УДК 502/504; 57; 63

НАУКОВІ ДОПОВІДІ НАЦІОНАЛЬНОГО УНІВЕРСИТЕТУ БІОРЕСУРСІВ І ПРИРОДОКОРИСТУВАННЯ УКРАЇНИ

Засновник:
Національний університет біоресурсів і природокористування України

Рік заснування: 2005

Рекомендовано до друку та поширення
через мережу Інтернет Вченою радою
Національного університету біоресурсів і природокористування України
(протокол №10 від 25 квітня 2025 р.)

Державна реєстрація:
Ідентифікатор медіа – R40-02082.
Рішення Національної Ради України з питань телебачення і радіомовлення
№ 1471, протокол № 28 від 23.11.2023 р.

Журнал входить до переліку
наукових фахових видань України
Категорія «Б». Спеціальності: 091 – Біологія, 101 – Екологія, 162 – Біотехнології та біоінженерія, 201 – Агрономія, 204 – Технологія виробництва і переробки продукції тваринництва, 205 – Лісове господарство, 206 – Садово-паркове господарство, 211 – Ветеринарна медицина, 212 – Ветеринарна гігієна, санітарія і експертиза (наказ МОН України № 409 від 14 березня 2020 року),
131 – Прикладна механіка, 133 – Галузеве машинобудування
(наказ МОН України № 886 від 02 липня 2020 року).

Журнал представлено у міжнародних наукометричних базах даних,
репозитаріях та пошукових системах:
Google Scholar, Національна бібліотека України імені В. І. Вернадського, BASE, AGRIS, Ulrichsweb, ERIH PLUS, Dimensions, University of Oslo Library, OUCI (Open Ukrainian Citation Index), Polska Bibliografia Naukowa, DOAJ, CABI, Litmaps, EBSCO

Адреса редакції:
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
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UDC 502/504; 57; 63

SCIENTIFIC REPORTS OF THE NATIONAL UNIVERSITY OF LIFE AND ENVIRONMENTAL SCIENCES OF UKRAINE

Founder:
National University of Life and Environmental Sciences of Ukraine

Year of foundation: 2005

Recommended for printing and distribution
via the Internet by the Academic Council
of National University of Life and Environmental Sciences of Ukraine
(Minutes No. 10 of April 25, 2025)

State Registration:
Media identifier - R40-02082.
Decision of the National Council of Television and Radio Broadcasting of Ukraine
No. 1471, Minutes No. 28, dated 23.11.2023.

The journal is included in the list
of Professional Scientific Publications of Ukraine
Category "B". Specialties: 0511 – Biology, 0521 – Environmental Sciences, 0522 – Natural Environments and Wildlife, 0512 – Biochemistry, 0811 – Crop and Livestock Production, 0821 – Forestry, 0812 – Horticulture, 0841 – Veterinary
(Order of the Ministry of Education and Science of Ukraine No. 409 of 14 March 2020),
0715 – Mechanics and Metal Trades, 0716 – Motor Vehicles, Ships and Aircraft
(Order of the Ministry of Education and Science of Ukraine No. 886 of 02 July 2020).

The journal is presented international scientometric databases, repositories and scientific systems:
Google Scholar, Vernadsky National Library of Ukraine, BASE, AGRIS, Ulrichsweb, ERIH PLUS, Dimensions, University of Oslo Library, OUCI (Open Ukrainian Citation Index), Polska Bibliografia Naukowa, DOAJ, CABI, Litmaps, EBSCO

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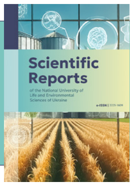
Received 26.11.2024 Revised 20.02.2025 Accepted 25.04.2025

Vol. 21, No. 2
2025



Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 633.111"324"-045.45

DOI: 10.31548/dopovidi/2.2025.09

Analysis of soft winter wheat hybrids for main morphological and productive traits of the ear

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Abstract. The study aimed to calculate the general combining ability of winter bread wheat varieties as maternal and paternal components for the main morphological and productive traits of the ear, to determine the level of variability of these traits and to identify promising genotypes for use in breeding programmes. In the study, F_1 hybrids of soft winter wheat obtained by crossing six varieties according to the full diaphyletic scheme were studied. The hybrids were evaluated based on the main indicators of ear productivity: length of the ear rod, weight of the ear, number of ears and grains in the ear, and weight of grains. To determine the general combining ability (GCA) of hybrids, a methodology was used that involves the evaluation of each variety as a mother and father component. Moreover, the index of phenotypic dominance of traits was determined to assess the inheritance of productivity and its structural elements. Significant variability in F_1 hybrids in terms of ear productivity was found. The highest rates of GCA as a maternal component were observed in the varieties Katrusia Poliska and Svitanok Myronivskyi, and as a paternal component in Myronivska 808, Nezabudka, and Svitanok Myronivskyi. For most hybrids, partial or complete dominance of individual traits was observed, indicating the influence of dominant genes on their formation. The calculation of the index of phenotypic dominance shows that for most hybrids, the index ranged from 0 to 1, which confirms partial dominance with the advantage of the best parental forms. The highest values of ear weight dominance were found in the following

Suggested Citation:
Havryliuk, I., & Kovalyshyna, H. (2025). Analysis of soft winter wheat hybrids for main morphological and productive traits of the ear. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 21(2), 9-23. doi: 10.31548/dopovidi/2.2025.09.

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combinations: Katrusia Poliska × Nezabudka, Myronivska 808 × Vodohrai, Katrusia Poliska × Myronivska 808. The results of the study indicate that the use of different varieties of soft winter wheat for crosses can provide promising hybrids with improved ear productivity. Observations of the inheritance of productive traits confirmed that partial and complete dominance are typical for most hybrids

Keywords: combinational ability; degree of phenotypic dominance; hybrid combination; parental components; inheritance; spikelet structure

Introduction

Ear traits are central in wheat yield formation, as their morphology and productivity determine the main elements of the yield structure. In the context of an unstable climate, declining natural soil fertility and growing demand for high-quality grain, the study of intraspecific variability and breeding potential of new hybrids is of particular importance. Indicators related to the structure of the ear, the amount and weight of grain are critical for assessing the adaptability of varieties, their plasticity and efficiency under different agricultural-environmental stresses. Therefore, a systematic analysis of these traits is a reasonable approach to the selection of breeding material aimed at increasing crop productivity.

According to the State Statistics Service of Ukraine, the area under wheat in Ukraine was growing until 2021, when it reached 7095 thousand hectares. However, after the outbreak of hostilities in the country, there was a significant reduction in these areas, and as of 2023, they amounted to only 4665 thousand hectares (State Statistics Service of Ukraine, n.d.). Given this, one of the ways to increase grain production is to develop new high-yielding winter wheat varieties.

The development of winter wheat varieties with high productive potential and universal use is an important area of breeding. In this regard, one of the most urgent problems is to determine the morphological and physiological parameters most closely related to the high level of winter wheat productivity. Studies have shown that important parameters that affect productivity are such characteristics as the length of the ear rod, the number of ears and grains in the ear, and the weight of grain per ear. H.S. Koliucha *et al.* (2016) analysed the use of representatives of the genus *Aegilops* as a source of resistance traits to major foliar diseases and grain quality for breeding soft winter wheat. The study emphasises the importance of wild relatives of cultivated cereals in the formation of immunity against pathogens, in the context of increasing biotic stress, which determines the research relevance for breeding programmes aimed at improving the resistance of varieties.

V.D. Tromsyuk & V.D. Bugayov (2021) in the research on winter triticale emphasised the importance of preliminary evaluation of parental forms in the development of high-yielding varieties, by studying the manifestation of heterosis and the nature of inheritance of the main productivity traits. The use of diallel analysis identified hybrid combinations with high performance for such traits as productive bushiness, number of grains per ear and grain weight per plant.

I. Havryliuk & H. Kovalyshyna (2024) evaluated soft winter wheat varieties by yield structure and grain quality indicators. The authors analysed the elements of productivity (number of ears, grains, weight of 1000 grains) that determine the yield potential of the variety. The study highlighted the importance of a comprehensive assessment of the morphological and qualitative traits of the ear to develop high-performance forms with improved baking properties. M.M. Kamara *et al.* (2022) investigated the genetic potential and models of inheritance of physiological, agronomic and quality traits of bread wheat under conditions of normal moisture and water deficit. The authors noted a significant influence of genotype on the manifestation of traits such as ear length, number of grains and total productivity. The study determined that under stressful conditions, the heritability of some trait changes, which requires a differentiated approach to breeding in a changing climate.

In modern research on soft winter wheat breeding, the development of high-yielding varieties adapted to changing climate conditions are prioritised. One of the most important areas is the study of morphological and productive traits of the ear, which have the greatest impact on yield formation. Scientists K. Din *et al.* (2021) demonstrated the importance of such indicators as the length of the ear rod, the number of ears per ear, the number of grains per ear, and the weight of grains, which directly correlate with the level of productivity. V.T. Kolyuchyi *et al.* (2007) and N.M. Bunyak (2023) emphasised the importance of morphological and physiological traits as indicators of wheat productivity potential. They emphasised that to develop high-yielding wheat varieties, it is necessary to consider not only general agronomic characteristics, but also a deep understanding of the heritability of these traits. They also noted that the development of new varieties requires an integrated approach that includes the use of adaptive resources, such as resistance to adverse environmental factors.

O.O. Filitska (2022) highlighted the prospects for improving wheat genotypes by increasing the potential and actual productivity of the ear, by studying the characteristics of the ear rod and the number of ears per ear. The study emphasised the importance of studying the physiology of the ear, as this organ has the greatest impact on yield formation. Furthermore, the length of the spikelet and the number of spikelets in the ear significantly affect the grain weight, which is an important criterion for breeding work. The search for genetic features of inheritance of these traits is an important part of modern breeding. S. El Hanafi *et al.* (2022) determined that the assessment of the general combining ability of F_1 hybrids improves the accuracy of the determination of the prospects of crosses to obtain varieties with high productivity.

Thus, numerous studies confirm the importance of an in-depth study of morphological and productive traits of winter durum wheat ears. This can be used to develop new varieties with high productivity levels, which is highly relevant for ensuring food security in the face of global climate change and geopolitical challenges.

The study aimed to investigate the general combining ability of F_1 winter wheat hybrids in terms of yield structure, in particular, ear length, ear weight, number of ears per ear, number of grains per ear and weight of grains per ear. The study assessed the genetic features of inheritance of these traits in hybrid combinations, analysing phenotypic dominance for increasing productivity and breeding improvement of winter soft wheat varieties.

