technological tools. As noted by A. Burliai *et al.* (2021), the key challenges are the high cost of investing in digital technologies and the need for specialised knowledge to use them effectively. Therefore, in order to support small and medium-sized enterprises in the agricultural sector, it is necessary to create favourable conditions for access to digital technologies through state support and infrastructure development. In the context of limited resources and difficult economic conditions, the use of digital technologies can become the main factor for increasing the competitiveness of agricultural enterprises (Kovalyshyn *et al.*, 2023). It is important that public authorities and financial institutions support these initiatives by providing small businesses with access to concessional loans and grants for technology adoption, which reduces barriers to innovation and increases their efficiency at all stages of production (Carolan, 2020; Nugraha *et al.*, 2023).

The analysis of the effectiveness of digital solutions in small businesses was also confirmed by X. Zhang and D. Fan (2024), who notes that in China, the introduction of agricultural robots and digital platforms for managing fields has significantly increased yields and reduced labour costs in agricultural enterprises. This also shows a trend where even businesses with limited resources can significantly improve the efficiency of their operations through the introduction of digital technologies. According to L. Klerkx *et al.* (2019), digitalisation allows agricultural enterprises to make more informed management decisions through access to up-to-date and accurate data. In particular, the use of big data analytics platforms helps farmers to predict yields, resource requirements and management needs based on meteorological and agronomic data, which reduces risks and improves operational efficiency. In addition, the use of artificial intelligence systems in the agricultural sector allows automatically adjusting the strategies of tillage, irrigation, and fertilisation in real time, which leads to significant economic and environmental benefits (Chandra & Collis, 2021; Charatsari *et al.*, 2024).

Research R. Gröbli and M. del Pilar (2022) shows that farmers who invested in digital technologies received financial benefits in the form of reducing production costs by 10-15%. An important component is also to increase the availability of financial services, such as lending, through the use of online platforms for farmers. This allows businesses to quickly receive the necessary funds for development, and reduce the financial risks associated with traditional ways of doing business. Thus, the results of the study indicate that digitalisation is an important factor in improving the efficiency of small and medium-sized agricultural enterprises in Kazakhstan. The introduction of modern technologies helps to reduce costs, increase yields, optimise production processes, and reduce the environmental burden. However, to ensure equal access to these technologies for all enterprises, support from the state and financial institutions is required, which will contribute to the development of the agricultural sector based on innovative technologies.

CONCLUSIONS

The integration of digital technologies into the activities of small and medium-sized agricultural enterprises in Kazakhstan has a significant potential to increase their efficiency and competitiveness. According to the results of the study, the introduction of digital technologies can significantly reduce costs by 12%. In addition, digitalisation helps to increase crop yields by 15%, which increases the efficiency of agricultural production. This indicates the high potential of digital solutions for improving agricultural productivity. Another important result is an increase in the efficiency of management processes. In particular, the introduction of digital technologies can reduce the time spent on making managerial decisions by 20%, which significantly increases the efficiency of management structures in the agricultural sector.

The results of the study confirm that the introduction of digital technologies significantly increases the operational and financial efficiency of small and medium-sized agricultural enterprises. In particular, ERP/CRM systems, agrotechnological platforms, and automation of business processes show a significant correlation with the increase in profitability of enterprises, with correlation coefficients of 0.45, 0.38, and 0.52, where the statistical significance levels are 0.01, 0.05, and 0.02. Energy efficiency is most positively affected by the use of ERP systems, the correlation coefficient of which is 0.62 at p-value 0.01, while automation shows $r = 0.55$ (p-value = 0.02), and agroanalysis – $r = 0.47$ (p-value = 0.03).

The results of the variance analysis show a statistically significant difference in profitability between enterprises implementing digital technologies, where F-statistics is 5.62 and p-value is 0.01, and those that do not apply them, where F-statistics is 2.34 and p-value is 0.05, emphasising the importance of digital transformation for improving business financial performance. Thus, digital technologies have a significant positive impact on reducing costs, increasing crop yields, improving management processes and financial efficiency of enterprises in the agricultural sector, which is confirmed by both qualitative and quantitative results of the study. The perspective of future research is an in-depth analysis of the impact of digital technologies on various aspects of the agricultural sector, in particular, on sustainable development, adaptation to climate change, and improvement of environmental efficiency.

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CONFLICT OF INTEREST

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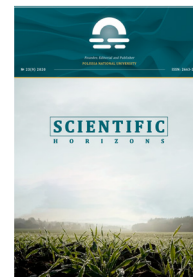
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Анотація. Метою дослідження було оцінити вплив впровадження цифрових технологій на підвищення ефективності діяльності малих і середніх сільськогосподарських підприємств у Казахстані. Для досягнення поставленої мети було використано комплекс методів, включаючи статистичний аналіз, порівняльний метод та контент-аналіз відповідей респондентів за допомогою анкетування. Результати дослідження показують, що інтеграція цифрових рішень дозволила значно скоротити управлінські та виробничі витрати, зменшивши їх на 12 %. Впровадження цифрових технологій сприяло підвищенню врожайності сільськогосподарських культур на 15 % та підвищенню ефективності агровиробництва. Крім того, діджиталізація скоротила час, необхідний для прийняття управлінських рішень, на 20 %, що підвищило ефективність управлінських процесів. Використання ERP/CRM-систем, агротехнологічних платформ та автоматизації бізнес-процесів позитивно корелює зі зростанням прибутковості з коефіцієнтами кореляції 0,45, 0,38 та 0,52 відповідно, що є статистично значущим (рівні значущості 0,01, 0,05 та 0,02). ERP-система ($r = 0,62$, p -значення = 0,01) показала особливо високу кореляцію з енергоефективністю, тоді як автоматизація ($r = 0,55$, p -значення = 0,02) та агроаналіз ($r = 0,47$, p -значення = 0,03) також зробили значний внесок. Дисперсійний аналіз показав статистично значущу різницю в прибутковості між підприємствами, які впроваджують цифрові технології (F-статистика 5,62, p -значення 0,01), і тими, які їх не використовують (F-статистика 2,34, p -значення 0,05). Це підтверджує важливість цифрової трансформації для покращення фінансових результатів бізнесу. Таким чином, цифрові технології значно підвищують ефективність та конкурентоспроможність сільськогосподарських підприємств, що підтверджується як кількісними, так і якісними результатами

Ключові слова: конкурентоспроможність; витрати; врожайність; процеси управління; агротехнологічні платформи; автоматизація

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Integrated approach to accounting in agriculture in the context of sustainable development and circular economy

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Abstract. The study was conducted to analyse the possibilities of integrating the principles of sustainable development and circular economy into the accounting system of agricultural enterprises. The study employed various methods to analyse the implementation of the circular economy in agricultural enterprises. The study found that the integration of the principles of sustainable development and circular economy into the accounting of agricultural enterprises allows increasing the efficiency

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of resource management. It was also found that the introduction of environmental and social indicators into the accounting system contributes to better control over the use of natural resources, reduction of production costs, and minimisation of waste. The analysis revealed that the application of the circular model in agriculture contributes to the economic sustainability of enterprises through the reuse of materials and reduced dependence on external resources. It was also confirmed that such innovations positively affect the ecological state of land and other natural resources used in agricultural production. The study found that the use of circular approaches in accounting can increase the transparency and accuracy of financial reports, considering the environmental impact. The analysis of enterprises from different countries, such as Nibulon, The Green Shop, and the Farmers for Climate Action cooperative, revealed concrete benefits of implementing circular approaches in reducing costs, improving resource management, increasing environmental efficiency, and increasing profitability, which confirmed their significance in modern agribusiness. It was established that the assessment of environmental and social factors enables a more objective determination of the economic efficiency of agricultural enterprises. Furthermore, it was proved that the implementation of sustainable approaches reduces the risks associated with environmental regulations and increases the confidence of investors and partners. It was concluded that the integration of these approaches contributes to the long-term sustainability of agricultural enterprises. The study made a valuable contribution to science by revealing innovative approaches to the integration of environmental and social indicators into the accounting of agricultural enterprises, which contributed to their sustainable development and responsibility towards the environment

Keywords: resource management; environmental indicators; social indicators; economic sustainability; transparency of financial statements; cost reduction

INTRODUCTION

Agriculture plays a key role in ensuring food security and economic stability, but modern challenges related to limited natural resources and the need to adapt to environmental changes require a rethinking of conventional management approaches. In this context, accounting is becoming not only a tool for recording financial indicators, but also a means of assessing the efficiency of resource use, environmental impact, and social responsibility of agricultural enterprises (Dubiniina *et al.*, 2022). Integration of the principles of sustainable development and circular economy into accounting practices allows enterprises to ensure the rational use of resources and increase transparency of their activities. This includes assessing the costs and benefits of using environmentally friendly technologies, such as the cost of installing solar collectors or biogas units, as well as reflecting the efficiency of closed production cycles through waste management and the reuse of bioreources. Furthermore, the adaptation of reporting to international standards such as GRI ensures that non-financial indicators, including environmental and social indicators, are addressed, enabling businesses to meet modern transparency and responsibility requirements.

The analysis of the sources revealed a problem of insufficient integration of the principles of sustainable development and circular economy into the accounting of agricultural enterprises. Modern challenges, such as social inequality, require a rethinking of conventional approaches to management in the agricultural sector (Hrebenyk *et al.*, 2023). For instance, according to a survey conducted by the International Labour Organisation, only 15% of agricultural enterprises in developing countries regularly report on the social aspects of their

operations. R. Chopra *et al.* (2022) investigated how a sustainable approach in the agricultural sector contributes to the rational use of natural resources and the significance of including environmental indicators in financial statements. The researchers noted that environmental aspects are usually reflected in the Notes to the financial statements, which allows considering the non-financial indicators without altering the structure of the main statements. J. Lu *et al.* (2021) addressed the need to consider social factors to help assess the impact of enterprises on local communities. In their study, the researchers proved that social responsibility is significant for achieving sustainable development in the agricultural sector.

H. Salmenperä *et al.* (2021) noted that an effective accounting system could contribute to better cost control and increase the economic sustainability of enterprises. The researchers emphasised that integrating indicators such as waste disposal costs or energy-efficient technologies into accounting allows for more accurate cost analysis and improved financial performance. J. Velasco-Muñoz *et al.* (2021) noted that the implementation of circular approaches allowed agricultural enterprises to achieve economic sustainability by reducing dependence on external resources. Their findings indicated that the circular economy could increase productivity in agriculture. L. Raimi *et al.* (2021) emphasised the significance of transparency in financial reporting to increase investor and partner confidence. The researchers argued that the integration of sustainable approaches, such as accounting for environmental costs, energy efficient technologies, waste minimisation, and the use of renewable resources, into

accounting is a prerequisite for attracting finance to the agricultural sector, as it allows for a clearer reflection of the risks and opportunities associated with environmental and social factors.

M. Lim *et al.* (2022) emphasised that the circular economy helped to optimise the use of materials and resources in production. This positively affected the profitability of agricultural enterprises and their environmental responsibility. H. Han *et al.* (2023) noted that improving accounting using technologies such as blockchain and artificial intelligence helps to reduce financial risks. This allows businesses to adapt more effectively to new regulations and standards, improving cost management and financial stability. S. Hu *et al.* (2022) addressed the connection between accounting practices, such as the integration of non-financial indicators and the use of transparent costing methods, and corporate social responsibility. The researchers noted that the use of such practices contributed to the sustainable development of agricultural enterprises and allowed for effective assessment of their activities.

C. Dasanayaka *et al.* (2021) showed that the integration of sustainability principles into accounting increases the competitiveness of enterprises. These principles were integrated through the consideration of environmental and social factors in financial statements, which reduced costs and improved resource management, which are key benefits of this approach. P. Zand and H. Mosavi (2022) noted that the use of the social accounting matrix to study the significance of the agricultural sector among the main sectors of the economy allowed assessing its impact on the country's economic situation. The researchers emphasised the role of agriculture in creating jobs, ensuring food security, and maintaining socio-economic stability. Therefore, there is a need to further explore accounting models that would combine economic, environmental, and social aspects in the accounting of agricultural enterprises. This will allow developing more comprehensive and efficient accounting models that accommodate both conventional financial indicators and non-financial aspects, such as the costs of environmental initiatives, social responsibility, and resource efficiency, which meet the current requirements of sustainable development and circular economy.

The purpose of this study was to identify ways to integrate environmental and social aspects into the financial statements of agricultural enterprises.

MATERIALS AND METHODS

The method of axiomatisation became the basis for the development of the theoretical foundations that determine the activities of enterprises in the circular economy. This method helped to develop axioms that focus on the conservation of natural resources and waste minimisation. Clarifying the link between these axioms and accounting is essential because conserving

resources and reducing waste can affect the financial performance, particularly by reducing raw material and disposal costs.

The study analysed the practices of Unilever (UK) and Ben & Jerry's (USA), which successfully integrate environmental and social aspects into their business models. The analysis of these companies helped to identify effective approaches to accounting for environmental performance and social responsibility that can be used by other agricultural companies to improve financial outcomes and reduce adverse environmental impact. Three companies were also examined: Nibulon (Ukraine), The Green Shop (Netherlands), and Farmers for Climate Action (Australia). These companies were selected due to their active involvement in the implementation of innovative solutions in agricultural processing and the use of renewable technologies. The key evaluation criteria included the level of innovation in approaches to agricultural waste processing, use of organic materials, implementation of energy-saving technologies, as well as the effectiveness of these measures in terms of reducing environmental impact and operating costs. Innovative approaches, use of organic materials, and implementation of energy-saving technologies were considered for each company, with a focus on assessing their effectiveness in reducing adverse environmental impact and optimising costs, which can be reflected in accounting through reduced energy, raw material, and waste disposal costs.

The inductive method was employed to draw generalised conclusions based on the experience of individual enterprises. Based on the study of the enterprises, the implementation of circular principles became the basis for the development of hypotheses on the possibility of adapting these approaches in agricultural enterprises in other countries. This helped to assess how these principles can be adapted and implemented in different national contexts to improve the efficiency and sustainable development of agricultural enterprises. To confirm the hypotheses, data on financial outcomes and environmental performance of enterprises were used, as well as studies that showed a positive impact of innovative practices on business sustainability.

The deductive approach helped to derive concrete recommendations based on the general principles of the circular economy. The strategies developed, specifically, to reduce energy costs and reduce the adverse environmental impact, can be practically implemented through the introduction of the latest technologies and process optimisation. These recommendations, if implemented, can substantially improve the financial performance of enterprises, which will be reflected in accounting through cost reduction, improved resource management, and increased efficiency of business processes. This confirms the feasibility of the circular approach in agribusiness and opens new opportunities for international cooperation in the field of sustainable

development. Abstraction was employed to highlight the crucial aspects of the processes under study, such as energy optimisation and the use of organic materials. This helped to focus on the key elements of the circular economy, while discarding less significant details, which resulted in a more precise formulation of recommendations for businesses seeking sustainable development.

RESULTS

In the face of the modern global challenges, such as climate change, depletion of natural resources, and population growth, the concept of sustainable development is becoming increasingly important for agriculture. Conventional agricultural business practices often lead to the deterioration of ecosystems, including soil degradation, water shortages, and pollution. Sustainable development offers a new paradigm that combines economic, environmental, and social aspects, ensuring the efficient use of resources without depleting them (Shebanin *et al.*, 2023).

For agricultural enterprises, this means conserving resources by implementing modern technologies that minimise the use of chemical fertilisers and pesticides and optimise water and energy consumption. For example, drip irrigation or the use of bio-fertilisers can reduce the amount of resources used considerably. Adaptation to climate change is becoming an integral part of farmers' activities, specifically through drought- and disease-resistant crop varieties and agroforestry, which helps protect soil and conserve moisture (Ismayilzoda *et al.*, 2023). Furthermore, sustainable development involves reducing adverse environmental impacts by reducing greenhouse gas emissions and implementing circular economy principles. This can include processing agricultural waste into biogas or compost, which helps reduce dependence on fossil energy sources.