Materials and Methods

The study of F_1 winter soft wheat hybrids was conducted in the 2023/24 growing season in two locations: on the breeding fields of the National Research Centre "Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine" and the Production Unit "Agronomic Research Station" of the National University of Life and Environmental Sciences of Ukraine. The study complied with the standards set out in the Convention on Biological Diversity (1992). The crosses were conducted between 6 winter wheat varieties (Nezabudka, Myronivska 808, Svitanok Myronivskyi, Sonata Odesa, Vodohrai and Katrusia Poliska) in a full diallel scheme on the breeding fields of the National Research Centre "Institute of Agriculture of NAAS of Ukraine" (Table 1).

Table 1. *Crossing of soft winter wheat varieties according to the full diaphyletic scheme*

	Nezabudka	Mironovskaya 808	Svitanok Myronivskyi	Sonata Odesa	Vodohrai	Katrusia Poliska
Nezabudka	–	+	+	+	+	+
Mironovskaya 808	+	–	+	+	+	+

***Table 1.** Continued*

	Nezabudka	Mironovskaya 808	Svitanok Myronivskyi	Sonata Odesa	Vodohrai	Katrusia Poliska
Svitanok Myronivskyi	+	+	–	+	+	+
Sonata Odesa	+	+	+	–	+	+
Vodohrai	+	+	+	+	–	+
Katrusia Poliska	+	+	+	+	+	–

Source: compiled by the authors based on research

To evaluate F_1 hybrids of soft winter wheat by the main indicators of ear productivity, the method of determining the general combining ability (GCA) was used. The hybrids were evaluated by the following parameters: length of the ear rod (cm), weight of the ear (g), number of ears per ear (pcs.), number of grains per ear (pcs.) and weight of grains per ear (g). The index of phenotypic dominance of traits (*h*) was used to determine the inheritance of productivity and its structural elements in the first generation of winter bread wheat hybrids. The dominance index was determined by the formula (Griffing, 1950):

$$h = \frac{F_1 - P_{min}}{P_{max} - P_{min}}, \quad (1)$$

F_1 – average value of the trait in the hybrid generation; P_{max} – average value of the trait in the parental form with the higher index; P_{min} – average value of the trait in the parental form with the lower index. This approach, based on modern genetic evaluation methods (Spriazhka & Zhemoida, 2022), can accurately determine the potential of hybrids to express productivity traits under different growing conditions and justify their use in the breeding process. The results were interpreted as follows (Beil & Atkins, 1965):

$h = 0$ – absence of dominance (AD) – additive effect of genes;

$0 < h < 1$ – partial dominance (PD);

$h = 1$ – complete dominance (CD);

$h > 1$ – superdominance (SD);

$h < 0$ – negative dominance (ND) – hybrid inferior to parents.

Each variety was evaluated for its general combining ability as a mother and father component. Observations and records were made following generally accepted methods (Tkachyk, 2016).

Results and Discussion

The degree of phenotypic dominance of traits. The distribution of F_1 winter wheat hybrids by the degree of phenotypic dominance (*h*) indicates the predominance of superdominance for most of the studied traits, which indicates a significant effect of heterosis (Fig. 1). The largest number of hybrids with the manifestation of dominance was observed for ear weight (15 hybrids) and grain weight per ear (12 hybrids), which indicates the important role of dominant alleles in the control of productive traits and their high breeding value. A similar trend was observed for the length of the ear spike, where 11 hybrid combinations demonstrated superdominance.

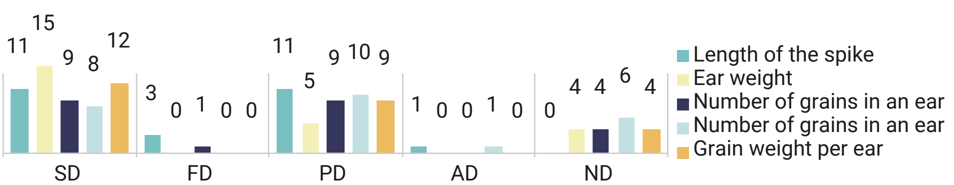

***Figure 1.** Distribution of first-generation winter soft wheat hybrids by h*

Note: SD – superdominance; FD – full dominance; PD – partial dominance; AD – absence of dominance – additive gene action; ND – negative dominance

Source: compiled by the author based on research

Partial dominance, characterised by a relatively weak expression of dominant alleles, was common among hybrids for ear length (11 cases), number of ears per ear (9), weight per ear (9) and number of grains per ear (10). This indicates the intermediate nature of the inheritance of these traits, which can complicate the selection process in the early stages. Complete dominance of traits was less common. The analysis detected in three F_1 hybrids for the length of the spikelet and some cases, for the number of spikelets per ear. The absence of dominance was recorded only in 2 hybrid combinations.

Negative dominance, in which hybrid combinations are inferior to both parental forms, was recorded in four to six hybrids, depending on the trait. Most of these cases were observed for the number of grains per ear (6 hybrids) and ear weight (4 hybrids). According to K. Din *et al.* (2021), who conducted a line × tester combining ability analysis in hybrid populations of winter bread wheat to assess genetic differences, inheritance of valuable economic traits, and determine heritability traits, the analysis determined that most of the studied traits are controlled by dominant genes. The obtained values of the degree of dominance indicated the predominance of non-additive gene action, therefore, the authors concluded that the selection of promising populations should be postponed until the next segregating generations to achieve greater breeding efficiency.

Thus, based on the weight of the ear, the trait was observed to be superdominant in most hybrids; based on the length of the ear and the number of spikelets in the ear, the trait was superdominant and partially dominant; based on the number of grains in the ear, the trait was mostly partially dominant; and based on the weight of the grains in the ear, the trait was superdominant. D.E. Qulmamatova *et al.* (2022), determining the genetic potential of spring durum wheat (*Triticum aestivum* L.) populations of first and subsequent generations of hybrids for yield traits, also found that the number of grains and grain weight per ear are inherited by the type of gene action, superdominance in F_1 hybrids.

In the study of the degree of phenotypic dominance (*h*) in hybrid combinations of soft winter wheat, significant variability in the inheritance of the studied traits was observed (Table 2). The highest values of superdominance ($h > 1$) were found for ear weight in the following combinations: Katrusya Poliska × Nezabudka ($h = 17.6$, Fig. 2), Mironivska 808 × Vodograi ($h = 7.5$) and Katrusya Poliska × Mironivska 808 ($h = 5.8$). This indicates a high potential for heterosis and the possibility of using these hybrids in breeding to increase productivity.

Table 2. *The degree of phenotypic dominance in F_1 hybrids*

Hybrid combination	The degree of phenotypic dominance (*h*) by				
	the length of the spikelet	ear weight	number of spikelets in an ear	number of grains in an ear	weight of grains per ear
Nezabudka × Mironovskaya 808	**2.5***	0.6	1.2	0.2	0.2
Nezabudka × Svitanok Mironovskiy	0.0	0.1	0.3	0.4	-0.3
Nezabudka × Sonata Odesa	0.3	0.2	0.3	0.0	0.1
Mironovskaya 808 × Nezabudka	1.0	**1.2***	**1.0***	0.6	**1.1***
Mironovskaya 808 × Svitanok Mironovskiy	**3.7***	-0.1	0.5	-1.4	-0.2
Mironovskaya 808 × Sonata Odesa	0.3	0.6	-1.6	0.4	0.4
Mironovskaya 808 × Vodohrai	**1.0***	**7.5***	**1.2***	-0.4	0.3
Mironovskaya 808 × Katrusia Poliska	**1.3***	-0.3	-0.6	-1.5	-0.8
Svitanok Myronivskyi × Nezabudka	0.7	0.9	**1.0***	**4.7***	0.9
Svitanok Myronivskyi × Sonata Odesa	0.7	**2.0***	**4.0***	**1.3***	**2.0***

***Table 2.** Continued*

Hybrid combination	The degree of phenotypic dominance (*h*) by				
	The length of the spikelet	ear weight	Number of spikelets in an ear	number of grains in an ear	weight of grains per ear
Svitanok Myronivskyi × Katrusia Poliska	0.6	**1.5***	**1.3***	0.4	**2.6***
Sonata Odesa × Nezabudka	**1.1***	**2.9***	0.9	0.1	0.5
Sonata Odesa × Mironovskaya 808	**1.3***	**1.9***	**3.5***	0.7	**1.7***
Sonata Odesa × Svitanok Myronivskyi	0.7	**1.2***	**1.1***	**1.6***	**1.8***
Sonata Odesa × Vodohrai	0.4	**1.4***	-0.8	0.4	0.6
Sonata Odesa × Katrusia Poliska	0.9	0.5	0.3	-0.2	0.6
Vodograi × Nezabudka (defect)	0.5	**2.1***	0.6	**23.3***	**1.5***
Vodohrai × Mironovskaya 808	**1.9***	**2.3***	0.7	0.1	**1.2***
Vodohrai × Svitanok Mironovskiy	**2.2***	**1.6***	**2.4***	**1.1***	0.5
Vodohrai × Sonata Odesa	0.3	-0.7	-0.7	0.2	**2.2***
Vodohrai × Katryna Poliska	**1.4***	1.7	0.6	**1.8***	**1.2***
Katrina Poliska × Nezabudka	**2.0***	17.6	**1.2***	**2.0***	**3.2***
Katrusia Poliska × Mironovskaya 808	**1.0***	5.8	0.8	-0.6	**3.8***
Katrusia Poliska × Svitanok Myronivskyi	**2.8***	1.1	**2.8***	**4.8***	**1.8***
Katrusia Poliska × Sonada Odesa	0.4	-5.3	**2.0***	-0.1	-2.3

Note: * – the values of indicators indicating the dominance of the trait in the hybrid combination are highlighted
Source: compiled by the authors based on research

***Figure 2.** Hybrid combination Katrusia Poliska × Nezabudka*
Note: ♀ – Katrusia Poliska, ♂ – Nezabudka, F_1 – a hybrid between the two
Source: compiled by the authors based on research

***Figure 3.** Hybrid combination Katrusia Poliska × Svitanok Myronivskyi*
Note: ♀ – Katrusia Poliska, ♂ – Svitanok Myronivskyi, F_1 – a hybrid between the two
Source: compiled by the authors based on research

In terms of spikelet length, the highest *h* values were found in the hybrids Myronivska 808 × Svitanok Myronivskyi (3.7) and Katrusia Poliska × Svitanok Myronivskyi (2.8) (Fig. 3). At the same time, in some hybrids, such as Nezabudka × Svitanok Myronivskyi (0.0), there was no dominance effect.

In terms of the number of spikelets per ear, a wide amplitude of variation in phenotypic dominance was observed: the highest level was observed in Svitanok Myronivskyi × Sonata Odeska (4.0) and Sonata Odeska × Myronivska 808 (3.5), indicating a high heterosis effect. However, there are negative *h* values in some combinations, such as Myronivska 808 × Sonata Odesa (-1.6) and Sonata Odesa × Vodohrai (-0.8).