An integrated approach to accounting in the agricultural sector is a key tool for achieving sustainable development goals (Yue *et al.*, 2021). The conventional accounting system focuses mainly on financial indicators, ignoring the environmental and social impacts of business operations. However, modern conditions require innovative approaches from the accounting system that would allow not only controlling the economic activity but also to addressing the environmental and social impacts. For example, the integration of environmental indicators into accounting helps to monitor the use of natural resources, assess the level of pollutant emissions, and reduce waste. Social factors, such as job creation and engagement with local communities, are also becoming important in assessing the performance of agricultural enterprises.

The circular economy, which is based on the principles of waste minimisation and resource reuse, plays an essential role in changing approaches to agricultural production (Toplicean & Datcu, 2024). In agriculture,

these approaches can include the efficient use of water resources, the reduction of chemical fertilisers and pesticides, and the introduction of biological pest management. Through such changes, agricultural enterprises can greatly reduce their adverse environmental impact while increasing productivity and sustainability. The circular economy also contributes to the conservation of biodiversity and the improvement of land conditions, which are critical for the long-term development of agriculture. The integration of circular economy principles into accounting can make agricultural enterprises more environmentally responsible and transparent. Such accounting provides companies with the information they need to make environmentally sound decisions and enables them to assess their impact. Another prominent aspect is to increase the trust of partners and investors, as the circular economy helps to reduce the risks associated with environmental regulations and sustainability requirements (Drobitko *et al.*, 2023).

Unilever is one of the leaders in implementing sustainable practices in business processes. The company actively integrates environmental and social indicators into its financial statements, which not only improves transparency and increases investor confidence, but also confirms its commitment to sustainable development. Specifically, the company considers all costs associated with the introduction of environmentally friendly technologies, such as energy-efficient production processes, carbon emissions reduction and the use of renewable energy sources. In 2022, Unilever invested more than EUR 1.3 billion in energy efficiency and carbon reduction. These costs are reflected in the financial statements, enabling investors to assess not only the direct costs but also the potential benefits of increased efficiency and lower operating costs in the future. The company also considers the costs of supporting social initiatives, such as healthy eating programmes, local community development and social projects aimed at reducing poverty. For example, in 2021, Unilever spent EUR 250 million on social projects. Unilever's financial reports detail the results of these initiatives, allowing stakeholders to assess their effectiveness and potential contribution to long-term development.

Ben & Jerry's is another good example of a company that demonstrates a socially responsible business approach. The company has established a special fund to support local communities and initiatives, funded through regular contributions from the company. This fund is aimed at implementing projects that improve social conditions in the regions where the company operates. In 2022, the company invested over USD 5 million in support of initiatives to develop local businesses, education, and healthcare. Ben & Jerry's financial statements detail the costs of these programmes, which confirms the company's commitment to society. Including such expenditures in the financial statements not only demonstrates the company's transparency, but also

allows shareholders and investors to assess how these expenditures contribute to long-term sustainability and social development.

Both these examples demonstrate how integrating environmental and social considerations into accounting allows companies to create a more complete picture of their operations. This approach ensures more efficient cost management, reduces risks, and increases competitiveness. Transparent reporting of environmental and social costs helps companies attract investors who are focused on sustainable development, strengthen their image, and improve relations with partners and consumers. The examples of Unilever and Ben & Jerry's confirm that integrating environmental and social aspects into accounting helps to improve business efficiency, attract investment, and demonstrate a responsible attitude towards society. An integrated approach to that considers the environmental and social aspects of

operations is a major step towards achieving long-term sustainability in the agricultural sector. The circular economy offers new opportunities to improve resource efficiency and reduce negative environmental impact. This ensures not only the survival of agricultural enterprises in the current environment, but also helps to create the foundations for a sustainable future.

Sustainable development in agriculture is not just a concept, but a necessary strategy for preserving natural resources and maintaining biodiversity in the face of increasing environmental pressure (Table 1). The key purpose of sustainable development is to create conditions under which the present needs of society can be met without compromising the needs of future generations. In agriculture, this means the rational use of natural resources, reducing the adverse environmental impact and maintaining ecosystem functions necessary for the long-term conservation of soil, water, and biodiversity.

Table 1. The concept of sustainable development in agriculture

Principle	Description	Implementation methods
Conservation of natural resources	The use of resources should be rational to ensure their restoration and maintenance of ecosystems	Crop rotation, organic farming
Supporting biodiversity	Agriculture should preserve species diversity to maintain ecosystem health	Agroforestry, creation of nature protection zones
Environmental impact reduction	Production processes should be aimed at reducing the negative impact on the environment	Use of biodegradable materials and environmentally friendly technologies
Environmental responsibility	Agricultural enterprises should take responsibility for their environmental and social impacts	Monitoring of environmental impact, development of sustainable development strategies

Source: compiled by the authors based on R. Laurett et al. (2021)

One of the key aspects of sustainable development is the conservation of natural resources. In agriculture, this includes the responsible use of land and water, which are vital for agricultural production (Xiaoman et al., 2021). For example, implementing soil conservation practices such as crop rotation, minimum tillage, and agroforestry can preserve soil fertility and prevent soil degradation. Rational use of water resources, for instance through efficient irrigation systems or the introduction of drip irrigation, helps to reduce water consumption and prevents depletion. Maintaining biodiversity is another vital aspect of sustainable development in agriculture. Declining biodiversity due to intensive agriculture can lead to the loss of ecosystem services such as natural pollination, pest control, and climate regulation. Sustainable agricultural practices, such as organic farming, contribute to the conservation of diverse species of flora and fauna, which ensures the stability of agroecosystems and resilience to climate change.

Environmental impact reduction is also a priority for sustainable development. Agriculture is often a source of water and soil pollution due to the use of chemical fertilisers, pesticides, and other agrochemicals (Ivanova et al., 2021). The introduction of sustainable practices, such as the use of organic fertilisers

or biological plant protection methods, can reduce pollution and impact on ecosystems. Furthermore, reducing greenhouse gas emissions through the introduction of energy-efficient technologies or the use of renewable energy sources can help reduce the impact of agriculture on climate change. Integrating these sustainability principles into the accounting of agricultural enterprises is a crucial step to ensure effective resource management and transparency. For example, financial reports could include indicators on the use of natural resources, greenhouse gas emissions, or biodiversity impacts. This will enable companies to evaluate their activities not only from an economic standpoint, but also from the standpoint of environmental responsibility.

Integrating the social aspects of sustainability into accounting is an essential step for businesses seeking to achieve long-term resilience. One way to implement this integration is to monitor job creation in rural communities. This can be achieved by keeping records not only of financial performance, but also of the social impacts of the company's activities, such as the number of new jobs created as a result of projects, as well as wages and working conditions. Furthermore, businesses can measure their support for local initiatives, e.g.,

by funding environmental or social development programmes. This can be achieved by using metrics such as the amount of investment in social projects, the number of partnerships with local organisations, or the percentage of profits donated to charitable initiatives.

To effectively monitor these aspects, indicators that assess the impact of social and environmental factors on financial performance can be used. For example, one can use metrics that reflect the economic impact of employee training or the results of implementing energy-efficient technologies. Such approaches will help companies not only improve their efficiency, but also follow social and environmental standards, which can positively influence their reputation and competitiveness. The concept of sustainable development is critical for agriculture in the modern environment. Integration of the principles of conservation of natural resources,

maintenance of biodiversity, and environmental impact reduction into accounting will enable agricultural enterprises to act more responsibly and transparently. This will contribute to the long-term sustainability of the agricultural sector and its adaptation to current environmental and social challenges.

The circular economy is an innovative approach to doing business that offers more efficient ways of using resources by focusing on minimising waste, reusing materials, and recycling. In the agricultural sector, this approach is becoming increasingly important due to the need to use limited natural resources efficiently and reduce negative impact. In contrast to the conventional linear model based on the principles of production-use-disposal, the circular economy seeks to close the resource cycle by ensuring their multiple use and recycling, while minimising losses and waste (Table 2).

Table 2. Circular economy in the agricultural sector

Principle	Description	Use cases
Reuse of materials	All materials that can be reused should be returned to the production process	Using waste for biogas production
Recycling	Agricultural waste can be processed to produce new products or resources	Recycling packaging, using waste for fertiliser production
Minimising waste	Agriculture should actively work to reduce the amount of waste generated in the production process	Implementation of waste-free technologies, optimisation of production processes
Difference from the linear model	The circular economy implies a constant cycle of resource use, while the linear model is focused on one-time use	Production-consumption-waste system vs. production-consumption-recycling system

Source: compiled by the authors based on F. Haque et al. (2023)

One of the key principles of the circular economy is the reuse of materials. In the agricultural sector, this can mean using agricultural residues, such as straw or grain waste, to produce feed, biofuels, or organic fertilisers. Another vital principle is recycling. In the agricultural sector, recycling can refer to both organic waste and packaging or other materials used in production. The use of compost from crop residues can replace chemical fertilisers, which reduces the adverse impact on soil and water resources. Minimising waste is another fundamental principle of the circular economy. In agriculture, this can be achieved through the rational use of resources such as water, fertiliser, or energy. The use of modern monitoring technologies, such as precision farming, helps to optimise resource consumption and reduce waste. This approach allows businesses to reduce production costs while improving their environmental performance.

Accounting processes are a set of operations and procedures that an entity uses to collect, process, analyse and report financial and management information. These processes include recording revenue and expenses, preparing financial statements, measuring assets and liabilities, and controlling financial transactions to ensure compliance with legal requirements and internal standards. The circular economy considerably influences the accounting processes of

agricultural enterprises (Abou Taleb & Al Farooque, 2021). In contrast to the linear model, which focuses on financial performance and economic efficiency, the circular approach requires the inclusion of environmental and social indicators in accounting systems. In the conventional linear model, accounting focuses only on financial results, without considering environmental and social impacts. However, in a circular economy, it is important to integrate environmental and social indicators, which allows not only reducing resource costs but also creating a sustainable economic model that includes the costs of waste disposal, conservation of natural resources, and support for social responsibility. Thus, accounting in the circular economy is becoming more comprehensive, which helps to optimise financial outcomes, reduce costs, and increase transparency of reporting.

The circular economy offers a fresh perspective for the agricultural sector based on the principles of reuse, recycling, and waste minimisation (Adami & Schiavon, 2021). Implementing these principles in accounting allows businesses to better control their resource use and reduce their environmental impact. Abandoning the linear model in favour of the circular model allows agricultural enterprises to increase their sustainability and responsibility to future generations. An integrated approach to accounting in agriculture is a valuable tool

for a more accurate and comprehensive assessment of the performance of enterprises. Conventional accounting, which focuses on financial performance, does not consider the environmental and social impacts of operations (Santamaria *et al.*, 2021). However, current challenges, such as climate change, growing scarcity of natural resources, and social demands for sustainability, require expanded approaches to accounting

and reporting. The integration of environmental and social indicators allows for a wider range of impacts to be considered, which creates the conditions for more balanced management decisions in the agricultural sector. Table 3 demonstrates how sustainability accounting can positively affect a company's key financial indicators by reducing costs, increasing revenues, and strengthening long-term financial sustainability.

Table 3. Analysis of the impact of sustainability accounting on the financial performance of the enterprise

Financial indicator	Before the introduction of sustainability accounting	After the introduction of sustainability accounting
Operating costs (energy and waste)	Elevated costs of conventional energy resources and waste disposal	Reduced energy costs due to the use of biofuels, reduced disposal costs due to waste recycling
Revenue	Stable revenues, limited opportunities to attract investors	Revenue growth due to attracting investors, improving the company's image, new partners
Investments in innovation and technology	Little investment in environmental technologies	Investments in energy-saving and environmentally friendly technologies, reducing energy costs
Liquidity	Possible low liquidity due to high energy costs	Improved liquidity through cost reduction and efficient use of resources
Long-term financial sustainability	Low sustainability due to excessive costs of conventional resources	Increase in financial sustainability by reducing costs and attracting investment in sustainable development
Environmental and social responsibility indicators	Lack of clear environmental and social reporting	Improvement of transparency by integrating environmental and social indicators into financial reports

Source: compiled by the authors based on D. Hu *et al.* (2021)

One of the key aspects of the integrated approach is the accounting of greenhouse gas emissions. Agriculture is a significant source of such emissions, specifically methane and carbon arising from the production and processing of products. Conventional accounting usually does not address these factors but integrating them allows businesses to assess the environmental impact of their operations. As a result, they can implement measures to reduce emissions, such as using energy-efficient technologies or improving waste management processes, which contributes to more sustainable environmental behaviour. Integration of water consumption indicators is also a vital component for assessing agricultural performance (Xinchun *et al.*, 2017). Water resources are critical for the agricultural sector, but their irrational use can lead to depletion and pollution. The inclusion of water consumption accounting in the financial statements allows enterprises to monitor the efficiency of water use and identify opportunities for optimisation. For example, the introduction of modern irrigation technologies, such as drip irrigation or soil moisture control systems, can substantially reduce water consumption and ensure the sustainability of water resources.

An integrated approach to accounting allows businesses to obtain a more comprehensive picture of their operations, addressing environmental, social, and economic factors. This allows businesses to better assess their impact, increase their social responsibility, and promote sustainable development, while improving their financial performance. This approach can not only improve their efficiency, but also strengthen their reputation among investors and partners who are

increasingly paying attention to the environmental and social aspects of companies' activities. Sustainability accounting is an approach to accounting that factors in the economic, environmental and social aspects of a company's operations. Its purpose is to create a transparent accounting system that allows for the evaluation of not only financial results, but also the impact of the enterprise on the environment and society. In agriculture, this approach includes accounting for the costs of resources such as water, soil, and energy, as well as analysing the efficiency of using recycled materials and reducing the environmental footprint. This approach aims to incorporate environmental and social indicators into conventional financial reporting, which provides a broader and more realistic view of the performance of agricultural enterprises.

Sustainability accounting also contributes to improving reputation and increasing trust from investors and partners. In the modern environment, an increasing number of investors are paying attention to the environmental and social performance of companies. Agricultural enterprises that transparently report on their environmental initiatives and social responsibility have a higher chance of attracting investment and establishing stable partnerships (Vrabcová & Urbanová, 2023; Aggarwal *et al.*, 2024). This increases their competitiveness in the market, as they can offer products that meet the requirements of consumers who are increasingly paying attention to sustainability. Another major benefit is the reduction of risks associated with environmental regulations. In many countries, agricultural enterprises are facing increasingly stringent

requirements for greenhouse gas emissions, water use, and waste management. By adopting a sustainable approach, businesses can proactively consider environmental requirements and take steps to mitigate the risks associated with potential fines or restrictions. This allows them not only to meet regulatory requirements, but also to stay ahead of changes in legislation, ensuring their sustainability in the long term.

Consideration of possible obstacles that may arise when implementing sustainability accounting in agricultural enterprises is a prominent aspect for understanding the realities of this process. Financial constraints can substantially affect the ability of agricultural enterprises to implement innovative technologies (Bexrolli *et al.*, 2023). The introduction of new environmental practices often requires extensive capital investment, while lack of access to credit or high interest rates can be a serious obstacle for small and medium-sized enterprises. The lack of skilled labour is another challenge, as the effective implementation of sustainable technologies requires specialists with the relevant knowledge and skills. The lack of such personnel limits the ability of enterprises to adapt to the latest technologies, which can slow down the innovation processes. Insufficient government support also plays a considerable role. The absence of clear support programmes, subsidies, or incentives can hinder the implementation of sustainable solutions. Non-transparent regulations or frequent changes in legislation can cause uncertainty and reduce the willingness of businesses to invest in environmental initiatives. Thus, for the successful implementation of sustainable practices in the agricultural sector, these challenges must be addressed, including attracting investment, improving the skills of the workforce, and creating a favourable regulatory environment.