In terms of the number of grains per ear, the hybrid combination Vodohrai × Nezabudka had a high dominance value (23.3). High values were also found in the combinations Katrusia Poliska × Svitanok Mironivskyi (4.8) and Svitanok Mironivskyi × Nezabudka (4.7, Fig. 4), which indicates a positive effect of dominant genes in these combinations. At the same time, in some combinations, in particular Myronivska 808 × Katrusia Poliska (-1.5) and Myronivska 808 × Svitanok Myronivskyi (-1.4), the effect of negative dominance of the trait was observed, which indicates their kinship and limits their effectiveness in breeding programmes.

Figure 4. *Hybrid combination Svitanok Myronivskyi × Nezabudka*
Note: ♀ – Svitanok Myronivskyi, ♂ – Nezabudka, F_1 – a hybrid between the two
Source: compiled by the authors based on research

The weight of grains per ear also varied widely. The maximum values of *h* were observed in the hybrid combinations Katrusia Poliska × Myronivska 808 (3.8) and Katrusia Poliska × Nezabudka (3.2, Fig. 2), indicating a significant heterotic effect. At the same time, in some combinations, such as Katrusia Poliska × Sonata Odesa (-2.3, Fig. 5) and Myronivska 808 × Katrusia Poliska (-0.8), a negative dominance value was observed. The dominance of most of the studied traits was observed in hybrid combinations: Svitanok Myronivskyi x Sonata Odesa (Fig. 6), Sonata Odesa x Myronivska 808, Sonata Odesa × Svitanok Myronivskyi (Fig. 7), Vodohrai × Svitanok Myronivskyi (Fig. 8), Katrusia Poliska × Nezabudka (Fig. 2), Katrusia Poliska × Svitanok Myronivskyi (Fig. 3). In the hybrid combination Svitanok Myronivskyi × Sonata Odeska, the dominance was observed for the following traits: ear weight (*h* = 2.0), number of spikelets per ear (*h* = 4.0), number of grains per ear (*h* = 1.3), weight of grains per ear (*h* = 2.0).

Figure 5. *Hybrid combination Katrusia Poliska × Svitanok Myronivskyi*
Note: ♀ – Katrusia Poliska, ♂ – Svitanok Myronivskyi, F_1 – a hybrid between the two
Source: compiled by the authors based on research

Figure 6. *Hybrid combination Svitanok Myronivskyi × Sonata Odesa*
Note: ♀ – Katrusia Poliska, ♂ – Svitanok Myronivskyi, F_1 – a hybrid between the two
Source: compiled by the authors based on research

Figure 7. *Hybrid combination Sonata Odesa × Svitanok Myronivskyi*

Note: ♀ – Katrusia Poliska, ♂ – Svitanok Myronivskyi, F_1 – a hybrid between the two

Source: compiled by the authors based on research

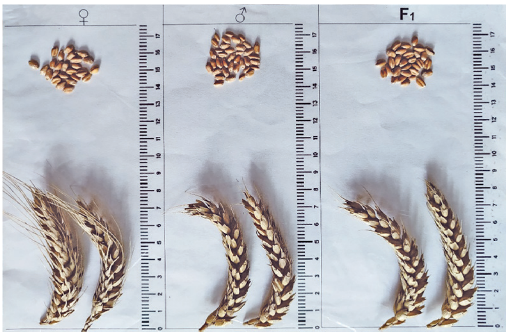

Figure 8. *Hybrid combination Vodohrai x Svitanok Myronivskyi*

Note: ♀ – Vodohrai, ♂ – Svitanok Myronivskyi, F_1 – a hybrid between the two

Source: compiled by the authors based on research

In the hybrid combination Sonata Odessa x Svitanok Myronivsky, superdominance was noted for the following traits: ear weight ($h = 1.2$), number of spikelets per ear ($h = 1.1$), number of grains per ear ($h = 1.6$), and grain weight per ear ($h = 1.8$). In the hybrid combination of Vodogray × Svitank Myronivsky, superdominance was observed in the following traits: length of the rachis ($h = 2.2$), ear weight ($h = 1.6$), number of spikelets per ear ($h = 2.4$), number of grains per ear ($h = 1.1$).

High rates of phenotypic dominance of ear length were also noted by M. Mohammadi *et al.* (2021), as a result of a study of hybrid combinations between durum wheat and Emmer wheat (*Triticum turgidum* ssp. *dicoccum*), where significant genetic variability and the presence of overdominance in several valuable agricultural traits, including ear length, were found. Incorporating the dominant type of inheritance of this trait, the authors recommend selective breeding in the next generations, when the manifestation of heterosis is partially stabilised, which will contribute to more efficient consolidation of valuable genotypes.

Similar results were obtained by H. Ustynova *et al.* (2024), who studied the inheritance of ear length in winter bread wheat hybrids with the participation of early and medium early, medium early and medium late varieties. In most combinations, the inheritance of this trait was of the positive dominance type. The authors found a significant level of heterosis for spike length in F_1 and frequent manifestation of positive transgressions in the second generation of F_2 (26 out of 40 combinations in 2019-2020), which indicates the active formation of new recombinations and confirms the feasibility of selection for this trait in subsequent generations.

S. Khomenko *et al.* (2021) noted that most F_1 wheat hybrids showed the phenomenon of overdominance and partial dominance for traits such as ear length and number of grains per ear. The authors highlighted the importance of selecting a trait system that ensure genetic progress and improve yield potential in breeding programmes. They determined that most wheat hybrids (64.3%) are characterised by superdominance and partial dominance for the following traits: ear length and number of grains per ear. According to their research, it is advisable to select for these traits in future generations to create new promising wheat lines.

M.M. Kamara *et al.* (2022) highlighted the high potential for improving wheat genotypes by increasing the number of grains per ear, which is an important aspect for increasing productivity, especially under water stress. The authors noted that by optimising parameters such as the number of grains per ear, the overall yield could be significantly increased. The study, which included the evaluation of different wheat genotypes under normal and drought conditions, showed that water deficit significantly reduced chlorophyll content, photosynthetic efficiency, grain moisture and other agronomic traits, including the number of grains per ear. However, a significant positive correlation was also observed between physiological parameters such as chlorophyll content, relative plant water content and grain yield under water deficit conditions. Thus, optimisation of traits such as the number of grains per ear is one of the factors in wheat breeding to increase its yield under climate change.

D.E. Qulmamatova *et al*. (2022) argued that ear traits are inherited by dominance from the best parental component. The study, which included the analysis of the genetic potential of winter bread wheat populations, determined that F_1 hybrids obtained by crossing six varieties demonstrate inheritance of spikelet structure traits by type of dominance. The analysis of the spikelet structure in F_1 hybrids showed that the number of grains in the spikelet and grain weight are inherited by the type of superdominance, which means the predominant influence of one of the parental components, which shows higher performance in these characteristics. The highest values for the number of grains and grain weight were observed in hybrids obtained in combinations with high-yielding parental components, which confirms the possibility of using such populations for further breeding to improve these traits.

Similar patterns of trait inheritance were established in the studies of I.A. Khorsun (2012) and S.S. Yurchuk (2024), based on the analysis of hybrid populations of soybean and winter rape to determine the degree of heterosis and type of trait dominance. The authors emphasised that in the presence of a high degree of dominance of a certain valuable economic trait, selection can be effective in the first generations. This opened prospects for the development of crossbreeding programmes with predictable transmission of valuable traits to offspring, which is a relevant approach for wheat breeding, for the characteristics of the ear structure.

General combining ability. The papers by M.M. Kamara *et al*. (2021) and T. Begna (2021) highlighted the importance of combinational ability for optimising wheat crossing schemes, as it can be used for new hybrid combinations with high productivity and resistance to adverse conditions. The researchers noted that to create adapted varieties, it is important not only to select maternal and paternal forms but also to correctly predict the inheritance of the main productive traits in hybrids.

Table 3 shows the results of the evaluation of the general combining ability (GCA) of winter soft wheat varieties as parent components in terms of ear structure in two different locations. The data indicate variability of GCA depending on the variety and growing conditions (locations).

Table 3. *General combining ability of soft winter wheat varieties as a mother component in terms of ear structure*

Varieties	Length of the spikelet		Spike weight		Number of spikelets in an ear		Number of grains in an ear		Grain weight from the ear	
	I	II	I	II	I	II	I	II	I	II
Nezabudka	-0.50	-0.57	-0.48	-0.67	-2.18	-2.60	-8.63	-8.37	-0.38	-0.45
Mironovskaya 808	-0.27	-0.24	-0.13	-0.39	-0.30	-1.02	-4.89	-6.26	-0.17	-0.41
Svitanok Myronivskyi	0.04	-0.10	-0.05	0.49	0.30	0.80	1.09	**8.75***	-0.05	**0.48***
Sonata Odesa	**0.41***	0.47	0.22	0.09	0.98	0.30	5.17	-0.63	**0.24***	-0.01
Vodohrai	0.02	-0.35	0.01	-0.16	-0.54	-0.16	1.01	-0.07	0.15	-0.02
Katrusia Poliska	0.29	**0.79***	**0.42***	**0.64***	**1.74***	**2.67***	**6.25***	6.59	0.20	**0.43***

Table 3. *Continued*

Varieties	Length of the spikelet		Spike weight		Number of spikelets in an ear		Number of grains in an ear		Grain weight from the ear	
	I	II	I	II	I	II	I	II	I	II
s^2	0.12	0.27	0.10	0.26	1.84	3.14	33.28	45.89	0.06	0.16
n	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
s	0.34	0.52	0.31	0.50	1.36	1.77	5.77	6.77	0.24	0.40
SE	0.14	0.21	0.13	0.21	0.55	0.72	2.36	2.77	0.10	0.16
$LSD_{0.05}$	0.34	0.52	0.31	0.51	1.36	1.77	5.77	6.78	0.24	0.40

Note: research locations are marked as I (breeding fields of the National Research Centre "Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine") and II (Agronomic Research Station of the National University of Life and Environmental Sciences of Ukraine); * – highlighted values of indicators are significantly higher than the average

Source: compiled by the authors based on research

In the breeding fields of the National Research Centre "Institute of Agriculture of NAAS of Ukraine" (location I), the variety Sonata Odesa was identified, which had significantly high values of the GCA for the length of the ear rod (0.41) and the weight of grain per ear (0.24). However, these values did not exceed the threshold of reliability in the second location and therefore cannot be considered stable. Similarly, Katrusia Poliska demonstrated a high level of GCA for the number of grains per ear (6.25), but the value was also not significantly higher than the average in the second location, indicating limited stability of the effect across locations. In the second location of the SE "Agronomic Experimental Station" of the National University of Life and Environmental Sciences of Ukraine (location II), significantly high values of the GCA for the trait number of grains per ear (8.75) and grain weight per ear (0.48) were found in Svitanok Myronivskyi, but the values did not exceed the threshold of reliability in the first location. In addition, Katrusia Poliska showed significantly high effects of GCA for ear length (0.79) and grain weight per ear (0.43) only in the same location.

At the same time, negative values of the GCA were recorded for the varieties Nezabudka, Myronivska 808 and Vodograi, which did not show significantly positive values of the GCA for any of the studied traits in both locations. This indicates a low potential for their use as mother components in breeding programmes. Significantly high values of the GCA in both locations were noted only for the variety Katrusia Poliska in terms of ear weight and number of spikelets per ear. Thus, according to the results of the GCA, among the studied varieties, Katrusia Poliska as a maternal component can be a universal donor of high spike weight and number of spikelets per spikelet. The varieties Svitanok Myronivskyi and Sonata Odeska require additional research under other conditions to establish their value as a maternal component for improving spike structure, and the varieties Nezabudka, Myronivska 808 and Vodograi are not advisable to use for such purposes.

According to the results of the analysis of the GCA of soft winter wheat varieties as the parental component (Table 4), significant differences between varieties and locations were also noted. At the location of the Agronomic Research Station of the National University of Life and Environmental Sciences of Ukraine, the varieties Nezabudka and Sonata Odessa were noted as parental components with a high statistically significant GCA rating for ear weight (0.38) and grain weight (0.15), respectively (Table 4). At the breeding fields of the National Scientific Centre "Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine", the varieties Mironivska 808 for ear weight (0.17) and Katrusya Poliska for grain weight per ear (0.11) were noted. Among the studied varieties, as a parental component, a reliably high level of GCA was noted in two locations for Myronivska 808 in terms of spike length (I 1.06, II 0.54) and number of spikelets in the spike (I 0.94, II 4.83), Svitanok Myronivsky in terms of the number of grains in the spike (I 4.99, II 4.83).

Table 4. *General combinability of soft winter wheat varieties as parental components based on ear structure indicators*

Varieties	Length of the spikelet		Spike weight		Number of spikelets in an ear		Number of grains in an ear		Grain weight from the ear	
	I	II	I	II	I	II	I	II	I	II
Nezabudka	0.11	0.06	-0.24	**0.38***	-1.04	-1.00	0.87	0.03	-0.12	0.06
Mironovskaya 808	**1.06***	**0.54***	**0.17***	0.22	**0.94***	**1.28***	0.39	0.17	0.04	0.09
Svitanok Myronivskyi	-1.04	-0.87	-0.04	-0.40	0.48	0.56	**4.99***	**4.83***	-0.12	-0.17
Sonata Odesa	0.09	-0.05	-0.08	-0.17	-0.90	-0.58	-4.23	-2.53	0.08	**0.15***
Vodohrai	-0.64	-0.05	0.10	-0.09	0.12	0.05	-0.41	-0.63	0.00	-0.08
Katrusia Poliska	0.41	0.36	0.10	0.07	0.40	-0.32	-1.61	-1.83	**0.11***	-0.05
s^2	0.56	0.24	0.02	0.08	0.64	0.68	9.29	6.70	0.01	0.01
n	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
s	0.75	0.49	0.15	0.28	0.80	0.82	3.05	2.59	0.10	0.12
SE	0.31	0.20	0.06	0.12	0.33	0.34	1.24	1.06	0.04	0.05
$HIP_{0.05}$	0.75	0.49	0.15	0.28	0.80	0.82	3.05	2.59	0.10	0.12

Note: research locations are marked as I (selection fields of the National Scientific Centre's Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine) and II (Agronomic Research Station of the National University of Life and Environmental Sciences of Ukraine); * highlighted values are significantly higher than average

Source: compiled by the authors based on research

Thus, for the varieties Nezabudka, Sonata Odeska and Katrusia Poliska, as a parental component, mathematically justified consistently high values of the GCA for the studied traits were not found, so they need further study in other locations. It is not advisable to use the variety Vodograi as a parental component to improve the spike structure. The variety Myronivska 808 as a parental component can serve as a universal donor to improve the spikelet length and number of spikelets per ear, and the variety Svitanok Myronivskyi as a parental component can improve the number of grains per ear.

The results of the analysis of variance indicate significant differences between varieties in terms of combinational ability, as evidenced by the values of standard deviation (s) and standard error (SE), especially in terms of the number of grains per ear. L.A. Zhivotkov *et al*. (1989) stated that due to the complexity of inheritance and the presence of high modification variability of the number of grains per ear, it is difficult to select and evaluate breeding material for this trait. This is confirmed by the results of the research, as the highest variability was found for the number of grains per ear (Tables 3 and 4). This also indicates significant genetic differences between the studied varieties and their different breeding potential in hybridisation schemes. Hence, there is a need for a more detailed study of Svitanok Myronivskyi as a parental component as a donor to improve the number of grains per ear, due to the high variability of the trait. S. Khomenko *et al.* (2021) noted the prospects of intraspecific crosses. Determining the parameters of plant productivity, the nature of their inheritance, and the combinational ability of varieties is an urgent task both in creating new varieties and in predicting the breeding and genetic effects of crosses.

Thus, the analysis confirms the expediency and necessity of an in-depth study of the combinational ability of varieties at the early stages of the breeding process. The identified differences between varieties in terms of spikelet structure indicate the potential for effective selection of parental components in hybridisation schemes. This also creates the preconditions for improving the efficiency of breeding by optimising the combination of genotypes with high overall combinational ability.

Conclusions

The study of the degree of phenotypic dominance (*h*) in hybrid combinations of soft winter wheat based on such indicators as spike length, spike weight and grain weight per spike revealed the manifestation of superdominance. This suggests that selection based on these traits may be highly effective in creating new lines. The highest values of superdominance in ear weight were found in the following hybrids: Katrusya Poliska × Nezabudka ($h = 17.6$), Mironivska 808 × Vodograi ($h = 7.5$), Katrusya Poliska × Mironivska 808 ($h = 5.8$). These hybrid combinations should be included in further breeding research and used in breeding programmes to increase the productivity of soft winter wheat.

High, statistically significant, positive effects of the overall general ability for various parameters (length of the ear rod, ear weight, number of ears and grains in the ear, weight of grain per ear) were observed in the following varieties of soft winter wheat:

- by the number of grains in the ear: Svitanok Myronivskyi (♂);
- high GCA for the complex of traits was noted in the varieties: Katrusia Poliska (♀), by ear weight and number of spikelets per ear, Myronivska 808 (♂), by ear length and number of spikelets per ear.

These varieties are recommended for use in breeding soft winter wheat as maternal and paternal components to increase crop productivity by improving such indicators as the number of grains per ear, ear weight, number of spikelets per ear and ear length.

In the context of the results obtained, a promising area for further research is an in-depth analysis of the heritability of traits in subsequent generations (F_{2-n}) using the recommended hybrid combinations. The stability of heterosis in different soil and climatic conditions and under variable agrophysical conditions should be prioritised. It is also advisable to conduct molecular genetic studies to identify markers associated with the manifestation of superdominance and high combinational ability, which will improve the accuracy of parental form selection and accelerate the development of new productive winter bread varieties.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Аналіз гібридів пшениці м'якої озимої за основними морфологічними та продуктивними ознаками колоса

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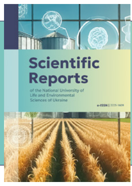
Анотація. Мета дослідження полягала у розрахунку загальної комбінаційної здатності сортів пшениці м'якої озимої у ролі материнського та батьківського компонентів за основними морфологічними та продуктивними ознаками колоса, встановленні рівня варіабельності цих показників та визначенні перспективних генотипів для використання в селекційних програмах. У ході дослідження вивчено гібриди F_1 пшениці м'якої озимої, отримані за допомогою схрещувань шести сортів за повною діалельною схемою. Оцінку гібридів здійснено за основними показниками продуктивності колоса: довжина колосового стрижня, маса колоса, число колосків і зерен у колосі, маса зерен. Для визначення загальної комбінаційної здатності (ЗКЗ) гібридів використано методику, що передбачає оцінку кожного сорту як материнського та батьківського компонентів. Також проведено визначення індексу фенотипового домінування ознак для оцінки успадкування продуктивності та її структурних елементів. Встановлено значну варіативність у гібридах F_1 за показниками продуктивності колоса. Найвищі показники ЗКЗ у ролі материнського компонента мали сорти Катруся Поліська, Світанок Миронівський, а у ролі батьківського – Миронівська 808, Незабудка, Світанок Миронівський. Для більшості гібридів спостерігали часткове або повне домінування окремих ознак, що вказує на вплив домінантних генів на їх формування. Розрахунок індексу фенотипового домінування свідчить, що для більшості гібридів індекс варіював від 0 до 1, що підтвердило часткове домінування з перевагою кращих батьківських форм. Найвищі значення наддомінування за масою колоса встановлено в таких комбінаціях: Катруся Поліська × Незабудка, Миронівська 808 × Водограй, Катруся Поліська × Миронівська 808. Результати дослідження свідчать, що використання різних сортів пшениці м'якої озимої для схрещувань дозволяє отримати перспективні гібриди з покращеними показниками продуктивності колоса. Спостереження за успадкуванням продуктивних ознак підтвердило, що часткове і повне домінування є характерними для більшості гібридів

Ключові слова: комбінаційна здатність; ступінь фенотипового домінування; гібридна комбінація; батьківські компоненти; успадкування; структура колоса

Received 06.01.2025 Revised 02.04.2025 Accepted 25.04.2025

Vol. 21, No. 2
2025



Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 633.854.78:631.5:581.111

DOI: 10.31548/dopovidi/2.2025.24

Water consumption of sunflower plants under the influence of cultivation technology elements

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Abstract. Proper management of the water regime of plants helps to increase yields. Insufficient or excessive water supply can negatively affect their growth and development, reducing final productivity. The purpose of the study was to identify the influence of weather conditions, fertiliser conditions, and the effect of a retardant on the productivity of sunflower hybrids. Field studies were conducted in 2021-2023 on typical low-humus chernozems. Studies have established that the decisive factor determining the level of yield and water consumption is the amount of soil moisture in 0-100 cm of the soil layer for the sowing period and the amount of precipitation for the general growing season. Total water consumption varied over the years of research: it was the lowest in 2022 and amounted to 2,533 m^3/ha, and the largest – in 2023 – 3,645 m^3/ha. On average, over three years of research, the total water consumption was 3,095 m^3/ha. The coefficient of water consumption, which characterised the moisture consumption for the development of 1 tonne of seeds with

Suggested Citation:

Harbar, L., Avramchuk, V., & Dovbash, N. (2025). Water consumption of sunflower plants under the influence of cultivation technology elements. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 21(2), 24-35. doi: 10.31548/dopovidi/2.2025.24.