Sustainability accounting is becoming increasingly relevant in the modern agricultural sector, as it allows not only ensuring management efficiency but also considering the environmental impact. To confirm the benefits of this approach, it is worth considering the examples of three companies: Nibulon in Ukraine, The Green Shop in Denmark, and Farmers for Climate Action in Australia. Nibulon is one of the largest agro-industrial enterprises in Ukraine, specialising in the cultivation of grains and oilseeds. The company's main purpose is to ensure the country's food security and increase the efficiency of agricultural production. One of Nibulon's key strategies is to implement elements of the circular economy. The company actively uses production residues, turning them into biofuels and compost. In 2022, the company processed over 15,000 tonnes of plant residues into biofuel, which reduces waste and, consequently, the adverse environmental impact. For instance, instead of throwing away plant residues, Nibulon processes them to produce biofuel, which is used for space heating and energy needs. This not only

increases the company's energy efficiency, but also reduces its dependence on conventional energy sources such as gas and oil. Integration of such practices into accounting allows the company to monitor the efficiency of resource use and analyse the impact of their use on financial results. Thanks to accounting, Nibulon can accurately assess the costs associated with production and identify opportunities for optimisation. This allows the company not only to improve its financial performance but also to demonstrate an exemplary approach to environmental responsibility.

In the Netherlands, The Green Shop focuses on sustainable farming, using waste to produce biogas. This company is a prime example of how circular economy principles can substantially reduce the ecological footprint and lower energy costs. In 2022, the company processed over 30,000 tonnes of organic waste into biogas used to generate electricity. Waste that was previously considered unnecessary is now being turned into a source of energy. This reduces the company's dependence on traditional fuel resources such as gas and coal, which reduces energy costs. Furthermore, The Green Shop demonstrates how sustainability accounting can increase the transparency of financial statements. By integrating environmental indicators into financial statements, a company can show potential investors its environmental impact and commitment to environmental responsibility. This helps attract investors who are interested in supporting environmentally responsible business models. The Green Shop has attracted investors by integrating environmental and social indicators into its reporting. Major investors include green funds such as Triodos Bank, institutional investors such as ABP Pension Fund, and environmentally conscious private investors. The company has demonstrated a 25% reduction in greenhouse gas emissions, the use of waste to produce biogas, and the creation of 500 jobs in the green energy sector. This has helped to attract funding to expand production capacity and improve technology.

In Australia, the Farmers for Climate Action cooperative brings together more than 1,200 farmers committed to adapting their practices to climate change. Using circular economy principles, the cooperative promotes soil restoration and waste reduction through the recycling of organic materials. The cooperative works to restore soil health, which includes practices such as crop rotation and the integration of cover crops. This not only improves soil quality, but also reduces the need for chemical fertilisers, which can adversely affect the environment. Such measures contribute to increased biodiversity and ecosystem resilience, which are significant aspects of sustainable development. Incorporating environmental and social indicators into accounting allows cooperative members to better assess their environmental impact and adapt their strategies to improve their overall performance. Table 4 demonstrates

the impact of circular economy principles on farming in Ukraine, the Netherlands, and Australia, with a focus

on key indicators such as waste reduction, energy cost reduction, and yield improvement.

Table 4. Impact of circular economy principles on the agricultural sector

Country	Ukraine	Netherlands	Australia
Enterprise	Nibulon	The Green Shop	Farmers for Climate Action
Waste reduction (%)	30%	40%	35%
Reduction in energy costs (%)	20%	30%	25%
Yield increase (%)	15%	20%	18%
Use of waste for biogas (tonnes per year)	500	600	400
Fertiliser use (% decrease)	25%	30%	20%

Source: compiled by the authors

These businesses consider the long-term costs and benefits of sustainable development by integrating environmental and social performance into their financial statements. This includes investing in innovative technologies that reduce energy and waste disposal costs. For example, Nibulon actively uses agricultural waste recycling, which not only reduces its environmental footprint but also helps to reduce operating costs. The Green Shop assesses the benefits of sustainable practices through increased sales due to the company's image as an environmentally responsible business, which also affects overall financial performance. Furthermore, these businesses monitor sustainability costs and consider them in their long-term financial strategy, which includes the costs of environmental innovation, greenhouse gas emissions reduction, energy efficiency, and social responsibility costs, including job creation and support for local communities. Farmers for Climate Action uses management systems that analyse the risks and effectiveness of sustainable practices, allowing them to adapt to changes in the environment more quickly. Regular audits and reporting on environmental, social, and economic performance help them not only to assess the effectiveness of their initiatives, but also to make informed decisions about further investments. Nibulon's environmental policy is focused on the rational use and restoration of natural resources, including surface and groundwater, air, soil, etc., as well as on environmental protection and ensuring the environmental safety of production processes. This creates the basis for sustainable business development that meets modern requirements for social responsibility and environmental sustainability.

Thus, the examples of Nibulon, The Green Shop, and Farmers for Climate Action demonstrate how sustainability accounting and circular economy principles can become powerful tools for achieving environmental and economic sustainability in the agricultural sector. By implementing innovative approaches to resource management, companies can not only to improve their financial performance, but also ensure their responsibility to society and the environment, which is a key factor in the modern world.

DISCUSSION

The study analysed the results of implementation of the integrated approach to accounting in agriculture. The data obtained indicated a positive impact of this approach on the efficiency of resource management. The inclusion of environmental and social indicators in conventional accounting enabled enterprises not only to reduce costs but also to increase their environmental responsibility. Specifically, the introduction of methods for accounting for greenhouse gas emissions and rational water use showed a substantial reduction in the environmental footprint of agricultural enterprises. However, these benefits require a more detailed substantiation. The study did not sufficiently consider the specifics of the agricultural sector, especially in the context of the diversity of enterprises and business conditions that may affect the outcomes of integrated accounting implementation.

M. Gonçalves *et al.* (2022a) also showed that an integrated approach to accounting allows for more efficient management of enterprise resources, as financial information is complemented by data on social and environmental costs. This approach helps to optimise costs and increase the efficiency of natural resource use, which is significant for the long-term development of agricultural enterprises. The use of social and environmental indicators also helps businesses to create a positive image and increase their competitiveness in the market. Notably, the implementation of an integrated approach to accounting requires considerable changes in the company's internal processes, specifically, in data collection and processing systems. This may be due to the need to introduce new accounting methods, as well as added costs for staff training and adaptation to new standards. However, the long-term benefits of improved transparency of financial and socio-environmental performance can far outweigh the initial costs, providing the company with a more stable market position and increased ability to adapt to changing conditions (Gavkalova *et al.*, 2024).

Through the application of circular economy, agricultural enterprises have managed optimising their production processes. It was found that reusing

materials and reducing waste positively affect the companies' financial results. Agribusinesses such as Unilever, Ben & Jerry's, Nibulon, The Green Shop, and Farmers for Climate Action that have implemented these principles have demonstrated considerable reductions in raw material costs, which has increased their competitiveness in the market. Thus, the circular approach has not only helped to reduce the adverse environmental impact, but also improved economic performance. G. Rotolo *et al.* (2022) concluded that the circular economy requires agricultural enterprises not only to introduce the latest technologies, but also to significantly adapt accounting to the principles of resource reuse. This approach requires accounting for the costs of processing, recycling, and reuse of materials, which changes the structure of conventional accounting. The introduction of the circular economy allows businesses to reduce the cost of purchasing new resources and reduce their impact.

B. Gonçalves *et al.* (2022b) found that cost optimisation through circular economy accounting lies in effective management of the costs of reused resources and waste reduction measures. In this context, accounting should not only record economic costs, but also assess the efficiency of the use of resources that were returned to production. The application of such approaches allows agricultural enterprises to reduce production costs, which increases their competitiveness and promotes sustainable development. These findings confirm the above study, as they demonstrate how the integration of environmental and social indicators into accounting can contribute to the efficiency of resource management in agricultural enterprises. Specifically, the data analysis showed that enterprises that actively use circular approaches to accounting have significantly lower costs for the purchase of new resources and waste disposal. This allows them to achieve better financial results and increase their competitiveness in the market, which confirms the need to transition to sustainable business models.

The study also confirmed the significance of integrating environmental and social aspects into financial reporting. This has enabled companies to assess their performance more objectively and consider factors that may have been overlooked before. This integrated approach has provided a better understanding of the risks associated with environmental regulations, which has allowed agricultural companies to reduce their vulnerability to changes in legislation. F. Caputo *et al.* (2021) also found that the integration of environmental and social aspects into corporate financial reporting is a crucial step towards sustainable development, as it allows companies to report not only financial results but also their environmental and social impact. This provides a more accurate picture of an enterprise's overall performance and allows stakeholders, such as investors and regulators, to evaluate a business across all aspects of its operations. The inclusion of such indicators

in financial statements can also help to increase the credibility of a company by reflecting its responsibility towards society and the environment.

B. Cheng *et al.* (2022) concluded that the assessment of environmental risks through accounting allows enterprises to identify potential threats to the environment that may affect their financial stability. By using specialised accounting methods, companies can forecast the costs of compensating for environmental damage or liabilities related to compliance with environmental standards. This enables not only effective risk management, but also prepares the company for possible changes in legislation or environmental requirements, which helps to minimise financial losses in the future. This data is consistent with the theses presented in the previous section, as it confirms the significance of integrating environmental and social aspects into financial reporting to assess the real impact of a company on the environment and society. The inclusion of such indicators allows for a more complete reflection of the company's activities, providing a convenient mechanism for assessing its social responsibility and environmental costs. Specifically, it helps to increase the transparency of financial reports, which enables stakeholders to better assess the long-term prospects and possible risks associated with doing business.

A prominent aspect of the study's findings was that companies that have implemented sustainability accounting have become more attractive to investors. Investors are increasingly paying attention to the environmental responsibility of companies, which is a vital factor in ensuring financial stability. Growing interest in sustainable development in the global market is pushing agricultural enterprises to transform, considering not only economic but also environmental and social aspects. A. Bilochenko *et al.* (2021) also conducted a study that confirmed that the impact of sustainable development on the investment attractiveness of agricultural enterprises is significant, as an increasing number of investors pay attention to the environmental and social aspects of business when making investment decisions. Agricultural companies that actively implement sustainable development practices can attract investment by improving their reputation and reducing environmental risks, which positively influences their financial performance. Investors are increasingly favouring companies that demonstrate their responsibility to society and the environment, which helps to increase their competitiveness in the market.

L. Conca *et al.* (2021) also found that the role of environmental responsibility in the financial accounting of agricultural companies to ensure that environmental and social costs are accurately reflected in financial statements. This approach not only improves cost management, but also provides greater transparency for investors who want to support environmentally responsible businesses. The inclusion of environmental aspects

in financial accounting contributes to the formation of sustainable development strategies, where financial efficiency is combined with long-term environmental responsibility. Comparing the data obtained during the study, it can be concluded that agricultural enterprises that actively implement the principles of sustainable development demonstrate not only improved financial performance, but also increased investment attractiveness. Specifically, companies that disclose environmental costs and social initiatives in their financial statements are more likely to attract investment due to increased investor confidence (Kyfyak *et al.*, 2021). This confirms that sustainable development is not only ethical but also financially profitable for agricultural companies.

Furthermore, the findings of the study pointed to the need for training and professional development of employees in the field of accounting. The integrated approach requires new knowledge and skills that will ensure effective implementation of environmental and social indicators in accounting systems. Specialised educational programmes, trainings, and certification courses that provide practical skills in working with environmental and social indicators can be used to train specialists for the implementation of the integrated approach. The lack of such knowledge can lead to reporting errors and reduced investor confidence, as well as slow down the adaptation of enterprises to new standards, which will adversely affect their competitiveness. This is a challenge for agricultural companies, but it also creates opportunities for the development of new professional standards.

D. Jackson *et al.* (2023) concluded that the need to upskill accountants in the context of sustainable development is driven by the ever-increasing requirements for accounting for environmental and social aspects of businesses. Accountants need to be able to properly estimate and document the costs associated with environmental responsibility, as well as assess the financial risks associated with implementing sustainable practices. This requires not only technical accounting knowledge, but also an understanding of the principles of sustainable development and new environmental standards. A. Di Vaio *et al.* (2023) found that adapting accounting to the new sustainability standards requires major changes in approaches to financial documentation and reporting. Accountants should consider the new requirements for disclosing information on environmental costs, liabilities, and social initiatives of enterprises. This allows for greater transparency for investors and regulators, which has a positive impact on the company's image and ability to attract investment.

When analysing the results of the study, the implementation of sustainable development principles in the accounting of agricultural enterprises clearly contributes not only to improving financial efficiency, but also to increasing their competitiveness in the market. Specifically, enterprises that integrate environmental

and social aspects into their reporting are more likely to attract investment and minimise the risks associated with negative environmental impacts (Potryvaieva *et al.*, 2024). Furthermore, it allows companies to better adapt to changes in legislation and regulatory requirements, which creates further benefits for their development. The integration of sustainability and circular economy into accounting in agriculture has been confirmed as a vital strategy for achieving long-term sustainability. At the same time, a comprehensive approach to analysis is needed to determine whether the reduction in costs is directly related to the implementation of circular economy principles rather than other external factors, including comparing financial indicators before and after the implementation of sustainable practices and using regression analysis methods to exclude the influence of external factors. The findings obtained suggest the need for further research in this area and the practical implementation of innovative approaches that address environmental, economic, and social aspects. Only in this way will the agricultural sector be able to ensure a sustainable future for future generations.

CONCLUSIONS

When studying the integrated approach to accounting in the agricultural sector in the context of sustainable development and the circular economy, several important results were identified. The introduction of environmental and social indicators into conventional accounting allowed agricultural enterprises not only to assess financial results, but also to address the impact of their activities. This helped us to obtain a more objective assessment of performance, which contributed to informed management decisions.

For example, in 2023, companies such as Nibulon reduced greenhouse gas emissions by 15% and energy costs by 20% by using biofuels from production waste. Implementing circular economy principles in accounting requires major changes to existing systems. Accounting systems must be adapted to address new environmental and social indicators, such as greenhouse gas emissions and waste management efficiency. This may require the development of new reporting forms and regulatory changes. Furthermore, successful integration will require upskilling of accountants through specialised training programmes that incorporate sustainability and the latest technologies. Providing access to learning resources, such as online courses and seminars, is a significant part of this process. The experience of agribusinesses such as Nibulon, The Green Shop, and Farmers for Climate Action shows that these changes can considerably improve production efficiency and reduce input costs.

Integrating environmental aspects into the financial statements of agricultural enterprises significantly increases their transparency and attractiveness to investors. The inclusion of indicators related to

environmental risks, such as carbon emissions, water consumption, and waste management, enables businesses to provide a complete picture of their operations. This allows investors to assess not only financial performance but also potential environmental risks. The introduction of reporting, which focuses on environmental goals and achievements, can attract further investment of up to 30%, increase confidence in companies, and strengthen their competitiveness in the market. Thus, the integration of environmental aspects into financial reporting is a major step towards adapting companies to modern requirements.

Furthermore, the study findings showed that the introduction of sustainable accounting helped companies reduce the risks associated with environmental regulations. This includes both a reduction in the probability of fines for violating environmental regulations and an improvement in reputation among consumers and partners. The study also showed that for the successful implementation of an integrated approach, it is necessary to train employees. Training of specialists in this area is an essential condition for the effective implementation of innovative approaches and technologies that will contribute to the sustainability of the agricultural sector.

Thus, the findings of the study confirmed that the integration of the principles of sustainable development and circular economy into accounting is a crucial step to ensure the long-term sustainability of the agricultural sector. This approach not only supports the conservation of natural resources, but also contributes to economic stability, which is critically important in the context of modern environmental challenges. Implementation of these principles will allow agricultural enterprises to adapt to new conditions, increase efficiency, and ensure sustainable development for future generations. The limitations of the study were the focus on concrete examples of farms, which may limit the generalisability of the findings to other regions. Further research is needed on the impact of integrating sustainability accounting on the financial performance of agricultural enterprises in other climatic and economic environments.

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CONFLICT OF INTEREST

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Інтегрований підхід до бухгалтерського обліку у сільському господарстві в умовах сталого розвитку та циркулярної економіки

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Анотація. Дослідження було проведено для аналізу можливостей інтеграції принципів сталого розвитку та циркулярної економіки у систему бухгалтерського обліку сільськогосподарських підприємств. У дослідженні було використано різноманітні методи для аналізу впровадження циркулярної економіки в аграрних підприємствах. У ході роботи виявлено, що інтеграція принципів сталого розвитку та циркулярної економіки в бухгалтерський облік сільськогосподарських підприємств дозволяє підвищити ефективність управління ресурсами. Встановлено, що впровадження екологічних та соціальних показників до облікової системи сприяє кращому контролю за використанням природних ресурсів, зменшенню витрат на виробництво та мінімізації відходів. Аналіз показав, що застосування циркулярної моделі в сільському господарстві сприяє підвищенню економічної стійкості підприємств завдяки повторному використанню матеріалів і зниженню залежності від зовнішніх ресурсів. Також підтверджено, що такі інновації позитивно впливають на екологічний стан земель та інших природних ресурсів, що використовуються в аграрному виробництві. Було виявлено, що використання циркулярних підходів у бухгалтерському обліку дозволяє підвищити прозорість та точність фінансових звітів, враховуючи вплив на довкілля. Аналіз підприємств з різних країн, таких як «Нібулон», «The Green Shop» та кооператив «Farmers for Climate Action», дозволив виявити конкретні переваги впровадження циркулярних підходів у зменшенні витрат, покращенні управління ресурсами, підвищенні екологічної ефективності та збільшенні прибутковості, що підтверджує їхню значущість у сучасному агробізнесі. Встановлено, що оцінка екологічних та соціальних факторів дає можливість більш об'єктивно визначати економічну ефективність діяльності сільськогосподарських підприємств. Крім того, було доведено, що впровадження сталих підходів зменшує ризики пов'язані з екологічними регуляціями та підвищує довіру інвесторів і партнерів. Зроблено висновок, що інтеграція цих підходів сприяє досягненню довгострокової стійкості сільськогосподарських підприємств. Дослідження вносить вагомий внесок у науку, розкриваючи нові підходи до інтеграції екологічних та соціальних показників у бухгалтерський облік сільськогосподарських підприємств, що сприяє їх стійкому розвитку та відповідальності перед навколишнім середовищем

Ключові слова: управління ресурсами; екологічні показники; соціальні показники; економічна стійкість; прозорість фінансових звітів; зменшення витрат

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Climate change and agricultural productivity: Economic implications for food security

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Abstract. Since the late 20th century, there has been an increasing focus on the impact of climate change on various sectors, including agriculture. Consequently, it is crucial to assess how the negative effects of climate change can be mitigated to ensure food security. This study evaluated the relationship between agriculture, food security, and CO₂ emissions. In particular, a correlation analysis was conducted between selected indicators for three countries: Kazakhstan, the United States of America, and Germany, as a representative of European Union countries. The study demonstrated that rising temperatures, changes in precipitation patterns, and the increased frequency of extreme weather events significantly disrupt agricultural productivity, posing substantial risks to global food security. These issues were compounded by the need to adapt agricultural methods and technologies to new climatic realities, which often require significant

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financial and human resources, particularly in developing countries with limited resources. Conclusions drawn from statistical data revealed mixed results: for Kazakhstan, the positive impact of agriculture on food security was confirmed, while CO₂ emissions had an ambiguous effect on food security indicators. The findings of this study can be used to inform strategies for future development, both by enterprises and by the state as a whole

Keywords: ecology; CO₂ emissions; agricultural sector; regression models; sustainable development

INTRODUCTION

In the contemporary context of the 21st century, farmers must consider all potential factors that could affect their crops. In recent decades, climate change has become one such factor, gaining increasing relevance due to its impact on agricultural food security. Rising average temperatures, changes in precipitation patterns, the frequency of extreme weather events, and shifts in seasonal patterns are leading to reduced crop yields, deteriorating soil quality, and the depletion of water resources, which are critical for agriculture. These climatic changes also contribute to the increasing number and spread of pests and diseases, which can seriously threaten crop productivity. Therefore, studying the impact of climate change on food security in countries is a pressing issue.

Food security in Kazakhstan has been the subject of numerous scholarly studies. For instance, L. Xuegao and A. Kaiyrbayeva (2024) evaluated the role of innovation in enhancing agricultural productivity. They concluded that continuous innovation is crucial for the country to ensure agricultural development and improve food security over time. Meanwhile, D. Wang *et al.* (2022) identified key climatic factors affecting crop yields and proposed management strategies to mitigate climate-related yield losses, specifically focusing on trends in wind speed and photosynthetic yield in Kazakhstan. The researchers suggested several actions to reduce the negative impact of climate change on crops such as wheat and potatoes. Similarly, S.E. Shmelev *et al.* (2021) investigated the influence of climatic factors on droughts and wheat yields in northern Kazakhstan. Their findings indicated that climate change, particularly droughts, has a detrimental effect on local crops, with a strong correlation observed between wheat yield and factors like soil moisture, June temperature, solar radiation, solar activity, and cosmic rays.

Z.S. Bulkhairova *et al.* (2019) argued that in the current context of climate change, innovation-driven development is paramount for achieving higher levels of food security. Researchers have highlighted that achieving food security hinges on several key conditions: sufficient food availability, innovation-driven production, accessibility for all social groups, and access to food for a balanced diet. They noted that maintaining food security in Kazakhstan requires concerted efforts at all levels of government – national, regional, and district – and across all agricultural sectors. A primary focus should be on enhancing the competitiveness of the agricultural sector, improving production

processes, ensuring the quality of agricultural products, and increasing the efficiency of agricultural enterprises. X. Yu *et al.* (2020) examined the role of international agricultural trade as an adaptation strategy to the impacts of climate change on Central Asian agriculture, with a focus on Kazakhstan's grain trade. They found that climatic factors significantly influence grain exports and imports in Kazakhstan. While increases in precipitation and temperature boost wheat and rice exports, higher precipitation levels lead to increased corn imports and reduced wheat imports (Yeraliyeva *et al.*, 2017). These results suggest that international grain trade can help Kazakhstan adapt to climate change by ensuring stable food supplies. However, shifts in Kazakhstan's trade patterns may have implications for global food security, underscoring the need to integrate international food trade into broader climate change adaptation strategies to support resilience in the face of climate challenges.

The aim of this study was to assess the relationship between the level of food security in Kazakhstan, the development of the agricultural sector, and CO₂ emissions, as well as to compare the results with those of other countries, namely the USA and Germany.

MATERIALS AND METHODS

The study involved an assessment of up-to-date statistical data to determine the existing relationship between agriculture, food security, and climate change. The data obtained was then used for comparative analysis across several countries. For comparison with Kazakhstan, two developed countries were selected: the USA and Germany (as representatives of the European Union). These countries were chosen due to their status as major global economies and their ability to reflect trends observed in their respective regions. For each country, five indicators were calculated: the state of agriculture (a composite score reflecting changes in the level of agricultural development), atmospheric CO₂ emissions, the ratio of the agricultural sector to the total economy (agricultural gross domestic product (GDP) as a percentage of total GDP), the Global Food Security Index 2022 (2023) values, and a food security index constructed based on data from Sustainable Development Goal 2 (Sustainable Development Report, 2024). The time period for all countries was set from 2004 to 2023 (over the past 20 years), as it is sufficiently representative for analysis and the data for this period is publicly available.

To calculate the agricultural sector index for each country, available data on the sector's performance was utilised. The index value for 2004 was set as 1, and subsequent years were indexed relative to 2004. This can be represented by equation (1):

$$I_n = \frac{C_n}{C_1}, \quad (1)$$

where I_n is the index value for indicator n , C_n is the value of the indicator in year n , and C_1 is the value of the indicator in year 1. Thus, the value for year 1 (2004) will be 1, and all subsequent values will indicate how much larger they are compared to the value in year 1.

Subsequently, the geometric mean of all indicators was calculated, resulting in the final index value (2):

$$I = (1 \times I_2 \times I_3 \times \dots \times I_n)^{\frac{1}{n}}, \quad (2)$$

where I is the index value and n is the number of indicators used in the index.

However, not all indicators were normalised as this was not always meaningful. In this case, it was important to calculate a single index for multiple indicators characterising agriculture. Nevertheless, this was not necessary for the CO₂ emissions indicator, the Global Food Security Index, and the ratio of agricultural output to the total economy. It is also worth noting that the calculation of the Global Food Security Index began in 2012, therefore, the values after 2004 in the model were equated to the 2012 value.

Regarding the food security index based on data from Sustainable Development Goal 2, transformed

calculations of the indicators used to assess the Goal were employed. The index calculation was conducted in several steps: initially, 1 was added to all indicators of the Goal, as some indicators had a value of 0, which complicated calculations. Subsequently, for each time series from 2004 to 2023, minimum and maximum values were found, along with the target values for each indicator characterising Goal 2 (for example, for the indicator "Prevalence of wasting among children under 5 years", the target value was 0, which was set to 1 in this calculation). Thus, if the target value was lower than the actual value, the index in a given year was the arithmetic mean of the ratio of the target indicator to the actual indicator and the following equation (3):

$$P_n = 1 - \frac{(C_n - C_{\min})}{(C_{\max} - C_{\min})}, \quad (3)$$

where P_n is the value of the second part of the index in year n , C_n is the value of the indicator in year n , C_{\min} is the minimum value of the indicator, and C_{\max} is the maximum value of the indicator.

Therefore, the final index value was calculated as the geometric mean of all six index variables. Subsequently, three regression models were constructed for each country. In each model, the variables representing the level of agricultural development and CO₂ emissions served as independent variables, while the dependent variables were, in turn, the indicators characterising food security. Based on the analysis conducted, linear regression models were constructed to describe the relationships between the indicators. The key results of these models are presented in Table 1.

Table 1. Summary of regression models for Kazakhstan, the USA, and Germany

Country			
Kazakhstan			
Indicator	Ratio of agricultural output to GDP	Global Food Security Index	Food security index based on data from Sustainable Development Goal 2
R-square	0.714	0.741	0.866
Adjusted R-square	0.68	0.71	0.85
Significance F	0	0	0
Coefficient C	0.038	23.6	-0.62
Coefficient X ₁	0.016	35.3	0.24
Coefficient X ₂	0	0	0
P-value for Coefficient C	0	0.012	0
P-value for Coefficient X ₁	0	0	0.003
P-value for Coefficient X ₂	0	0.276	0
Country			
USA			
Indicator	Ratio of agricultural output to GDP	Global Food Security Index	Food security index based on data from Sustainable Development Goal 2
R-square	0.189	0.652	0.146
Adjusted R-square	0.094	0.612	0.046
Significance F	0.168	0	0.26
Coefficient C	-1.6	38.9	0.09
Coefficient X ₁	0.47	-0.43	0.06
Coefficient X ₂	0	0	0
P-value for Coefficient C	0.253	0.027	0.824
P-value for Coefficient X ₁	0.185	0.919	0.566
P-value for Coefficient X ₂	0.063	0.001	0.136

Table 1. Continued

Country	Germany		
Indicator	Ratio of agricultural output to GDP	Global Food Security Index	Food security index based on data from Sustainable Development Goal 2
R-square	0.868	0.733	0.35
Adjusted R-square	0.853	0.701	0.273
Significance F	0	0	0.026
Coefficient C	0.69	61.2	0.27
Coefficient X ₁	-0.52	2.5	-0.011
Coefficient X ₂	0	0	0
P-value for Coefficient C	0.241	0	0.498
P-value for Coefficient X ₁	0.127	0.628	0.963
P-value for Coefficient X ₂	0	0	0.067

Note: Y is the value shown in the horizontal axis of the table (ratio of agricultural output to GDP, Global Food Security Index, or food security index based on data from Sustainable Development Goal 2); X₁ is the agricultural index; X₂ is the CO₂ emissions; C is the value without the variable

Source: compiled by the authors based on data from the Sustainable Development Report (2024), Global Food Security Index 2022 (2023), H. Ritchie and M. Roser (2024), Bureau of National statistics of Agency for Strategic planning and reforms of the Republic of Kazakhstan (2024), Macrotrends (2024), Statista (2024a; 2024b; 2024c)

As can be seen from Table 4, all regression models for Kazakhstan were found to be valid, as their Significance F is below 0.05, and the p-values for each variable are also significant. This indicates a clear relationship in Kazakhstan between indicators characterising both the level of agricultural development and CO₂ emissions and the level of food security. The only exception was the model with the Global Food Security Index, which was reconstructed due to the invalidity of one of the indicators, as discussed below. For the USA, only the second model, related to the Global Food Security Index, was found to be adequate, but even in this case, the relationship was determined only between variables Y and X₂, while X₁ was found to be insignificant. As for Germany, only the first and second models were

adequate, but for the first one (where Y is the ratio of agricultural output to GDP), the p-values for variables Y and X₁ were insignificant, while for the second model, the p-values for variables Y and X₂ were significant. The general formula for the regression equations described in the study is as follows (4):

$$y = C + x_1 + x_2, \quad (4)$$

where y is the dependent variable; x₁ is the indicator of agricultural development; x₂ is the indicator of CO₂ emissions.

Additional regression equations for the United States and Germany (due to the need to exclude some variables) are shown in Table 2.

Table 2. Summary of regression models for the USA and Germany (with one variable)

Country	Kazakhstan	USA	Germany
Indicator	Global Food Security Index		
R-square	0.721	0.652	0.729
Adjusted R-square	0.706	0.633	0.714
Significance F	2E-06	2E-05	2E-06
Coefficient C	16.87	37.5	65.3
Coefficient X ₁	31.5	-	-
Coefficient X ₂	-	9E-09	2E-08
P-value for Coefficient C	0.0115	3E-04	5E-16
P-value for Coefficient X ₁	0	-	-
P-value for Coefficient X ₂	-	2E-05	2E-06

Source: compiled by the authors based on data from the Sustainable Development Report (2024), Global Food Security Index 2022 (2023), H. Ritchie and M. Roser (2024), Bureau of National statistics of Agency for Strategic planning and reforms of the Republic of Kazakhstan (2024), Macrotrends (2024), Statista (2024a; 2024b; 2024c)

As can be seen from Table 2, by removing one of the independent variables, the models become adequate and can be considered.

RESULTS

Since the 2010s, climate change has emerged as a significant factor impacting agricultural production in

many regions worldwide. These changes include rising average temperatures, altered precipitation patterns and intensity, increased frequency of extreme weather events, and shifting seasonal patterns. These phenomena introduce additional risks to agriculture and necessitate the adaptation of farming practices to new conditions (Kerr *et al.*, 2021; Roy *et al.*, 2024). One of the key manifestations of climate change is rising temperatures, leading to increased evaporation and, consequently, reduced water availability for crops (Abbass *et al.*, 2022). This process is particularly critical for regions with limited water resources, such as the Mediterranean, East and Southern Africa, and parts of South and Southeast Asia. Elevated temperatures have been linked to reduced crop yields, potentially threatening global food security (Shebanina *et al.*, 2024).