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the corresponding amount of by-products, changed under the influence of weather and climatic conditions of the year, morphobiological features of the hybrids that were studied, technological methods, fertiliser optimisation, and in 2021 amounted to 822 to 1,546 m^3/t; in 2022 – 716 to 1,299, and in 2023 – from 937 to 1,796 m^3/t. The highest water consumption rate per 1 tonne of sunflower seeds was obtained in 2023. In the RGT Wollf hybrid, it changed as fertilisation rates increased from 1,664 to 996 m^3/t, Alzan – 1,672-1,108, ES Bella – 1,796-1,187, Lime – 1,727-1,115 m^3/t. The use of Setar retardant for sunflower cultivation helped to reduce the coefficient of water consumption and ensured more rational use of moisture by plants for the development of a crop unit. Fertiliser showed the greatest impact on reducing the water consumption coefficient. In the most unfavourable years of cultivation for moisture, the efficiency of using moisture by sunflower plants with nutrition optimisation increased significantly, which indicates the effectiveness of using fertilisers and the Setar retardant. The results obtained will be useful for agricultural enterprises in increasing the efficiency of resource use and improving financial results

Keywords: moisture; fertilisers; oilseeds; productivity; retardant

Introduction

Modern cultivation technologies, especially intensive hybrids, help to increase production volumes, maximising the genetic potential of the crop, which is relevant in the context of climate change. A detailed study of the morphobiological features of sunflower helps to unlock the potential of specific varieties and hybrids. Improving technological methods of cultivation creates optimal conditions for the growth and development of plants, increasing yields. Insufficient soil supply with nutrients and moisture is the main reason for low sunflower yields. Optimal sowing times help to avoid critical periods of humidity requirements. The absorption of nutrients depends on the moisture reserves in the soil: with sufficient moisture, plants better absorb nutrients, and with insufficient moisture, it is impractical to apply high fertilisation rates. Sunflower is very sensitive to fertilisers, which is a key factor in shaping its productivity (Revto & Naboka, 2022).

According to V.V. Gamayunova & V.S. Kudrina (2018), during the period of plant growth and development, a significant role is assigned to the level of water and heat resources. Less attention is paid to the the availability of effective and active temperatures, although at certain stages of plant development, these indicators have a significant impact on the passage of production processes, and this issue is now a priority and is relevant. However, the moisture supply of plants is of limiting importance in the process of growth and development, the development of productivity not only of sunflower, but also of other crops. Most of all, attention is focused on studying this issue in conditions of insufficient and unstable moisture, in which almost the entire territory of Ukraine is now located (Domaratskyi *et al.*, 2022).

When studying the process of growth and development of sunflower plants, attention is focused not only on the amount of precipitation and its distribution during the growing season of the crop, but also on the presence of moisture that will be available to plants in the soil. In addition, the influence of moisture supply on the growth and development of sunflower plants with various fertiliser options is also relevant. This can be judged by conducting biometric measurements of plants grown under different effects of nutrients and different levels of moisture supply. As noted by L. Chaves *et al.* (2014), the use of nitrogen and potassium does not significantly affect plant height. However, the introduction of phosphorus and ensuring a sufficient level of moisture have a positive effect on the specified biometric indicator. When determining the diameter of the stem, its parameters increase with the introduction of nitrogen and potassium, while the effect of phosphorus is not observed. An increase in nitrogen application rates contributes to an increase in the diameter of the sunflower stem up to 19.7% compared to options without fertilisers. In turn, the biometric parameters of sunflower plants also increased with an increase in moisture supply indicators. With an increase in productive moisture in the soil against the background of the use of fertilisers, there is also an increase in the number of leaves on the plant and the area of leaves.

In the case of sunflower cultivation, crop rotation is of great importance. Z. Dehtiarova (2023) argued that in the context of an increase in the share of sunflower in the structure of crop rotation, there is a decrease in its yield as a result of a deterioration in the availability of moisture. According to the saturation of the sunflower crop rotation by 60%, moisture consumption is at the level of 2,969 m^3/ha. When reducing the shares to 40 and 20%, the indicators were 2,713 and 2,824 m^3/ha. Studies show that with the share of sunflower in crop rotation at the level of 40%, the water consumption coefficient is the lowest.

When growing sunflower seeds, precipitation is the main source of moisture in the soil. Their number is insufficient, with an uneven distribution. The predominant amount of precipitation falls during the spring-summer growing season of crops. Analysis of weather conditions over the past 10 years shows that against the background of close indicators for crop moisture supply, there is a significant decrease in the amount of productive precipitation. Ye.O. Domaratsky *et al.* (2021) noted an increase in the number of heavy rains, which, in turn, leads to the creation of stressful conditions and has a negative impact on the growth and development of plants and their productivity. The level of yield of field crops is significantly determined by the total water consumption, moisture reserves in the 0-100 cm soil layer during sowing and precipitation during the growing season, and is characterised by a direct relationship between these indicators. Therefore, crops in years with sufficient moisture supply form higher yields.

However, providing sunflower plants with moisture at various stages of their development plays an important role in shaping crop productivity. V.F. Kaminskyi & V.V. Hanhur (2018) emphasised that sunflower is not a crop that removes a large amount of basic nutrients from the soil, as it is characterised by a compensatory return of them to the soil with by-products. However, to form a certain crop, the plant must take these minerals from the soil.

Analysing the water consumption of sunflower plants, A. Kovalenko *et al.* (2020) noted that they take as much moisture from the soil layer of 0-100 cm as it was accumulated during the pre-sowing and growing season. With insufficient precipitation during the growing season, sunflower plants can meet their needs due to the moisture reserves in the soil layer up to 200 cm by 50-60%. However, according to A.V. Panfilova & V.V. Hamaiunova (2019), this can cause problems when growing the next crop. G.V. Pinkovskyi & S.P. Tanchyk (2020) concluded that due to the emergence and introduction of new hybrids of foreign and Ukrainian breeding, which are characterised by a high adaptive potential, sowing using high-quality seed material and the use of modern technologies, it is possible to increase the level of efficiency of growing sunflower seeds due to obtaining an increased crop yield.

Thus, in the conditions of climate change and unstable water supply, increasing sunflower productivity requires a comprehensive approach that considers the interaction of agrotechnical techniques, moisture availability, and fertiliser systems. Improving cultivation technologies, considering the morphobiological features of hybrids, helps to rationalise the use of resources and optimise crop development. The purpose of the study was to determine the influence of weather conditions, fertilisers, and retardants on the productivity of sunflower hybrids.

Materials and Methods

Field research was conducted at the Agronomic Experimental Station, a separate division of the National University of Life and Environmental Sciences of Ukraine, in 2021-2023. The soils of the experimental field are typical low-humus chernozems. The humus content in the soil of the experimental field was 4.32%. Typical low-humus chernozem was characterised by an average supply of phosphorus and potassium, and low nitrogen.

The analysis of weather conditions during the years of the study shows a significant difference between the indicators, which had a significant impact on the course of sunflower production processes. They were manifested in an increase in the average daily values of air temperature indicators, which was observed in all growing seasons of the research years. The growing season of sunflower was characterised by uneven distribution of precipitation and insufficient amount, which did not allow creating optimal conditions for the passage of production processes and, accordingly, did not contribute to the maximum implementation of the genetic potential of sunflower plants. The amount of precipitation during the growing season of the crop varied by year: in 2021 it was 301.8 mm, in 2022 – 300.5, in 2023 – 441.6 mm, which was reflected in the plant productivity. The study met the requirements of the Convention on Biological Diversity (1992).

The experiment was three-factor. Factor A – sunflower hybrids (RGT Wollf, Alzan, ES Bella, Lime); Factor B – fertiliser (calculation for planned yields by the balance method); Factor C – application of retardant Setar (use in microstages BBCH 30-32, 0.5 l/ha). The experiment consisted of four repetitions. The area of the sown plot was 56 m^2, accounting – 42 m^2. The predecessor in the experiment was winter wheat. The density of sunflower plants for the harvest period was 55 thousand plants per hectare. Fertilisers were applied according to the scheme of the experiment: nitrogen – for pre-sowing cultivation, phosphorous and potassium – for main treatment. The content of available moisture in the soil was determined by the thermostatic-weight method. The total water consumption of sunflower seeds was determined by the water balance using the equation:

$$E = O + (Wn - Wk), \tag{1}$$

where *E* – amount of water consumed during the growing season, m^3/ha; *Wn, Wk* – indicators of the initial and final moisture reserve in the soil, m^3/ha; *O* – amount of precipitation during the growing season, m^3/ha. The water consumption coefficient was calculated using the equation:

$$Kw = E : Y, \tag{2}$$

where *Kw* – water consumption coefficient, m^3/t; *E* – amount of water consumed by plants during their growing season, m^3/ha, *Y* – sunflower seed yield, t/ha. In the phase of full ripeness of sunflower seeds, the amount of accumulated aboveground biomass was determined (typical plants were selected in each version of the experiment, followed by drying the attachments at temperatures of 105°C to a completely dry state of plant material and calculations were performed per 1 ha.

The sunflower seeds were collected in sections by direct harvesting. The bunker weight of seeds was recalculated for the crop from 1 ha, considering contamination and humidity in terms of 8% (DSTU 7011:2009, 2010). Based on the results of the obtained indicators, a correlation analysis was carried out between yield indicators and productive moisture reserves for the sowing period (Rozhkov *et al.*, 2016).

Results

The main sunflower crops in Ukraine are concentrated in conditions characterised by insufficient or unstable moisture levels. Under unfavourable weather conditions, the genetic potential of sunflower is only 45-50% realised. In conditions of unstable moisture, the moisture content in the soil is a limiting factor in creating favourable conditions for the growth and development of plants and their productivity. An important role, in this case, is played by the correct selection of varieties and hybrids of the crop for cultivation. The results of studies conducted in different growing areas indicate that a higher yield is formed by sunflower crops that were better provided with moisture. The amount of precipitation in the autumn-winter period and the first half of the growing season must be considered. Calculations of moisture reserves showed a significant difference in indicators over the years of research. According to them, during 2021-2023, moisture reserves in the metre-long soil layer during the sunflower growing season changed from 3,217 m^3/ha (2022) up to 4,402 m^3/ha (2023) (Table 1). Precipitation was characterised by indicators in 2021 – 2,489 m^3/ha, 2022 – 1,923, 2023 – 2,963 m^3/ha. In turn, according to calculations, moisture consumption during the growing season ranged from 2,533 to 3,645 m^3/ha. The highest indicator was received in 2023.

Table 1. *Moisture availability during the growth and development of sunflower hybrids, m^3/ha*

Year of research	Reserves of productive moisture in the soil for the sowing period, m^3/ha	Precipitation during the growing season, m^3/ha	Moisture reserves, total, m^3/ha	Moisture balance for the harvesting period, m^3/ha	Moisture consumption during the growing season, m^3/ha
2021	1,513	2,489	4,002	895	3,107
2022	1,294	1,923	3,217	684	2,533
2023	1,439	2,963	4,402	757	3,645

Source: compiled by the authors

Sunflower plants need different amounts of moisture during the growing season at different stages of development. In the period from the beginning of the development of plants and baskets, plants consume approximately 25% of all the moisture necessary for them. At this stage of development, plants use moisture from the upper layers of the soil. However, at the stages of basket development and flowering, the plant consumes about 60% of the total demand. Insufficient amount of moisture during the specified period leads to the development of underdeveloped baskets and cotyledons.