Changes in the quantity and distribution of precipitation also lead to significant alterations in agricultural ecosystems (Karavolias *et al.*, 2021; Qi *et al.*, 2021). Some regions may experience decreased rainfall, exacerbating drought risks, while others may face more intense rainfall and flooding (Romanenko & Kovalevskii, 2022). Excessive precipitation can cause soil erosion and nutrient leaching, negatively impacting soil fertility. As a result, farmers find it increasingly difficult to predict optimal planting and harvesting times, reducing agricultural productivity and resilience (Nguyen & Scrimgeour, 2021). Additionally, the increased frequency of extreme weather events, such as hurricanes, cyclones,

and storms, leads to substantial losses in agricultural production and infrastructure damage. In particular, hurricanes in North and South America destroy crops and significant economic losses (Buono, 2021). These events pose a serious challenge to agriculture and require substantial effort and investment from farmers for recovery. Climate change also shifts the timing of the growing season, necessitating revisions to crop cultivation methods. Adapting agriculture to new climatic conditions requires the adoption of resilient crop varieties and the development of innovative practices such as agroforestry and drip irrigation (Ismayilzada *et al.*, 2023). However, adaptation is associated with high costs and risks, which is particularly relevant for developing countries where resource constraints may hinder the adoption of new technologies.

The study assessed the impact of indicators describing the level of agricultural development and CO₂ emissions on several variables characterising food security. After calculating all relevant indices, correlation matrices were constructed for each country. A portion of the obtained results is presented in Table 3.

As can be seen from Table 3, Kazakhstan exhibits predominantly positive correlations. Notably, the agricultural development index is strongly correlated with the Global Food Security Index (0.849) and the Sustainable Development Index (0.761), while CO₂ emissions have a moderate correlation with agricultural development (0.531). Data for the USA is presented in Table 4.

Table 3. Correlation matrix for selected indicators in Kazakhstan

Indicators	Agricultural development index	CO ₂ emissions	Ratio of agricultural output to GDP	Global Food Security Index	Sustainable Development Goalbased Index
Agricultural development index	1	0.583	0.179	0.849	0.761
CO ₂ emissions		1	-0.566	0.383	0.879
Ratio of agricultural output to GDP			1	0.138	-0.362
Global Food Security Index				1	0.623
Sustainable Development Goal-based Index					1

Source: compiled by the authors based on data from the Sustainable Development Report (2024), Global Food Security Index 2022 (2023), H. Ritchie and M. Roser (2024), Bureau of National statistics of Agency for Strategic planning and reforms of the Republic of Kazakhstan (2024), Macrotrends (2024)

Table 4. Correlation matrix for selected indicators in the USA

Indicators	Agricultural development index	CO ₂ emissions	Ratio of agricultural output to GDP	Global Food Security Index	Sustainable Development Goalbased Index
Agricultural development index	1	-0.692	0.001	-0.569	-0.154
CO ₂ emissions		1	0.314	0.808	0.359
Ratio of agricultural output to GDP			1	0.363	0.431
Global Food Security Index				1	0.75
Sustainable Development Goal-based Index					1

Source: compiled by the authors based on data from the Sustainable Development Report (2024), Global Food Security Index 2022 (2023), H. Ritchie and M. Roser (2024)

Table 4 reveals a more diverse correlation pattern for the USA. The agricultural development index has a negative correlation with the Global Food Security

Index (-0.569) but shows no significant correlation with other food security indicators. Data for Germany is presented in Table 5.

Table 5. Correlation matrix for selected indicators in Germany

Indicators	Agricultural development index	CO ₂ emissions	Ratio of agricultural output to GDP	Global Food Security Index	Sustainable Development Goal-based Index
Agricultural development index	1	-0.753	-0.786	-0.602	-0.451
CO ₂ emissions		1	0.921	0.854	0.591
Ratio of agricultural output to GDP			1	0.738	0.705
Global Food Security Index				1	0.393
Sustainable Development Goal-based Index					1

Source: compiled by the authors based on data from the Sustainable Development Report (2024), Global Food Security Index 2022 (2023), H. Ritchie and M. Roser (2024), Statista (2024a; 2024b; 2024c)

Table 5 for Germany highlights the ecological and structural transformation of the agricultural sector. There is a significant positive correlation between emissions and the share of agriculture in GDP (0.921), the Global Food Security Index (0.854), and the index based on the second Sustainable Development Goal (0.591). The agricultural development index also shows

a fairly high level of correlation with all indicators except the Sustainable Development Goal-based index. Thus, the strongest relationship between indicators was observed in Kazakhstan, while in other countries it was less significant. Based on the obtained data, the resulting regression equations can be described. They are presented in Table 6.

Table 6. Regression equations for different countries in the context of their impact on food security indicators

No.	Country	Indicator	Equation
1		Ratio of agricultural output to GDP	$y=0.038+0.016x_1-1.54*(10^{(-10)})$
2	Kazakhstan	Global Food Security Index	$y=16.87+31.5x_1$
3		Food security index based on data from Sustainable Development Goal 2	$y=-0.62+0.24*x_1+3.03*(10^{(-9)})$
4	USA	Global Food Security Index	$y=37.5+8.88*(10^{(-9)})x_2$
5	Germany	Global Food Security Index	$y=65.3+2.14*(10^{(-8)})x_2$

Note: the numbering is provided for ease of reference in subsequent text

Source: compiled by the authors based on data from the Sustainable Development Report (2024), Global Food Security Index 2022 (2023), H. Ritchie and M. Roser (2024), Bureau of National statistics of Agency for Strategic planning and reforms of the Republic of Kazakhstan (2024), Macrotrends (2024), Statista (2024a; 2024b; 2024c)

As Table 6 demonstrates, the majority of adequate models were found for the Global Food Security Index. A more detailed description of the results obtained from equations 1-5 is necessary to understand their adequacy:

1. For every 1% increase in the agricultural development index, the ratio of agricultural output to GDP improves by 0.016%; for every 1 billion tonnes increase in CO₂ emissions, the ratio of agricultural output to GDP decreases by 0.154%.

2. For every 1-unit improvement in the agricultural development index, the Global Food Security Index improves by 31.5.

3. If the agricultural development index increases by 1, the food security index based on data from Sustainable Development Goal 2 improves by 0.24; if CO₂ emissions increase by 1 billion tonnes, the food security index based on data from Sustainable Development Goal 2 improves by 3.03.

4. If CO₂ emissions increase by 1 billion tonnes, the Global Food Security Index improves by 8.88 units.

5. If CO₂ emissions increase by 1 billion tonnes, the Global Food Security Index improves by 2.14 units.

Considering the described results, it can be concluded that four of the obtained models appear to be inadequate (do not accurately reflect the real situation). The first regression equation and its corresponding results are quite adequate, demonstrating how improvements in the agricultural sector can influence its ratio to GDP (which indirectly indicates a country's ability to ensure food security). However, the remaining four equations raise doubts about their validity, as an increase in CO₂ emissions within a country should not positively impact food security. On the other hand, this could be explained by the fact that the more production a country has (even if it increases CO₂ emissions), the easier it is to ensure food security. However, this could only apply

to food processing plants, while overall environmental pollution reduces agricultural efficiency, and therefore the expected impact should be negative. In any case, the obtained results should be further studied in subsequent research.

As part of the study, the impact of individual agricultural indicators on food security in Kazakhstan was also assessed. The first step was to construct a correlation matrix for these indicators to identify those suitable for further analysis (Table 7).

Table 7. Correlation matrix of agricultural development indicators and food security in Kazakhstan

Indicator	Food security index		
	based on data from Sustainable Development Goal 2	Gross agricultural output/GDP	Global Food Security Index
Adjusted sown area of cotton	-0.8674	0.4143	-0.576
Adjusted sown area of open-field vegetables	0.8641	-0.0967	0.9015
Adjusted sown area of oilseed crops	0.8807	-0.1967	0.8247
Adjusted sown area of potatoes	0.3684	-0.0483	0.0005
Adjusted sown area of cereals (including rice) and legumes	0.1232	-0.0619	0.2859
Adjusted sown area of sugar beet	-0.1912	0.4834	0.0289
Cotton yield	0.7282	-0.2433	0.6352
Sugar beet yield	0.6149	0.0148	0.8571
Open-field vegetable yield	0.9020	-0.2311	0.8321
Oilseed crop yield	0.7842	-0.043	0.6842
Cereals (including rice) and legumes yield	0.3984	0.2572	0.1125
Potato yield	0.8618	-0.161	0.854
Total adjusted sown area of crops	0.7952	-0.21	0.7601
Gross cotton harvest	-0.5298	0.3047	-0.2452
Gross sugar beet harvest	0.2658	0.246	0.5563
Gross open- and closed-field vegetable harvest	0.8766	-0.1165	0.8929
Gross oilseed crop harvest, thousand tonnes	0.8755	-0.095	0.8338
Gross potato harvest	0.7732	-0.0941	0.5307
Gross grain (including rice) and legume harvest	0.4361	0.2814	0.2031
Gross agricultural production (services)	0.6426	0.1807	0.9467

Source: compiled by the authors

Based on the results presented in Table 7, it was decided that only the food security index based on data from Sustainable Development Goal 2 and the Global Food Security Index would be used for further analysis, as they had a sufficient number of variables with a high correlation coefficient with the potential independent variable. In subsequent analysis, indicators were used only if the correlation level between the independent and dependent variables exceeded ± 0.6 .

The next step was to construct regression equations. The initial equations were found to be inadequate, primarily due to some dependent variables having high p-values. As a result, inadequate variables were excluded, allowing for the construction of final regression equations. The equation for the independent variable Food security index based on data from Sustainable Development Goal 2 is shown in equation (5):

$$y = -1.61 - 0.001434x_1 + 0.0194x_2 + 0.0113x_3 - (5 \cdot 10^{-5})x_4 - (6 \cdot 10^{-4})x_5 + (8.65 \cdot 10^{-5})x_6, \quad (5)$$

where y is the dependent variable (food security index based on data from Sustainable Development Goal 2); x_1 is the sown area of cotton; x_2 is the sown area

of open-field vegetables; x_3 is the yield of open-field vegetables; x_4 is the total sown area of crops; x_5 is the gross production of open- and closed-field vegetables; x_6 is the gross potato harvest.

In this case, a one-unit increase in the sown area of cotton decreases the index by 0.001434 (a 1% change leads to a 0.288% decrease); a one-unit increase in the sown area of open-field vegetables increases the index by 0.0194 (a 1% change leads to a 5.52% increase); a one-unit increase in the yield of open-field vegetables increases the index by 0.0113 (a 1% change leads to a 5.25% increase); a one-unit increase in the total sown area of crops decreases the index by $5 \cdot 10^{-5}$ (a 1% change leads to a 2.04% decrease); a one-unit increase in the gross production of open- and closed-field vegetables decreases the index by $6 \cdot 10^{-4}$ (a 1% change leads to a 4.97% decrease); a one-unit increase of potato production increases the index by $8.65 \cdot 10^{-5}$ (a 1% change leads to a 0.3% change). Regarding the Global Food Security Index, the following equation (6) was formulated:

$$y = 64.944 + 0.034x_1 - 0.0195x_2 + 0.0703x_3 + (5.9 \cdot 10^{-6})x_4, \quad (6)$$

where y is the dependent variable (Global Food Security Index); x_1 is the sugar beet yield; x_2 is the yield of open-field vegetables; x_3 is the gross production of open- and closed-field vegetables; x_4 is the gross output of agricultural products (services).

In this case, a one-unit increase in sugar beet yield increases the index by 0.034 (a 1% change leads to a 0.1786% increase); a one-unit increase in the yield of open-field vegetables decreases the index by 0.0195 (a 1% change leads to a 0.7172% decrease); a one-unit change in the gross production of open- and closed-field vegetables increases the index by 0.0703 (a 1% change leads to a 0.431% change); a one-unit change in the gross output of agricultural products (services) leads to an increase of $5.9 \cdot 10^{-6}$ (a 1% change leads to a 0.17588% increase). Therefore, based on the conducted analysis, different indicators have varying impacts on food security levels in Kazakhstan. However, some overlap, namely the yield of open-field vegetables and the gross production of open- and closed-field vegetables. This may suggest that additional attention should be paid to these indicators to achieve a higher level of food security.

The research has demonstrated the importance of developing policies that address the specific needs of each region, ensuring food security while simultaneously combating climate change. In Kazakhstan, the most effective approach would be to increase investments in sustainable agriculture, improve water resource management, and introduce cleaner technologies to safeguard food supplies in the face of climate challenges. For the United States, reallocating subsidies to promote sustainable farming and implementing carbon-reducing technologies could in turn help reduce inefficiencies and environmental harm. Meanwhile, Germany should prioritise organic and small-scale farming alongside energy-efficient methods to strike the right balance between environmental sustainability and food security.

On a broader scale, countries must integrate food security into their climate action plans, foster global cooperation to share knowledge, and base decisions on sound data. All three countries should work towards the global goal of zero hunger (Sustainable Development Goal 2) while simultaneously addressing the dual challenge of climate change mitigation and adaptation. To achieve real progress, governments should increase funding for programs that help agriculture adapt to a changing climate, especially in the most vulnerable regions, by providing subsidies to encourage the adoption of sustainable practices. By taking these steps, countries can build more resilient agricultural systems, ensure food supplies, and reduce the impacts of climate change. This can lay the groundwork for policy development to design solutions tailored to their unique circumstances, addressing the interconnected issues of agricultural development and food security, alongside climate-related challenges.

DISCUSSION

Thus, the study assessed the relationship between agricultural development, CO₂ emissions, and food security indicators in Kazakhstan, the USA, and Germany. A positive correlation was found between the agricultural indicator and food security in Kazakhstan. However, the relationship with CO₂ emissions was less clear-cut, as varying correlations were observed across countries and indicators. Therefore, further research is needed to more accurately determine the existence of such a relationship. In the current study, a statistical assessment was conducted to evaluate the impact of agricultural development on food security, leading to the conclusion that such a relationship exists, at least in Kazakhstan. However, the influence of climate change on food security was evident in all three countries studied. The impact of climate change on agricultural pests was specifically examined by S. Skendzic *et al.* (2021). Their research highlighted that climate change significantly affects crops and associated pests, although many uncertainties remain. Small-scale climate variability (changes in temperature, precipitation, and humidity) influences insect populations in complex ways, favouring some species while suppressing others (Ivanova *et al.*, 2021). These changes affect insect distribution, abundance, growth, and behaviour, which can lead to more frequent pest outbreaks and range expansions, particularly in northern regions. The authors described how climate change may also reduce the effectiveness of current pest control approaches, posing additional risks to food security. Addressing these risks will require proactive, science-based strategies, including improved integrated pest management, monitoring of climate changes, and forecasting of subsequent likely changes in this area.

B. Behera *et al.* (2023) assessed agriculture, food security, and climate change in South Asia, specifically examining the impact of climatic (temperature, precipitation, CO₂ emissions) and nonclimatic (agricultural production, fertiliser use, cereal land) factors on food security in six South Asian countries using data from 2000 to 2019. Their findings indicated that increased agricultural production positively influenced food security, CO₂ emissions had a negative impact on food security, and the interaction between precipitation and temperature negatively affected crop yields, thus harming food security. The level of influence was determined to be "strong", suggesting that a significant portion of food security challenges is attributed to these factors. The researchers also formulated policy recommendations, including training farmers in climate-resilient methods to improve yields and safety, promoting renewable energy in agriculture to reduce CO₂ emissions, and encouraging regional cooperation for comprehensive policies and sustainable food systems. As can be seen, both studies highlighted the negative impact of climate change on national food security. A similar result was

obtained in the current study for Kazakhstan, but not for the USA and Germany, which may suggest that the findings for these countries are inadequate.