During the period of physiological ripeness (seed moisture 35-40%), there is a decrease in the intensity and speed of biological processes, physiological evaporation of water, as a result of which seeds lose up to 2.0% of moisture in dry weather conditions. The water supply of sunflower plants depends on the current level of moisture reserves in the soil and weather conditions during the growing season of the crop (precipitation, temperature, relative humidity). In conditions of a high level of soil moisture supply, sunflower plants consume moisture in increasing amplitude. One of the factors that determines the moisture consumption of sunflower plants for transpiration is the biological characteristics and genotype of the hybrid or variety, which explains the low internal resistance of water in the conducting bundles of the stem, while the low internal resistance of stomata to water vapour.

The amount of water consumed by a plant at different depths depends on the soil's moisture reserves, precipitation, and effective temperatures at a certain stage of plant development. Sunflower seeds with sufficient or excessive moisture can use moisture inefficiently. However, when growing it in arid conditions, there is a more rational use of moisture. An indicator that allows identifying the effectiveness of the impact of a particular technological measure on the use of moisture by plants, together with indicators of total water consumption, is the water consumption coefficient. The indicator shows the consumption of moisture by plants to form a unit of yield (per 1 tonne of sunflower seeds with the corresponding amount of by-products). This indicator depends on the biological characteristics of the variety or hybrid, the availability of nutrients, technological methods, and weather conditions of the growing season. The findings showed that the reserves of productive moisture during the sowing period depended on the weather characteristics of the growing year. Sunflower hybrids under study consumed an average of 305 to 495 m^3/t of water for the development of 1 tonne of dry matter over the years of research (Table 2).

Table 2. *Indicators of the coefficient of water consumption by sunflower plants per 1 tonne of dry matter of the crop, m^3/t*

Hybrid	Variant	Retardant treatment	2021	2022	2023	Average
RGT Wollf	$N_{40}P_{20}K_{60}$	1	502	420	547	492
		2	463	400	523	464
	$N_{60}P_{35}K_{90}$	1	435	401	491	444
		2	413	350	458	409
	$N_{80}P_{50}K_{120}$	1	396	352	459	404
		2	376	325	423	376
	$N_{100}P_{65}K_{150}$	1	321	296	383	335
		2	310	275	356	315
	$N_{120}P_{80}K_{180}$	1	309	271	335	307
		2	288	251	322	289
Alzan	$N_{40}P_{20}K_{60}$	1	477	398	554	477
		2	458	384	522	456
	$N_{60}P_{35}K_{90}$	1	419	357	494	424
		2	397	342	454	399
	$N_{80}P_{50}K_{120}$	1	399	334	473	403
		2	378	310	417	369
	$N_{100}P_{65}K_{150}$	1	362	304	420	363
		2	339	286	392	340
	$N_{120}P_{80}K_{180}$	1	317	266	369	318
		2	301	258	353	305
ES Bella	$N_{40}P_{20}K_{60}$	1	479	407	562	484
		2	467	386	518	458
	$N_{60}P_{35}K_{90}$	1	464	381	517	455
		2	449	371	476	434
	$N_{80}P_{50}K_{120}$	1	426	361	464	419
		2	407	355	445	405
	$N_{100}P_{65}K_{150}$	1	380	340	428	385
		2	366	315	383	357
	$N_{120}P_{80}K_{180}$	1	336	291	377	336
		2	312	273	348	312
Lime	$N_{40}P_{20}K_{60}$	1	507	408	539	486
		2	485	388	518	465
	$N_{60}P_{35}K_{90}$	1	474	386	495	453
		2	450	381	446	427
	$N_{80}P_{50}K_{120}$	1	424	358	446	412
		2	389	343	401	379
	$N_{100}P_{65}K_{150}$	1	370	325	401	367
		2	342	304	367	340
	$N_{120}P_{80}K_{180}$	1	328	288	355	326
		2	310	269	330	305

Note: 1 – water treatment; 2 – application of Setar retardant

Source: compiled by the authors

Determination of water consumption coefficients for the development of 1 tonne of seeds showed that the indicator depended on the conditions of moisture availability of the year of research and the yield of sunflower hybrids under study. Indicators varied over the years in a fairly wide range (Table 3).

Table 3. *Indicators of the coefficient of water consumption of sunflower per 1 tonne of seeds, m³/t*

Year	Fertiliser variants	RGT Wolff		Alzan		ES Bella		Lime	
		1	2	1	2	1	2	1	2
2021	$N_{40}P_{20}K_{60}$	1,466	1,345	1,494	1,406	1,501	1,432	1,546	1,459
	$N_{60}P_{35}K_{90}$	1,233	1,155	1,273	1,186	1,406	1,328	1,381	1,289
	$N_{80}P_{50}K_{120}$	1,118	1,046	1,159	1,068	1,238	1,159	1,214	1,106
	$N_{100}P_{65}K_{150}$	893	861	1,015	942	1,079	996	1,046	959
	$N_{120}P_{80}K_{180}$	885	822	974	901	1,050	968	999	933
2022	$N_{40}P_{20}K_{60}$	1,212	1,141	1,248	1,184	1,299	1,212	1,254	1,173
	$N_{60}P_{35}K_{90}$	1,141	989	1,097	1,038	1,178	1,131	1,162	1,131
	$N_{80}P_{50}K_{120}$	993	911	1,009	938	1,026	989	1,055	1,005
	$N_{100}P_{65}K_{150}$	828	763	870	812	938	859	918	839
	$N_{120}P_{80}K_{180}$	789	716	836	787	898	833	876	817
2023	$N_{40}P_{20}K_{60}$	1,664	1,558	1,672	1,544	1,796	1,599	1,727	1,613
	$N_{60}P_{35}K_{90}$	1,413	1,306	1,424	1,306	1,592	1,464	1,525	1,370
	$N_{80}P_{50}K_{120}$	1,261	1,157	1,316	1,146	1,397	1,302	1,365	1,207
	$N_{100}P_{65}K_{150}$	1,044	967	1,157	1,050	1,223	1,088	1,176	1,057
	$N_{120}P_{80}K_{180}$	996	937	1,108	1,033	1,187	1,063	1,115	1,038
Average	$N_{40}P_{20}K_{60}$	1,446	1,352	1,481	1,382	1,502	1,420	1,525	1,420
	$N_{60}P_{35}K_{90}$	1,268	1,155	1,268	1,181	1,394	1,311	1,363	1,268
	$N_{80}P_{50}K_{120}$	1,130	1,042	1,168	1,056	1,223	1,155	1,219	1,113
	$N_{100}P_{65}K_{150}$	927	867	1,018	938	1,086	986	1,053	955
	$N_{120}P_{80}K_{180}$	895	828	976	910	1049	958	1002	935

Note: 1 – water treatment; 2 – application of Setar retardant
Source: compiled by the authors

According to the calculations, the coefficient of water consumption by sunflower plants for the development of 1 tonne of seeds in 2021 ranged from 822 to 1,546 m³/t under the influence of experimental factors and unregulated factors. Indicators for 2022 varied from 716 to 1,299 m³/t, and in 2023 – from 937 to 1,796 m³/t. Thus, the water consumption coefficient was influenced by the norms of fertilisers applied, morphobiological features of hybrids, the Setar preparation, and environmental factors. The highest water consumption rate per 1 tonne of sunflower seeds was obtained in 2023. In the RGT Wolff hybrid, it changed as fertilisation rates increased from 1,664 to 996 m³/t, Alzan – 1,672-1,108, ES Bella – 1,796-1,187, Lime – 1,727-1,115 m³/t. Notably, with the increase in fertiliser application rates, the sunflower yield increased, while simultaneously, there was a decrease in the water consumption coefficient. The use of the Setar preparation also provided a decrease in this indicator. The correlation coefficient between sunflower yield and productive moisture reserves in the metre-long soil layer for the sowing period was r = 0.8624, which indicates a strong correlation between the indicators.

Discussion

The findings showed that the yield of sunflower hybrids depended on the weather conditions of the growing year, in particular, water availability. At different stages of growth and development, sunflower plants require different amounts of moisture, which ensures optimal conditions for the flow of production processes in plants. According to S.M. Kalenska *et al.* (2019), during the sowing-flowering period of baskets, sunflower plants use 70-85 mm of moisture from the soil. While in the period of sowing-full shoots, sunflower crops evaporate 2-4 mm/ha per day. This is due to the lack of vegetation covering the soil during the specified period. Closing the rows reduces evaporation from the soil surface. In addition, there is an increase in water absorption by plants. Sunflower plants absorb 100-120 mm of water during the basket–maturation period.

When assessing the moisture availability of crops, the availability of moisture in the soil at the time of sowing, the amount of precipitation during the growing season and the remaining moisture in the soil at the time of harvest are considered. F. Filho *et al.* (2013) investigated that soil type affects water use by sunflower plants. The use of organic fertilisers (manure) ensures the growth of elements of the crop structure (weight of 1,000 seeds, number of seeds in the basket) and contributed to the efficient use of water from the soil.

As a result of the conducted studies, it was established that the reserves of soil moisture in the context of the years of research were quite different and ranged from 129.4 to 151.3 mm. However, according to A.V. Melnyk & S.A. Hovorun (2014), optimal humidity is considered to be humidity in the root layer at the level of 60-70% in relation to the lowest field moisture capacity, which implies the presence of 160-180 mm in the soil in the meter layer with a value of productive moisture reserves of at least 100 mm. In turn, the findings of S.V. Kokovikhin *et al.* (2015) indicate an improvement in the effectiveness of fertiliser exposure and an increase in the yield of sunflower seeds with higher precipitation during the growing season of the crop. According to the results of current studies, the coefficient of water consumption of sunflower per 1 tonne of seeds decreased with increasing yield (due to the influence of increasing fertilisation rates).

Research by V.V. Nesterchuk (2015) pointed out that the total water consumption of sunflower crops in some years of research varied depending on the amount of precipitation and soil moisture reserves, while the total water consumption ranged from 3,386 to 4,644 m^3/ha. However, when growing individual sunflower hybrids, the indicator under study varied in a wider range – from 3,682 to 4,119 m^3/ha.

Similar results were obtained by V.V. Gamayunova & V.S. Kudrina, (2018) in studies conducted in the Southern Steppe of Ukraine, which show that the use of biologics had an impact on the yield and water consumption of sunflower plants. On average, crop gains, depending on fertiliser options, ranged from 8.8 to 50.2%. For foliar top dressing, a decrease in the water consumption coefficient was noted, which amounted to 1,320 m^3/t in the control variant and 873.4 m^3/t in the variant with two fertilisations, which indicated a more efficient use of moisture for the development of a crop unit. That is, it decreased by 51.1%.