M. Lupascu *et al.* (2023) explored the challenge of balancing food security, climate change mitigation, and rural livelihoods in the tropical peatlands of Indonesia, carbon-rich areas threatened by agricultural expansion. Using data from various sources, the authors analysed land use trends in Indonesia over the past 30 years, with a particular focus on food crops and monoculture tree crops such as oil palm and rubber. They found that peatland regions contribute minimally to food security but are highly susceptible to land use changes associated with carbon emissions from tree crops. The researchers concluded that integrating climate-smart agriculture, such as paludiculture, could enhance food production and reduce emissions, although peatland conservation should remain a priority. They identified existing challenges such as a lack of comprehensive peatland definitions, varying government sectoral maps, and inconsistent policies that hinder sustainable practices. In this regard, it is important to align food security initiatives with efforts to achieve sustainable development goals. The impact of climate change on agriculture and its mitigation strategies were discussed by G.S. Malhi *et al.* (2021). They noted that growing global populations and climate change are increasing pressures on agriculture to meet food and nutritional needs. Climate change is expected to reduce agricultural productivity through impacts on temperature, precipitation, and greenhouse gases, which affect pest infestations, soil fertility, and plant physiology (Shahini *et al.*, 2024). Various strategies can mitigate these effects; the authors argue that their implementation, both by businesses and governments, can alleviate economic losses and increase farmers' incomes while sustaining production. However, a multidisciplinary approach is needed to implement viable, climate-resilient solutions. The other two studies mentioned also highlighted the negative impacts of climate change on agriculture, although the findings of the current study do not entirely align with these. Nevertheless, agricultural development and improved efficiency remain possible under any conditions, including changing climates.

A.A. Chandio *et al.* (2020) examined the short-term and long-term impacts of climate change on agriculture. Their study assessed how climate change affects agricultural production and rural household incomes in China. They found that increasing the area under grain crops, greater fertiliser use and energy consumption positively influenced agricultural value, while changes in temperature and precipitation had a long-term negative impact on farmers. Based on these findings, the researchers recommended adapting irrigation practices to suit current weather conditions. A. Gomez-Zavaglia *et al.* (2020) explored opportunities for mitigating the

impacts of climate change. They noted that rising temperatures, changing precipitation patterns, and increased pollution threaten crop yields and nutrient quality, creating a double risk of droughts and floods that damage soil and increase crop water demand. Climate change also promotes the spread of pests and weeds, expanding their impact on agriculture. To enhance resilience, crops resistant to drought and temperature changes should be developed, and irrigation systems and soil management should be improved.

CONCLUSIONS

Thus, the correlation and regression analyses presented in this study reveal the complex interplay between agriculture, CO₂ emissions, and food security indicators in Kazakhstan, the USA, and Germany. Kazakhstan exhibited the strongest and most positive correlations among the variables examined, suggesting that investments in agricultural development and effective environmental management can significantly enhance food security. In contrast, the USA and Germany displayed more diverse and intricate relationships, reflecting structural and ecological transformations in their agricultural sectors. These findings indicate that the impact of agricultural and environmental policies on food security varies considerably across countries, depending on their specific socioeconomic, climatic, and institutional contexts. While regression models confirm the relationship between key variables, their limitations in certain contexts, such as the USA and Germany, highlight the need for further methodological refinements and the inclusion of additional factors. The study also identified specific agricultural indicators that exert a stronger influence on food security within each country.

The study highlighted the critical importance of integrating climate resilience into agricultural policies and practices. Developing innovative approaches, such as using climate-resilient crop varieties, sustainable irrigation systems, and precision agriculture, is essential to mitigate the adverse effects of climate change. Furthermore, fostering international cooperation and knowledge sharing can accelerate the adoption of effective strategies, particularly in regions most vulnerable to climate impacts. The findings also underscore the need for robust policy frameworks that align agricultural development with sustainable practices and address the dual challenge of enhancing food security while minimising environmental degradation. Future research should focus on identifying specific government actions that can be taken to bolster food security, especially in Kazakhstan.

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CONFLICT OF INTEREST

None.

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Зміна клімату та продуктивність сільського господарства: економічні наслідки для продовольчої безпеки

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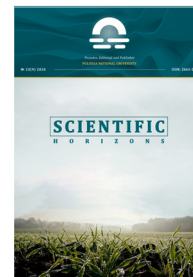
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Анотація. З кінця ХХ століття дедалі активнішими стали обговорення з приводу змін клімату та їхнього впливу на різні сфери діяльності, зокрема й сільське господарство. У зв'язку з цим, проведення оцінки з приводу того, яким чином негативний вплив на зміну клімату може бути знижено для забезпечення продовольчої безпеки, є актуальним. У рамках цього дослідження було проведено оцінку в контексті існування взаємозв'язку між сільським господарством, продовольчою безпекою та викидами CO₂. Зокрема, проводився кореляційний аналіз між обраними показниками для трьох країн: Казахстану, Сполучених Штатів Америки та Німеччини, як представника країн Європейського Союзу. У роботі було показано, що підвищення температури, зміна характеру опадів і збільшення частоти екстремальних погодних явищ істотно порушують продуктивність сільського господарства, створюючи істотні ризики для глобальної продовольчої безпеки. Ці проблеми поглиблюються необхідністю адаптації сільськогосподарських методів і технологій до нових кліматичних реалій, що часто вимагає значних фінансових і людських ресурсів, особливо в країнах, що розвиваються, де такі ресурси обмежені. Висновки на основі статистичних даних засвідчили неоднозначні результати: для Казахстану позитивний вплив сільського господарства на продовольчу безпеку було підтверджено, тоді як викиди CO₂ мали неоднозначний вплив на показники продовольчої безпеки, результати, отримані в рамках дослідження, можуть бути використані для формування стратегій подальшого розвитку як з боку підприємств, так і держави в цілому

Ключові слова: екологія; викиди CO₂; аграрний сектор; регресійні моделі; сталий розвиток

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The grain market in Kazakhstan: An economic analysis of exports and domestic consumption

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Abstract. This study aimed to identify contemporary trends in Kazakhstan's grain market functioning. The analysis focused on production, consumption, export, and import indicators, price dynamics, and the self-sufficiency rate of grain in Kazakhstan during 2019-2023. The research utilised official statistical data on Kazakhstan's agricultural sector and grain market performance. A comprehensive analysis of the grain market was conducted. The statistical data analysis revealed both positive and

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negative trends that significantly influenced the grain market in Kazakhstan from 2019 to 2023, as well as the country's food self-sufficiency. The findings indicated a 1.7% decline in production rates and a 16.7% reduction in industrial grain consumption, accompanied by an increase in grain usage for seeding purposes. Annual personal consumption by the population did not exceed 1.1% of the total grain utilisation in the country. A 3.9% increase in sown areas did not result in higher yields, which decreased by 9.6%. The highest yields were observed in the Qyzylorda Region, where wheat cultivation dominated. Although imports did not surpass exports, they increased more than sevenfold over time. During the study period, grain reserves in the country grew by 9%, accompanied by a significant rise in market prices. These indicators did not prevent Kazakhstan from maintaining a high level of grain self-sufficiency, enabling further development of grain exports. This research contributed new insights into the future development of the grain market in Kazakhstan, demonstrating that an export-oriented strategy combined with increased production could be a viable pathway for successful sectoral growth. This approach could mitigate the risk of a food crisis while preserving the country's high self-sufficiency in grain

Keywords: production; sown area; self-sufficiency level; resource balance; price index

INTRODUCTION

The Republic of Kazakhstan has long been one of the most successfully developing countries in Central Asia, maintaining its status as the region's economic leader. With a population of 19.8 million, Kazakhstan's gross domestic product (GDP) grew by 97.37% between 2008 and 2023 (Bureau of National..., 2023b; Statista, 2023). Geographically, Kazakhstan benefits from extensive fertile lands, strategic location, and favourable climatic conditions, alongside significant economic potential, natural resources, and human capital. These factors contribute to the development of its agricultural sector and support its food security.

Within the international scientific community, researchers have frequently addressed issues of food security, both at the national and global levels. Reviewing events affecting the food commodity market, M. Ardan *et al.* (2023) noted that the 2008 global economic crisis triggered food collapses in many countries, leading to widespread poverty and threats to food security. As a result, food security became an international priority. During the economic recession, global efforts succeeded in improving food security. However, since 2020, the SARS-CoV-2 pandemic has once again destabilised food security in many countries, including Kazakhstan, as observed by M. Jia *et al.* (2022). Investigations into food system functioning during the pandemic by K. Chen and R. Mao (2020) concluded that the primary threat stemmed from export and import restrictions on agricultural goods. Similar conclusions were drawn by T. Falkendal *et al.* (2021), who analysed the pandemic's effects on the agricultural market, highlighting price surges and food shortages as major consequences. Furthermore, the onset of the Russian-Ukrainian war in 2022 exacerbated the pandemic's impact on the food system. This was demonstrated in research by M. Nasir *et al.* (2022), which examined the effects of military actions in Ukraine on the global food market.

Kazakhstan ranks among the world's largest producers and exporters of food products. The report Global Food Security Index 2021 (The Economist, 2018;

2021) indicated that Kazakhstan was ranked 41st out of 113 countries in terms of food security, a significant improvement from 57th place in 2018. When addressing food security, particular attention must be paid to the grain market, which is of primary importance (Bulgakov *et al.*, 2020). The analysis of Kazakhstan's grain market presents considerable interest. Exploring the trends and challenges in the grain markets of Asia, R. Sendhil *et al.* (2022) concluded that between 2011 and 2022, Central Asian countries experienced a significant increase in sown areas for grain crops and a surge in their consumption. This has heightened demand for grains, particularly wheat, positioning it as a critical commodity in international trade. Analysing Kazakhstan's grain production, S. Tokenova *et al.* (2019) identified that improving the economic efficiency of the grain sector remains a key priority. Other researchers, such as T. Stathers *et al.* (2020), emphasised the importance of reducing post-harvest grain losses as a vital objective. In their study of wheat and maize markets in Asia, U. Grote *et al.* (2021) predicted that the production of these grain crops would decline in the future, underscoring the need to sustain and enhance their cultivation in Central Asian countries. This is particularly relevant to wheat, given that Asian nations are major producers. Increasing maize production is also crucial, primarily due to its growing use as livestock feed in animal husbandry (Havryliuk & Kovalyshyna, 2024).

A review of previous studies reveals that research on the grain market typically focuses on two primary aspects: production and/or trade. These elements are closely linked to the assessment of food security accessibility. While this has established a solid theoretical foundation, limitations remain, as prior research often considers only select indicators rather than adopting a comprehensive approach. However, statistical data available for analysis, particularly in Kazakhstan, highlight the grain market as a promising avenue for further research. This study aims to address this research gap within the international academic discourse. It

emphasises the importance of analysing not only production and trade but also the functionality of both the domestic grain market and external economic activities related to this commodity. Additionally, it explores price index dynamics and the self-sufficiency level of grain in the country.

This research aimed to identify the main trends in the development of various grain crops in Kazakhstan.

MATERIALS AND METHODS

To achieve the research objectives, a three-stage approach was employed, combining qualitative and quantitative methods. Qualitative methods were used to analyse the theoretical underpinnings of previous studies, while quantitative methods were applied to analyse official statistical data. In the first stage, the role of agriculture in the national economy and the significance of grain crops within the agricultural sector were examined. Additionally, the dynamics of Kazakhstan's grain market from 2004 to 2023 were analysed. This stage involved a comprehensive analysis of the following statistical data: agriculture's contribution to GDP (Bureau of National Statistics, 2024a), employment in the agricultural sector (Bureau of National Statistics, 2024j), the quantity and dynamics of sown areas in the country (Bureau of National Statistics, 2024c), the quantity and dynamics of sown areas for grain (including rice) and legume crops, including a breakdown by region (Bureau of National Statistics, 2024b), and the dynamics of gross harvest and yield of grain (including rice) and legume crops (Bureau of National Statistics, 2024d; 2024e). To analyse the dynamics of these indicators, the growth rate formula (1) was used:

$$\text{Growth rate} = \frac{P_t}{P_b} \times 100\% - 100\%, \quad (1)$$

where P_t is the value of the indicator in the current period and P_b is the value of the indicator in the base period.

Following the initial analysis of agriculture's contribution to Kazakhstan's economy and the dynamics of grain crop development from 2004 to 2023, the second stage involved a more detailed examination of data from 2019 to 2023. The primary focus was on production, consumption, and price dynamics. To analyse production, consumption, exports, and imports, the following statistical data were examined: the structure of production by grain type and gross harvest (Bureau of National Statistics, 2024d; 2024e), major grain producers (Bureau of National Statistics, 2023a), yield by region (Bureau of National Statistics, 2024b), dynamics and structure of the grain balance and grain utilisation (excluding processed products) (Bureau of National Statistics, 2024f). To analyse price dynamics, chainlinked price indices for grain crops in Kazakhstan (Bureau of National Statistics, 2024h) were compared with global grain price indices (Food and Agriculture..., 2024).

The third stage initially analysed the dynamics of grain exports and imports (Bureau of National Statistics, 2024f), the structure of exports and imports (Bureau of National Statistics, 2024g), and then assessed the country's export potential through relative indicators: the level of grain self-sufficiency and the ratio of exports to grain production. The level of grain self-sufficiency was calculated using the following formula (2):

$$\text{SR} = \frac{P}{IU} \times 100\%, \quad (2)$$

where SR is the level of grain self-sufficiency, P is the country's grain production in a given year, and IU is the domestic use of grain in the country, excluding exports, in a given year. Finally, the export-oriented strategy for developing the grain market in Kazakhstan was analysed, and measures to achieve this strategy were proposed.

RESULTS

Agricultural development in Kazakhstan does not occupy a prominent position within the national economy. Given that GDP is one of the most critical indicators of national accounts, reflecting the overall economic performance of a country, attention should be directed towards agriculture's contribution to the GDP. In the first half of 2024, the share of agriculture, forestry, and fisheries accounted for merely 2.5% of total GDP. Together with the industrial and construction sectors, these activities constitute Kazakhstan's productive sector. For comparison, during the same period, the industrial sector contributed 28.3% to GDP, while the construction sector accounted for 5.1%. In the first half of 2023, the share of agriculture, forestry, and fisheries in GDP was slightly higher at 2.7%. By contrast, the industrial and construction sectors contributed 29.32% and 4.92%, respectively. Looking further back, in the first half of 2007, agriculture, hunting, and forestry accounted for 2.23% of GDP, while the industrial and construction sectors contributed 30.78% and 1.7%, respectively (Bureau of National Statistics, 2024a). This data indicates that the share of agriculture in Kazakhstan's GDP has fluctuated over the years, periodically declining but consistently remaining below 3%.

While agriculture's contribution to Kazakhstan's GDP is relatively small, it is crucial to consider the sector from other perspectives, such as employment and production advantages. A substantial portion of the population is employed in agriculture, accounting for 11.9% of the total workforce in 2023, making it the fourth-largest sector by employment in the country (Bureau of National Statistics, 2024j). Moreover, compared to other agricultural products, grain cultivation offers several advantages for any nation. Notably, it typically boasts a higher level of profitability. In the event of adverse social or economic conditions, the grain market tends to experience lower levels of losses compared to other agricultural commodities. Additionally, grains

enjoy a high level of liquidity, meaning they are generally easier to sell than, for example, vegetables (Petryshyn, 2016). A key factor influencing grain production is the area of land under cultivation. The total sown area for agricultural crops in Kazakhstan increased by 32.2% between 2004 and 2023, reaching 23.8 million hectares in 2023 (Bureau of National Statistics, 2024c). Specifically, the sown area for grain crops increased by 22.7% during the same period, from 14.28 million hectares in 2004 to 17.53 million hectares in 2023 (Bureau of National Statistics, 2024b).

The largest sown areas for grain (including rice) and leguminous crops in Kazakhstan were located in three regions in 2004: Akmola, Kostanay, and North Kazakhstan. In that year, Akmola accounted for 25.3% of the total sown area for grain and leguminous crops. Kostanay and North Kazakhstan regions followed, contributing 21.4% and 21.2%, respectively. Certain regions, such as Turkistan, Jetisu, Mangystau, and Abai, did not cultivate grain crops at all during this period. By 2023, the Akmola Region retained its leading position in grain cultivation, with sown areas comprising 28.3% of the total national sown area for grain and leguminous crops. Between 2004 and 2023, the sown area for grain in Akmola increased by more than 1.3 times, reaching 4.9 million hectares. Similarly, Kostanay and North Kazakhstan regions remained among the leaders, expanding their sown areas by 44.1% and 12.6%, respectively, during the same period. As of 2023, Akmola, Kostanay, and North Kazakhstan regions achieved the highest levels of grain cultivation area expansion since 2004. Meanwhile, regions such as Turkistan, Jetisu, and Abai, which had previously

not engaged in grain cultivation, began sowing these crops in 2022. However, their combined share of the total sown area remained modest, accounting for no more than 5.9% in 2022 and 5.5% in 2023 (Bureau of National Statistics, 2024b).

The gross harvest of grain, including rice and legumes, in Kazakhstan reached 17.1 million tonnes in 2023, representing a 38.2% increase compared to 2004. However, grain production has exhibited fluctuations over the period from 2004 to 2023, with a record harvest achieved in 2011. The dynamics of the overall grain harvest closely mirror those of wheat, the country's primary grain crop. Field productivity, which determines the gross grain harvest, is expressed through the yield of this agricultural crop. According to official statistical data presented in Figure 1, the grain yield, including rice and leguminous crops, increased by 17% between 2004 and 2023. Following the global financial crisis of 2008-2011, Kazakhstan not only restored grain production to pre-crisis levels but significantly improved its performance. The year 2011 was the most productive, after which the gross harvest and yield of grain demonstrated positive growth until 2019. However, events during 2019-2023, including the SARS-CoV-2 pandemic and its repercussions, as well as the large-scale military conflict in Ukraine, significantly impacted grain cultivation and export in Kazakhstan. Furthermore, changing weather and climatic conditions contributed to fluctuating trends in grain production and yield. Given these developments, a detailed analysis is focused on the 2019-2023 period to examine changes, assess the country's self-sufficiency in grain, and propose measures to mitigate the risk of a potential food crisis.

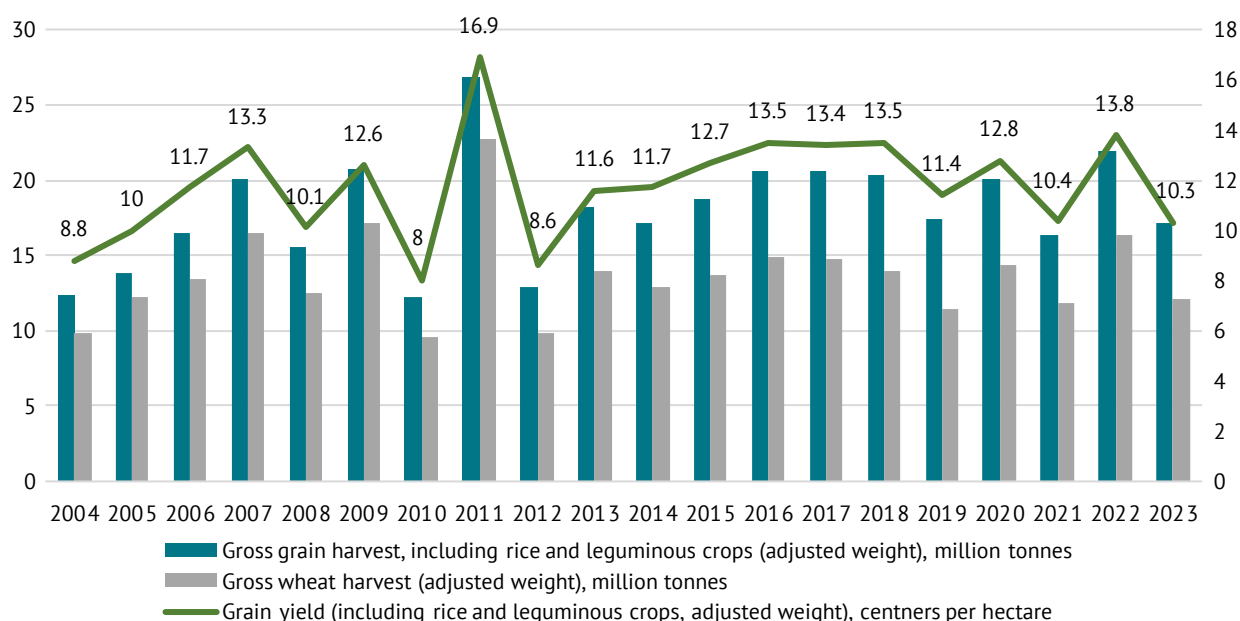


Figure 1. Gross grain harvest and yield (including rice) and leguminous crops in Kazakhstan, 2004-2023

Source: compiled by the authors based on data from the Bureau of National Statistics (2024d; 2024e)

The gross harvest of grain (including rice) and legumes, in Kazakhstan exhibited a cyclical pattern between 2019 and 2023. Production peaked in 2020 and 2022, followed by declines in 2019, 2021, and 2023. For instance, grain yields in 2023 experienced a significant 25.4% decrease compared to the previous year (Bureau of National Statistics, 2024d). Winter and spring wheat accounted for the largest share of total grain production. In 2019, wheat contributed 65.7% of the gross grain harvest. This proportion increased annually in subsequent years, except for 2023. Specifically, wheat's share of the gross harvest rose to 71.1% in 2020, 72.1% in 2021, and 74.5% in 2022. However, a sharp decline occurred in 2023, reducing this figure to 70.8% (Bureau of National Statistics, 2024e). In addition to wheat, Kazakhstan cultivates other crops, including winter and spring barley, maize (corn), oats, winter and spring rye, sorghum, millet, buckwheat, triticale (a wheat-rye hybrid), and mixed cereal grains (Bureau of National Statistics, 2023a).

Barley, both winter and spring varieties, ranks second in production volume after wheat. From 2019 to 2021, barley production declined by 38.2%, dropping from 3.8 million tonnes in 2019 to 2.4 million tonnes in 2021. In 2022, barley production rebounded significantly, increasing by 38.9% to reach 3.3 million tonnes. Maize (corn) ranks third in production volume. Between 2019 and 2021, maize production rose by 26.1%, from 0.9 million tonnes in 2019 to 1.1 million tonnes in 2021. However, in 2022, maize production decreased slightly by 2.8% compared to 2021 levels. Oats and rye (winter and spring varieties) rank fourth and fifth in production volume among grain crops in Kazakhstan. Oat production declined by 31.7% from 2019 to 2021, decreasing from 0.3 million tonnes in 2019 to 0.2 million tonnes in 2021. However, it rose by 25.7% between 2021 and 2022. Rye production, in contrast, increased more than 2.5 times over the 2019-2022 period, from 0.02 million tonnes in 2019 to 0.06 million tonnes in 2022 (NatStat..., 2023).

In 2023, the structure of grain production in Kazakhstan was as follows: winter and spring wheat

accounted for 74.5% of the total grain output, followed by winter and spring barley at 16.1%, maize (corn) at 7.3%, oats at 0.9%, and winter and spring rye at 0.1%. Other grain crops, including sorghum, millet, buckwheat, triticale (a wheat-rye hybrid), and mixed cereals, collectively constituted no more than 1.1% of the total grain production in the country (Bureau of National Statistics, 2023a). Agricultural organisations have traditionally been the primary producers of grain crops in Kazakhstan. In 2023, these organisations accounted for 58.7% of the gross harvest of grain and leguminous crops (including rice). Individual entrepreneurs or peasant and farming households contributed 41.1%, while household farms accounted for only 0.2% of the total gross harvest (Bureau of National Statistics, 2023a). Regionally, the highest grain yield (including rice) and leguminous crops in Kazakhstan during the 2019-2023 period was recorded in the Qyzylorda Region (Bureau of National Statistics, 2024b).

The examined trends in grain production in Kazakhstan demonstrate the potential to establish a balance of resources and utilisation of grain within the country (Table 1). From the data in Table 1, it can be concluded that Kazakhstan's grain market during the 2019-2023 period was shaped by both domestic and external sources. Domestic grain production consistently outweighed imports in the market structure. In 2019, domestic production accounted for 53.9% of total resources, but this share decreased to 47.8% in 2023. The country's internal grain needs were met through carryover stocks from previous years and increased grain imports (Bureau of National Statistics, 2024f). This trend indicates that Kazakhstan maintains a level of grain independence from other countries. However, it is notable that grain imports have risen annually. By 2023, imports had grown more than sevenfold compared to 2019. Over the same period, domestic production declined, with the rate of reduction in gross grain harvest (adjusted weight) reaching 1.7%.

Table 1. Dynamics and structure of grain resource balance and utilisation in Kazakhstan (excluding processed products), 2019-2023

Indicator	Year									
	2019		2020		2021		2022		2023	
	million tonnes	%	million tonnes	%	million tonnes	%	million tonnes	%	million tonnes	%
I. Resources										
Stocks at the beginning of the year	14.5	44.9	11.8	36.1	12.7	41.5	11.6	32.4	15.8	44.1
Production (gross harvest in adjusted weight)	17.4	53.9	20.1	61.5	16.4	53.6	22	61.5	17.1	47.8
Imports	0.4	1.2	0.8	2.4	1.5	4.9	2.1	6.1	2.9	8.1
Total resources	32.3	100	32.7	100	30.6	100	35.8	100	35.8	100
II. Utilisation										
Industrial consumption	6	18.6	5.9	18	4.9	16	5	14	5	14

Table 1. Continued

Indicator	Year									
	2019		2020		2021		2022		2023	
	million tonnes	%	million tonnes	%	million tonnes	%	million tonnes	%	million tonnes	%
	Including:									
Feed for livestock and poultry	3.9	12.1	3.7	11.3	2.7	8.8	2.8	7.8	2.6	7.3
Sowing purposes	2.1	6.5	2.2	6.7	2.2	7.2	2.3	6.2	2.4	6.7
Processing for food purposes	4.3	13.3	4.4	13.5	4	13.1	4.5	12.6	4.5	12.6
Other industrial uses	1.9	5.9	2.2	6.7	2.3	7.5	2.1	5.9	2.1	5.9
Losses	0.58	1.8	0.49	1.5	0.46	1.5	0.36	1	0.36	1
Exports	7.4	22.9	6.6	20.2	6.9	22.5	7.5	20.9	9	25.1
Personal consumption by the population	0.35	1.1	0.36	1.1	0.36	1.2	0.36	1	0.35	0.9
Stocks at the end of the year	11.8	36.5	12.7	38.8	11.6	37.9	15.8	44.1	14.5	40.5

Source: compiled by the authors based on data from the Bureau of National Statistics (2024f)

An analysis of the grain utilisation structure reveals a decline in industrial consumption during the 2019-2023 period, with a reduction rate of 16.7%. This decrease specifically pertains to the use of grain as feed for livestock and poultry (Bureau of National Statistics, 2024f). For instance, the reduction rates in livestock numbers during this period were significant: cattle declined by 11% (from 7.4 million head in 2019 to 6.6 million in 2023), sheep and goats by 2.5% (from 19.1 million to 18.7 million), swine by 40.1% (from 0.8 million to 0.5 million), and poultry by 1.8% (from 45 million to 44.2 million) (Bureau of National Statistics, 2024j). This trend is directly linked to the decline of animal husbandry in Kazakhstan, leading to a reduced demand for grain-based feed in 2023 compared to 2019. The drop in demand for feed for dairy and meat production has consequently diminished grain consumption for industrial purposes.

Conversely, the use of grain for sowing purposes has increased. The rate of decline in grain usage for livestock and poultry feed during 2019-2023 reached 33.3%. According to the Government of Kazakhstan, the annual demand for grain seeds for sowing in the country is 2 million tonnes (Resolution of the..., 2023). Throughout the 2019-2023 period, this figure consistently exceeded 2.1 million tonnes, with an increase in grain utilisation for sowing purposes of 14.3% during the same period. A portion of the grain produced in Kazakhstan has been processed for food purposes, such as flour, groats, and other food products derived from grain, as well as for industrial purposes, including the production of compound feed. Grain processing for food purposes increased by 4.7% during the 2019-2023 period, while processing for other industrial purposes grew by 10.5%. Grain losses have also been observed during utilisation. Throughout 2019-2023, grain losses did not exceed 1.8% of the total grain volume. The trend in this indicator has been positive, with annual reductions in

grain losses. Over the entire period, losses decreased by more than 1.5 times, highlighting improvements in grain management efficiency.

Beyond production and utilisation processes, it is essential to consider price dynamics for grain crops. Between 2019 and 2023, grain crops accounted for an average of 70.6% of Kazakhstan's sown areas. Specifically, in 2019, grain (including rice) and leguminous crops comprised 69.6% of the total sown area, followed by 70.3% in 2020, 70.2% in 2021, 69.6% in 2022, and 73.5% in 2023. Given these statistics, price trends in Kazakhstan's grain market largely influence the overall production efficiency of domestic grain producers. The demand for bakery products and bread – and consequently for domestic grain consumption for food purposes – remained stable during 2019-2023 (Bureau of National Statistics, 2024f). However, it is important to note that this market accounted for an average of only 13% of total grain utilisation during the analysed period. As such, it cannot serve as the primary determinant of grain pricing, even under conditions of intensified or reduced state regulation.

One of the key determinants of grain pricing on the global market is the price of oil and its derivatives. Previous research has demonstrated that a decline in global oil prices could result in a corresponding reduction in grain prices, particularly wheat, by approximately 4% (Petryshyn, 2016). During 2018-2023, oil prices increased by a factor of 1.1 (Minfin, 2024). Following this logic, the researchers suggest that a higher increase in oil prices could lead to an even more pronounced reduction in grain prices on the global market. The dynamics of chain-linked indices for global grain price indices reported by the Food and Agriculture Organization and producer price indices in Kazakhstan during 2019-2023 are presented in Figure 2. Furthermore, in 2020, Kazakhstan introduced trade restrictions, including a temporary ban on the export of socially

significant products within Central Asia. Export restrictions on wheat and other goods were imposed from 2 April to 1 September 2020 (Kim *et al.*, 2020). These bans and export quotas, particularly on wheat and its

products, led to a local increase in prices for these commodities (Giap, 2020). Additionally, the trade war between the USA and China during 2020 and 2021 contributed to the rapid rise in prices.

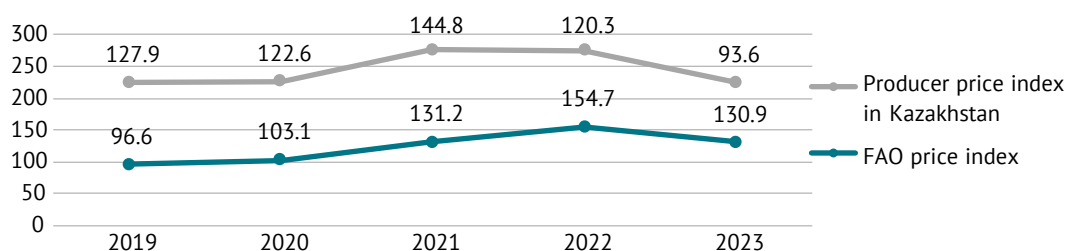


Figure 2. Chain-linked indices of Food and Agriculture Organization Global grain prices and producer price indices in Kazakhstan, 2019-2023

Note: chain-linked indices compare the current year to the previous year's indices

Source: compiled by the authors based on Food and Agriculture Organization (2024), Bureau of National Statistics (2024h)

An analysis of the data presented in Figure 2 suggests that global market dynamics significantly influenced Kazakh grain producers, with domestic pricing closely aligned with the global grain price index. Notably, grain reserves in Kazakhstan grew by more than 9% over the period 2019-2023. This increase in reserves may either reflect declining grain prices, which could reduce producers' motivation to sell, or a reduction in domestic consumption within the country. Upon reviewing statistical data, it becomes evident that the increase in grain reserves in Kazakhstan was not driven by a drop in prices for certain types of grain or a corresponding lack of interest among producers in selling their stock. During the analysed period, the producer price index for grain in Kazakhstan showed a consistent upward trend (Bureau of National Statistics, 2024h). Therefore, the larger carry-over grain stocks in Kazakhstan are attributed to a decline in domestic consumption rather than price-related factors (Bureau of National Statistics, 2024f).