The same results were obtained by O.I. Polyakov & A.D. Shcherbak (2022), according to which the water consumption of sunflower varieties and hybrids was determined by the level of crop yield. The yield level was influenced by additional mineral fertiliser. The lowest total water consumption by the crop yield was observed in the version without the use of fertilisers and, depending on the genetic characteristics of the variety and hybrid, they ranged from 359.2 to 372.8 mm. Moisture was most effectively used against the background of applying $N_{60}P_{90}$, as evidenced by the lowest coefficient of water consumption, which depended on the application of the growth regulator and varied in the cross-section of hybrids from 1,039 to 1,177 m^3/t and grades from 1,217 to 1,246 m^3/t.

The positive impact of fertilisation and foliar treatments on the growth of regulatory preparations of biological origin and optimisation of water consumption of sunflower crops is also evidenced by Yu. Domaratskyi *et al.* (2022). The researchers found that growth-regulating preparations provide a more rational use of soil moisture for the development of a unit of dry matter. The lowest water consumption coefficient was obtained by using Helavit Combi on the P64GE133 hybrid, which was 1283 m^3/t of sunflower seeds. In turn, studies conducted in 2015-2016 in the Yelanets district of the Mykolaiv Oblast are aimed at studying the elements of the water balance of sunflower under the influence of fertiliser options and growth-regulating drugs, indicate a decrease in the specific water consumption of the crop (up to 30%) for their action, which indicates the economy of water consumption, despite the increase in total water consumption by 7%.

O.L. Zhygailo *et al*. (2021) analysed the impact of climate change on sunflower yields in the Northern Steppe of Ukraine, focusing on the need to adapt growing technologies to new weather conditions. In turn, V.M. Totsky (2014) focused on the impact of fertiliser and tillage systems on crop productivity, which allows evaluating the effectiveness of various agrotechnical approaches. Research by H.V. Pinkovskyi & S.P. Tanchyk (2019) showed that the timing of sowing and the density of standing plants significantly affect the productivity and water consumption of medium-early sunflower hybrids, which is important for optimising the water regime. A.V. Kokhan (2016) investigated sunflower water consumption depending on technological elements, emphasising the importance of synergy between fertiliser, tillage, and water supply systems to achieve high yields. Thus, previous studies indicate the importance of considering a complex of agroecological factors in sunflower cultivation, which ensures the realisation of the potential of modern hybrids in the context of climate change.

Thus, the results of the study confirmed a close relationship between weather conditions, the level of moisture availability, fertiliser standards, treatment with retardants, and the efficiency of sunflower water consumption. The increase in yield occurred against the background of a decrease in the coefficient of water consumption, which indicates a more rational use of moisture in conditions of optimal mineral nutrition. The obtained data allow identifying the most effective agrotechnological solutions for increasing the productivity of sunflower hybrids in conditions of unstable moisture.

Conclusions

Analysis of the weather conditions of the years of research indicates a significant difference between the indicators, which was reflected in the course of production processes of sunflower plants. They were manifested in an increase in the average daily values of air temperature indicators, which was observed in all growing seasons of the years of research and insufficient precipitation with an uneven distribution. Modern sunflower hybrids have different reactions to moisture conditions. During 2021-2023, moisture reserves in the meter-long soil layer for the sunflower growing season ranged from 3,217 m^3/ha (2022) up to 4,402 m^3/ha (2023). According to calculations, moisture consumption during the growing season ranged from 2,533 to 3,645 m^3/ha.

The coefficient of water consumption for the development of 1 tonne of sunflower seeds under the influence of the factors under study varied depending on the year of research: in 2021, it ranged from 822 to 1,546 m^3/t; in 2022 – from 716 to 1,299, and in 2023 – from 937 to 1,796 m^3/t. The highest coefficient of water consumption per 1 tonne of sunflower seeds was obtained in 2023: in the RGT Wollf hybrid, it changed as fertiliser doses and retartant action increased from 1,664 to 996 m^3/t, Alzan – 1,672-1,108, ES Bella – 1,796-1,187, Lime – 1,727-1,115 m^3/t. The data obtained confirm that increasing the level of fertiliser and the use of retardants not only increases yields, but also increases the efficiency of using soil moisture, which is critical in arid regions. A strong positive correlation was established between the reserves of productive moisture in the soil for the sowing period and the yield of hybrids (r = 0.8624), which indicates the importance of considering water supply when planning agricultural technologies. In the experiment, high doses of mineral fertilisers in combination with retarding treatment were more effective, which helped to reduce the specific water consumption for the development of 1 tonne of seeds.

The prospect of further research is the possibility of a multidimensional study and identification of the degree of influence of fertilisers, trace elements, new preparations, an increase of regulatory substances and technological methods of growing field crops on their water consumption, and further application in cultivation technologies in difficult climatic conditions.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Водоспоживання рослин соняшнику за впливу елементів технології вирощування

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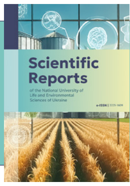
Анотація. Правильне управління водним режимом рослин сприяє підвищенню врожайності. Недостатнє або надмірне вологозабезпечення може негативно вплинути на їх ріст і розвиток, знижуючи кінцеву продуктивність. Метою дослідження було виявити вплив погодних, умов удобрення та дії ретарданту на формування продуктивності гібридів соняшнику. Польові дослідження були проведені у 2021-2023 рр. на чорноземах типових малогумусних. Дослідженнями встановлено, що вирішальним фактором, який визначає рівень урожайності і водоспоживання, є кількість ґрунтової вологи в 0–100 см шарі ґрунту на період сівби та кількість опадів за загальний період вегетації. Сумарне водоспоживання різнилося за роками досліджень: найнижчим воно було в 2022 році і склало 2533 м^3/га, а найбільшим – у 2023 році – 3645 м^3/га. У середньому за три роки досліджень сумарне водоспоживання склало 3095 м^3/га. Коефіцієнт водоспоживання, що характеризував витрати вологи на формування 1 т насіння з відповідною кількістю побічної продукції, змінювався за впливу погодно-кліматичних умов року, морфобіологічних особливостей гібридів, які вивчали, технологічних прийомів, оптимізації удобрення та становив у 2021 р. від 822 до 1546 м^3/т; у 2022 р. – 716 до 1299, а в 2023 р. – від 937 до 1796 м^3/т. Найвищий коефіцієнт водоспоживання на 1 т насіння соняшнику було отримано у 2023 році. У гібрида РЖТ Волльф він змінювався у міру зростання норм добрив від 1664 до 996 м^3/т, Альзан – 1672–1108, ЕС Белла – 1796–1187, Лайм – 1727–1115 м^3/т. Застосування ретарданту Сетар за вирощування соняшнику сприяло зменшенню коефіцієнту водоспоживання та забезпечувало більш раціональне використанню вологи рослинами на формування одиниці врожаю. Найбільший вплив на зменшення коефіцієнту водоспоживання показало удобрення. У найбільш несприятливі за зволоженням роки вирощування ефективність використання вологи рослинами соняшнику за оптимізації живлення істотно підвищується, що свідчить про ефективність застосування добрив і ретарданту Сетар. Отримані результати будуть корисними для аграрних підприємств у підвищенні ефективності використання ресурсів і покращенні фінансових результатів

Ключові слова: волога; добрива; олійні культури; продуктивність; ретардант

Received 20.11.2024 Revised 27.02.2025 Accepted 25.04.2025

Vol. 21, No. 2
2025



Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 551.52:631.461.3

DOI: 10.31548/dopovidi/2.2025.36

Influence of temperature in aquaponic system on nitrification processes

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Abstract. Aquaponics systems that combine aquaculture and hydroponics ensure a sustainable circulation of resources, and temperature is a key factor in determining the efficiency of nitrification processes and the overall productivity of such ecosystems. The study conducted an overview of scientific research published in the period 2014-2022 on the impact of temperature on nitrification processes and the overall efficiency of aquaponics systems. More than 100 scientific sources were analysed, including articles from international scientific journals, monographs and other publications covering various aspects of temperature effects on biological processes in aquaponics. Studies on the temperature ranges that are optimal for maintaining nitrifying bacteria activity and aquaculture health, as well as their interaction with factors such as nitrogen levels in the system and plant productivity, were emphasised. Studies demonstrated that temperature is an important factor in determining the rate of nitrification processes, fish and plant productivity, and the sustainability of the ecosystem. Too high a temperature can accelerate the nitrification process, but it also creates stress for the fish, which reduces their viability. Instead, low temperatures can slow down processes but increase the resistance of living organisms. This review has provided a thorough assessment of current approaches

Suggested Citation:

Klimenko, M., Grokhovska, Yu., & Yashchenko, L. (2025). Influence of temperature in aquaponic system on nitrification processes. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 21(2), 36-48. doi: 10.31548/dopovidi/2.2025.36.

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to temperature control in aquaponics systems and recommendations for the practical application of the results obtained in different climatic and technological situations. In addition, the prospect of developing new approaches to temperature optimisation to ensure the efficiency and sustainability of aquaponics systems in the future is discussed

Keywords: aquaponics; nitrates; phosphates; nutrients; ammonium nitrogen; clarius catfish

Introduction

Aquaponics, the integration of aquaculture and hydroponics, is an innovative technology that enables sustainable food production where fish and plants interact in a closed ecosystem. One of the key processes in such systems is nitrification, the biological oxidation of ammonium to nitrite and nitrate by nitrifying bacteria. This process is important for maintaining water quality, as it helps to reduce the concentration of toxic ammonium accumulated as a result of the metabolic activity of fish. Temperature is one of the main factors affecting the speed and efficiency of nitrification. It directly affects the metabolism of microorganisms, in particular the activity of nitrifying bacteria such as *Nitrosomonas* and *Nitrobacter*. Since the temperature regime in aquaponic systems can vary depending on the time of year, geographical location and other conditions, it is necessary to determine how different temperature ranges affect this process.

In Ukraine, there are fish farms in Vasylkiv and the villages of Kamianka Buzka in Lviv and Zaborol in Rivne regions. The technologies for rearing Clarius catfish and other fish species developed by local specialists are constantly being improved, but there are no scientific publications. An interesting publication is N.E. Hrynevych *et al.* (2021), which investigated the sanitary and biological parameters of water at critical points of the mentioned aquaculture system after passing through mechanical and biological filters. The authors noted the high efficiency of the biological filter for maintaining the sanitary condition of water in the UZV for sterlet rearing.