One of the key indicators of the balance of grain resources and utilisation in Kazakhstan is the performance of exports and imports. Over the period 2019-2023, wheat and meslin were the most imported and exported types of grain. Wheat and meslin imports increased more than 25-fold during this period, while their exports grew by over 1.1 times. Barley also accounted for a significant portion of both imports and exports during this time. Barley imports rose tenfold, whereas its exports decreased by 1.4 times. In 2018, grain sorghum was not exported. Except for this grain type, the export of other cereals, including oats, maize, rice, buckwheat, millet, and miscellaneous grains, increased by 1.4 times between 2019 and 2023. All these grain types, including sorghum, were also imported, but their import volumes decreased by 3.2 times over the analysed period (Bureau of National Statistics, 2024g).

To determine whether Kazakhstan has the potential to export grain, it is crucial to consider not only the absolute figures provided in Table 1 but also the relative indicators. The country's self-sufficiency in grain simultaneously ensures food security and imposes constraints on the growth of grain exports (Wei *et al.*, 2019). Based on calculations using Formula 2, the level of grain self-sufficiency in Kazakhstan was 132.5% in 2019, 150.6% in 2020, 136.4% in 2021, 178.6% in 2022, and 138.9% in 2023. In 2021 and 2023, there were significant declines in the self-sufficiency level, amounting to 14.2% and 39.7%, respectively, compared to the preceding years. Despite fluctuations in grain yield between 2019 and 2023, an analysis of Kazakhstan's grain requirements suggests that the production levels were sufficient to meet domestic demand, whether for industrial use, household consumption, or seed reserves for the following calendar year. This trend indicates the country's complete self-sufficiency in grain and the feasibility of exporting without jeopardising food security. The ratio of grain exports to production in Kazakhstan was 42.5% in 2019, 32.8% in 2020, 42.1% in 2021, 34.1% in 2022, and 51.7% in 2023.

The Government of Kazakhstan has developed a strategy for the development of the agroindustrial complex for the period 2021-2030, outlining target indicators for the cultivation and export of agricultural crops. Given the significant proportion of wheat in overall grain production, it is critical to prioritise the development of this specific crop. The target yields for wheat cultivation in Kazakhstan for 2021, 2022, and 2023 were set at 9.3 centners per hectare (cwt/ha), 10.2 cwt/ha, and 11.4 cwt/ha, respectively (Resolution of the..., 2023). Based on official statistical data, it can be concluded that the target indicators for 2021 and 2022 were fully achieved, with the 2022 yield surpassing the target by 1.2 times, reaching 12.8 cwt/ha

compared to 9.2 cwt/ha in 2021. However, in 2023, grain producers in Kazakhstan failed to meet the target yield of 11.4 cwt/ha, as the actual figure was only 9.2 cwt/ha (Bureau of National..., 2024d). This data highlights the importance of not only increasing production volumes but also improving the sustainability of wheat production. Achieving this requires the adoption of innovative approaches to modelling cultivation practices (Kubitza et al., 2020). One of the objectives set by the Government of Kazakhstan for 2030 is to triple the export of agro-industrial products compared to 2020 levels (Resolution of the..., 2023). Based on these target indicators, it can be inferred that Kazakhstan has adopted an export-oriented strategy for grain crops. However, considering the trends in yield indicators and domestic demand, it is crucial to enhance the productivity of grain crops, particularly wheat, to avoid a food crisis and maintain a high level of self-sufficiency in grain.

DISCUSSION

Agriculture represents a significant component of Kazakhstan's economy. Sown area, yield, and gross harvest are the primary criteria for assessing success in grain cultivation (Hartmane et al., 2024). Analysis reveals that the sown area for grain, legumes, and rice in Kazakhstan increased by 32.2% from 2004 to 2023, with gross harvest rising by 38.2% and yield improving by 17% over the same period. The Akmola Region consistently accounts for the largest sown area among all regions of Kazakhstan, a trend that has persisted since 2004. The analysis indicates that Kazakhstan reached its peak gross grain harvest in 2011, and the figure has continued to rise since 2012. However, between 2019 and 2023, fluctuations in both gross harvest and yield levels were observed. Notably, a downturn in these metrics coincided with global events such as the SARS-CoV-2 pandemic and Russia's full-scale invasion of Ukraine. Similar conclusions were drawn by L. Liu et al. (2023), who investigated the impact of global shocks on grain trade. They found that the pandemic heightened Central Asian countries' reliance on Ukrainian and Russian grain. In 2021, Kazakhstan, alongside Eritrea, Mongolia, and Armenia, sourced 99% of its wheat from Russia and Ukraine (Babets et al., 2024). The onset of the Russian-Ukrainian war in February 2022 led to a 50% reduction in grain imports from these two countries to Kazakhstan (Kim et al., 2025). However, the findings of this study demonstrate that imports accounted for only 6-8.1% of Kazakhstan's total grain resources. Thus, the claim that the Russian-Ukrainian war significantly impacted Kazakhstan's grain resources was not supported by this research. It was established that the war influenced grain price dynamics rather than import volumes. This aligns with the conclusions of T. Hassen and B. Bilali (2022), who, in their study on food security, argued that military conflicts primarily affect pricing policies.

The period from 2019 to 2023 was selected for a more detailed analysis. Given the numerous advantages of grain cultivation in Kazakhstan, this market was examined over the specified timeframe across five key aspects: production, consumption, foreign economic activities, price dynamics, and self-sufficiency levels. These findings align with the conclusions of C. Elleby et al. (2019), who studied changes in the global agricultural market following the pandemic. Their research highlighted that the pandemic and its aftermath impacted not only grain cultivation but also its pricing mechanisms. However, the present study did not account for other potential determinants of influence. For instance, possible climatic changes in Kazakhstan, which might have affected grain production, were explored by X. Yu et al. (2020). The researcher suggested that Kazakhstan could enhance its grain exports and reduce imports due to climatic factors, particularly changes in precipitation levels and temperature. An increase in rainfall by 1 millimetre from the late spring through the summer months could potentially boost wheat exports by 0.7% and decrease imports by over 1.5%. An increase in temperature by 1°C, starting from the late spring through the summer months, could potentially lead to an increase in wheat exports by over 20% and a reduction in imports by more than 49%. Examining the impact of climate change on production in the agricultural sector, M. Habib-ur-Rahman et al. (2022) determined that a decrease in minimum temperatures by 2.2°C and an increase in maximum temperatures by 2.8°C could result in a 12% decline in wheat yields and a 17.2% decrease in rice yields. In their study of the global grain market, O. Balkhausen and S. Vogel (2012) noted that favourable climatic conditions in 2011 contributed to record wheat productivity on a global scale and a sharp rise in wheat yields in Kazakhstan.

In analysing grain productivity in Kazakhstan, the following indicators were considered: production levels, the structure of gross output, and key producers. Grain production decreased by 6.1% during the study period. The largest share of total grain production in Kazakhstan was accounted for by winter and spring wheat, representing over two-thirds of the total gross grain harvest. The primary producers of grain were agricultural enterprises, which cultivated the majority of the grain crops. Despite the Akmola Region having the largest sown area for grain, the highest yields were recorded in the Qyzylorda Region. When examining grain consumption within the country, the following indicators were analysed: industrial usage, consumption for food purposes, and individual consumption by the population. The use of harvested grain for livestock and poultry feed decreased by more than 33%, reflecting a decline in livestock farming activities. Conversely, the use of grain for sowing purposes increased by 14.3%, and for food purposes by 4.5%.

An analysis of grain price trends revealed that the pricing of Kazakhstan's grain market is predominantly influenced by external factors and closely linked to the global grain price index, rather than by domestic determinants (Yaheliuk *et al.*, 2024). However, in studying the relationship between prices and wheat self-sufficiency, T. Tanaka and J. Guo (2020) concluded that the interplay between global and local prices is bidirectional, with self-sufficiency playing a crucial role in mitigating external impacts of international price volatility. An evaluation of Kazakhstan's foreign economic activity in the grain sector indicated that during 2019-2023, the grain market operated through both domestic and external sources, with production exceeding imports. Imports increased by more than sevenfold during the period. The largest share of grain imports into Kazakhstan consisted of wheat and meslin.

According to the findings of C. Elleby *et al.* (2019), the consequences of the pandemic, such as supply chain disruptions and income losses, led to food insecurity in many countries. However, based on the present study, an analysis of grain self-sufficiency in Kazakhstan reveals a decline in this indicator during 2021 and 2023. Nonetheless, this did not prevent the country from maintaining a high level of self-sufficiency in grain without compromising food security, even while accounting for exports. The researchers also determined that self-sufficiency is directly influenced by the size of sown areas. In examining food security across Central Asian countries, Y. Zhao *et al.* (2022) argued that many nations in the region have a surplus of agricultural land, meaning the available agricultural area exceeds domestic demand. This characteristic is also evident in Kazakhstan, where agricultural land reserves surpass domestic requirements. Consequently, the country has significant potential to expand its exports in this sector. Research into Kazakhstan's grain trade potential by Y. Wang *et al.* (2022) suggested that, despite holding a small share in the global grain market, the country has strong export advantages in wheat, buckwheat, and barley. These findings partially align with the results of the present study.

To achieve the government's goal of increasing agricultural exports by 2030, and given the trends in consumption and yields, Kazakhstan must enhance wheat productivity to maintain a high level of self-sufficiency and prevent a domestic food crisis. These conclusions align with the study by M. Wang and F. Wei (2021) on regional disparities in grain production efficiency in Kazakhstan. The researchers emphasised the importance of increasing grain production to support potential export growth, particularly to the People's Republic of China. Further, a more detailed analysis of Kazakhstan's grain market is required to deepen understanding and optimise development strategies.

CONCLUSIONS

Grain is a vital commodity for Kazakhstan's national economy. Significant fluctuations in grain production indicators, particularly evident from 2019, prompted a detailed analysis of the Kazakh grain market between 2019 and 2023. Given its high liquidity and profitability, the grain market holds a prominent position within the agricultural sector. Grain production trends from 2019 to 2023 indicate a 1.7% decline in production growth rates, a 9.6% reduction in grain crop yields, and a 3.9% increase in sown areas. The market remains heavily concentrated on a single type of grain – winter and spring wheat. Additionally, over half of the total grain production is carried out by agricultural enterprises, which demonstrate the highest efficiency in the Qyzylorda Region. This region consistently reports the highest annual yields for cereals, legumes, and rice. Grain utilisation trends show a 33.3% decline in its use as livestock and poultry feed, alongside a 14.3% increase in its use for seeding purposes. Processing grain for food purposes and other industrial uses grew by 9.8% and 10.5%, respectively. Grain losses decreased by more than 1.5 times over the study period, while personal consumption by the population remained stable from 2019 to 2023, accounting for no more than 1.2% of the total grain usage in the country. Price formation in the grain market is predominantly influenced by external determinants rather than internal factors.

The grain market in Kazakhstan operates through both external and internal sources. Export and import trends for grain during the analysed period demonstrate a more than sevenfold increase in imports and a 1.2-fold increase in exports. Self-sufficiency in grain decreased in 2021 and 2023, yet this did not pose a threat to food security and allowed for continued grain exports. Thus, Kazakhstan needs to develop its grain market by increasing production and focusing on an export-oriented strategy. A limitation of this study is the absence of analysis of additional factors influencing the market's functioning beyond external global shocks, such as the pandemic and the Russian-Ukrainian war. For instance, the importance of weather conditions, soil fertilisation, and other factors in grain cultivation warrants further exploration.

Kazakhstan's grain market demonstrates effective performance indicators and significant development potential. To formulate improvement measures, further research is essential. It would be prudent to analyse the market in greater detail through the lens of sustainability – not only from an economic perspective but also from social and environmental viewpoints. This approach would enable an assessment of the grain market in Kazakhstan in the context of sustainable development, identifying challenges that need to be addressed in both the short and long term. Addi-

tionally, it would be beneficial to evaluate all factors affecting the wheat market to identify vulnerabilities and develop measures for enhancing the export-oriented development strategy, considering emerging challenges.

None.

None.

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CONFLICT OF INTEREST

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Ринок зернових культур у Казахстані: економічний аналіз експорту та внутрішнього споживання

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Анотація. Мета даного дослідження полягала у виявленні сучасних тенденцій функціонування ринку зерна в Казахстані. Інтерес представив аналіз показників виробництва, споживання, експорту та імпорту, динаміки цін і показника самозабезпечення зерном у Казахстані за 2019-2023 роки. У дослідженні аналізувалися офіційні статистичні дані функціонування казахстанської сільськогосподарської галузі та ринку зерна. У цьому дослідженні було проведено комплексний аналіз ринку зернових. В результаті аналізу статистичних даних встановлено як позитивні, так і негативні тенденції, які чинили значний вплив на ринок зернових культур в Казахстані за 2019-2023 роки і продовольче самозабезпечення країни. У результаті аналізу встановлено, що темпи виробництва знизилися на 1,7 %, а показники споживання зерна характеризувалися зниженням виробничого споживання на 16,7 %, але збільшенням споживання на посівні цілі. Особисте споживання населенням щорічно не перевищувало 1,1 % від загального обсягу використання зерна в країні. Збільшення посівних площ на 3,9 % не призвело до збільшення врожайності, яка зменшилася на 9,6 %. Найбільша врожайність спостерігалася в Кизилординській області, де найбільше вирощувалася пшениця. Імпорт не перевищував експорт, але з плином часу збільшився більш ніж у 7 разів. За досліджуваний період збільшилися запаси зерна в країні на 9 % та значним збільшенням цін на ринку. Такі показники не завадили Казахстану залишатися країною з високим рівнем самозабезпечення зерном і надають можливість надалі розвивати експорт зернових культур. Дане дослідження вносить нові дані в майбутній розвиток ринку зерна в країні, оскільки встановлено, що експортоорієнтована стратегія з подальшим збільшенням виробництва може бути одним із варіантів успішного розвитку галузі без загрози продовольчої кризи та зі збереженням високого рівня самозабезпечення зерном

Ключові слова: виробництво; посівна площа; рівень самозабезпечення; баланс ресурсів; індекс цін

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Erratum: Technological Aspects of Energy-Efficient High-Quality Cleaning of Indoor Air from Harmful Impurities

Erratum: Технологічні аспекти енергоефективного високоякісного очищення повітряного середовища приміщень від шкідливих домішок

Dear readers,

There was a technical error in the paper “Technological Aspects of Energy-Efficient High-Quality Cleaning of Indoor Air from Harmful Impurities” Vol. 24, No. 4, “Pages 17-24 ([https://doi.org/10.48077/scihor.24\(4\).2021.17-24](https://doi.org/10.48077/scihor.24(4).2021.17-24)):

A note was omitted during the layout:

“*Conflict of interest: none.*”

The editors apologise for the inaccuracy and assure you that no conflict of interest arose during the preparation and publication of this article.

Thank you for understanding.

Sincerely yours,
Editorial team



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