Previous scientific studies, as well as the dissertation study, have raised certain aspects of the functioning of nitrification processes in aquatic ecosystems and technologies, but omit several key issues. O.M. Vodyanitskyi *et al.* (2016) analysed the impact of the type of biofilter filler on the development of nitrifying microorganisms in water recycling systems, but the temperature factor, as one of the determinants of the activity of microbial consortia, was not the subject of the study. V.O. Yurchenko *et al.* (2021) examined nitrification processes in drinking water sources and water treatment facilities, but the specific conditions of closed aquaponic systems, in particular the temperature sensitivity of microbiocenoses, were not considered. The thesis of M.V. Zadorozhny (2023) addressed the effect of temperature on nitrification processes, but it did not provide a comprehensive analysis of the relationships between temperature regimes, the structural and functional state of nitrifying microorganisms, and the efficiency of inorganic nitrogen transformation in aquaponics. P. Debroy *et al.* (2024) investigated the effect of temperature on the productivity of aquaponic systems and fish growth. The authors determined that optimisation of water temperature is a critical factor in maintaining ecosystem stability and increasing biomass. These results highlight the importance of temperature control for the effective management of aquaponic farms. The study by L.K. Tolentino *et al.* (2019) analysed temperature stabilisation methods to improve nitrification efficiency in aquaponic systems. The study demonstrated that maintaining a stable temperature regime significantly improves the activity of nitrifying bacteria and overall water quality. The authors proved that temperature optimisation is a key factor in ensuring the sustainable operation of aquaponic plants. Thus, the issue of systematic generalisation and critical analysis of modern scientific data on the influence of temperature on nitrification processes in aquaponic systems remains relevant, determining the study goal.

Despite substantial research on the effect of temperature on nitrification in traditional biological systems, this issue remains insufficiently investigated in the context of aquaponics. Different researchers have provided conflicting results regarding the optimal temperature conditions for the stable operation of aquaponics systems. As temperature can have not only a direct impact on microbiological processes, but also indirectly through changes in other parameters (e.g. oxygen or ammonium levels), studying this issue is important for improving aquaponics technology. The review aimed to collect and systematise data on the effect of temperature on nitrification processes in aquaponic systems, to identify existing contradictions in scientific research and to identify potential areas for further research.

The research was based on the analysis of scientific sources covering the influence of temperature in aquaponics systems on nitrification processes. The literature search was conducted in the databases Scopus, Web of Science, Google Scholar, as well as in the open archives of scientific publications, ResearchGate, PubMed, and SpringerLink. The following keywords were used to select materials: "aquaponics", "nitrification", "temperature effect on nitrification", "ammonia oxidation in aquaponics". Articles published after 2010 and before 2022 that contain empirical data on the temperature effect on nitrification rates, nitrogen toxicity, and biofilters were prioritised. The analysed sources were grouped per key aspects of the topic: temperature requirements of fish in aquaponic systems, features of the nitrogen cycle, the effect of temperature on the activity of nitrifying bacteria, and methods of temperature control. The publications that did not contain experimental data, were limited to a general description of aquaponics or did not consider the effect of temperature on nitrification, were rejected. This approach formed a generalised picture of current research and identified the main trends in the study of temperature-dependent nitrification processes in aquaponic systems.

Aquaponic system – a symbiosis of hydroponics and aquaculture

The aquaponics system is an integrated environmental technology that combines hydroponics and aquaculture. The water containing fish waste serves as a source of nutrients for plants, which in turn purify water from pollution, creating a closed cycle. Fish produce organic waste, including ammonia, which is converted into nitrates with the help of bacteria, an important nutrient for plants. This reduces the need for additional fertilisers and ensures efficient use of water, which is a critical resource in such systems. Aquaponics is a sustainable, efficient and environmentally friendly method of food production that has achieved widespread use in both scientific research and aquaponic farms in the last decade.

D.C. Love *et al.* (2015) conducted an international survey of aquaponics practitioners, analysing the diversity of systems, fish and plant species, and challenges faced by aquaponics farm operators. R. Junge *et al.* (2017) proposed key strategic aspects of aquaponics development, emphasising the need for standardisation and further research to ensure wider adoption of this technology. The point is that the integration of aquaculture and hydroponics is necessary to create sustainable food production systems.

S. Goddek *et al.* (2015; 2019) implemented a systematic theoretical and review approach that covers aspects of constructive design, technological management, and strategic development of aquaponics systems. This approach provided a broad methodological basis for further applied research and contributes to the formation of a holistic view of the functioning of aquaponics as an integrated bioengineering technology. Its practical value is determined by the development of scientifically based recommendations for adapting systems to different farming conditions.

In contrast, the experimental study by U. Knaus & H.W. Palm (2018) on the impact of fish density on plant growth within an aquaponic system is noteworthy. Such a highly specialised approach provides specific practical data on optimising the biomass of both biological components of the system, which is particularly important for the commercial sector.

H. Monsees *et al*. (2017) presented an interdisciplinary approach that analyses the economic and environmental aspects of aquaponics for growing tomatoes in commercial settings. Such a comprehensive analysis can be used to assess the profitability of the technology in the real market and form an idea of its sustainable development. In turn, M. Yildiz *et al*. (2017) investigated fish welfare in the context of water quality parameters, demonstrating a biocentric approach to the functioning of aquaponics systems. The practical significance of this study is determined by the establishment of critical control parameters that ensure the homeostasis and biological stability of the system.

Despite the difference in the objects and methods of research, all authors agree on a positive assessment of the effectiveness of aquaponics as a promising technology of integrated production. At the same time, the diversity of approaches – from theoretical and conceptual to empirical and bioethical – indicates a high degree of interdisciplinarity of aquaponics and the need for further research that integrates technological, environmental, economic and biological aspects of aquaponics systems. No conflict of interest is present.

The aquaculture module generates organic waste, which is converted by nitrifying bacteria into nitrates – a key source of nutrition for plants in hydroponics. The accumulation of toxic forms of nitrogen without this process can worsen the condition of the fish and the stability of the system. The hydroponic module performs a biofiltration function, absorbing nitrates and other nutrients, which maintains water purity. The root system of plants enriches the water with oxygen, improving conditions for microorganisms.

The influence of the aquaculture module on the temperature regime of the aquaponics system

Optimisation of water parameters (pH, temperature, dissolved oxygen, nitrogen compounds) is key to ensuring a balance between the needs of fish, plants and bacteria, making aquaponics a promising approach to sustainable food production. Water temperature is a critical factor for the successful cultivation of different fish species in aquaponics systems. Each species has specific temperature requirements that need to be considered to ensure optimal growth, health and productivity.

Although the authors of C. Somerville (2015) unanimously recognise water temperature as one of the key factors determining the efficiency of aquaponics systems, a detailed comparative analysis shows both a certain consistency in the conclusions and discrepancies that need to be clarified. All the analysed studies emphasise the critical role of a stable temperature regime for the growth, metabolic activity and overall welfare of fish. At the same time, the ranges of optimal temperatures vary significantly depending on the fish species: for example, for tilapia and clarius catfish, the optimal temperatures are in the range of 24-29°C and 25-28°C, respectively (Hochman *et al*., 2018), while for trout and sturgeon, these values are much lower – 7-18°C and 18-22°C, respectively (Buzby & Lin, 2014).

These data indicate pronounced interspecific differences in the thermal adaptation of aquatic organisms, which in closed aquaponic systems requires a reasonable selection of compatible fish and plant species. Particular attention should be paid to the ratio of temperature requirements of fish and nitrifying bacteria, given that the optimal temperature range for the activity of bacteria of the genus *Nitrosomonas* and *Nitrobacter* is usually 25-30°. Thus, conditions that are optimal for most tropical fish species can also facilitate effective nitrification, while keeping cold-water species such as trout may be accompanied by a reduction in biological treatment intensity.

Temperature fluctuations constitute a separate group of risks for aquaponics systems, as even minor deviations from the optimal range can lead to metabolic stress in fish, reduced feed intake, homeostasis disorders, and inhibition of nitrifying bacteria activity. When the temperature rises above 30°C, the level of dissolved oxygen in the water may decrease, which increases the physiological load on both biological components of the system (Love *et al*., 2014; Poloviy *et al*., 2024).

Thus, the literature review demonstrated that although the main conclusions regarding the need for temperature stability are consistent, there are both interspecies differences in fish thermal preferences and potential contradictions in achieving the optimum for different components of the aquaponic system. This creates the need for further research aimed at studying the relationship between temperature regimes, fish productivity, nitrifying bacteria activity and functional stability of the system.

Threatening pollutants in aquaponics systems

Aquaponics systems are highly efficient environmental innovations that combine aquaculture and hydroponics, where fish and plants function in close symbiosis. To ensure the stable functioning of these systems, it is critical to control water quality, as its chemical composition directly affects fish health, plant growth and microbiological processes. The most sensitive parameters are the concentrations of nitrogenous compounds (ammonium, nitrates), phosphates, organic toxins and dissolved oxygen levels.

Ammonium (NH_4^+) is the primary product of nitrogen metabolism in fish and can be used as a source of nitrogen for plants in small amounts. However, its excess, especially in the form of free ammonia (NH_3), is toxic to both fish and plants. According to I. Zidni (2019), toxic effects for fish occur at ammonium concentrations above 0.5 mg/dm^3, and for species such as tilapia and clarius catfish, even 1 mg/dm^3 can be fatal. Y. Zhang *et al.* (2021) indicate that the optimal level of ammonium for plants is 1.0 mg/dm^3, but excessive levels cause growth inhibition due to toxic effects on the roots.

Nitrates (NO_3-) produced by nitrification are less toxic, but at high concentrations can cause the formation of methemoglobin in fish, which impairs oxygen transport (Buzby & Lin, 2014). For fish, the optimal level of nitrate is up to 50 mg/dm^3, and for heat-loving species, up to 100 mg/dm^3. At the same time, such limits are also effective for plants that actively consume nitrates at concentrations of 5-30 mg/dm^3 (Eck, 2019). Phosphates (PO_4^3-) are essential for plants, but excessive amounts of them cause algae growth, eutrophication and hypoxia, which is harmful to fish. Optimal concentrations of – are 0.2-0.5 mg/dm^3, and levels above 1 mg/dm^3 are associated with impaired fish metabolism and inhibition of plant growth (Eck, 2019). Organic toxins (e.g. phenols, amines) that can enter the system with feed or as a metabolic by-product pose a threat to both fish and plants. The permissible limit for such compounds is up to 0.1 mg/dm^3 (Buzby & Lin, 2014). The permissible limit for the following compounds is up to 0.1 mg/dm^3

The level of dissolved oxygen is a key parameter that determines the survival of all components of the system. For most fish species, the minimum acceptable oxygen level – is 5 mg/dm^3 (Rakocy *et al*., 1993), and at levels below 3 mg/dm^3, there is a risk of hypoxia. In plants, oxygen deprivation causes root rot and impaired nutrient uptake (Cohen *et al*., 2014).

An analysis of the sources cited indicates a significant degree of agreement on the critical toxicity limits for the main water parameters. Most sources agree that:

- Ammonium should not exceed 0.5-1.0 mg/dm^3 for fish, while plants can tolerate slightly higher levels;
- Nitrates are optimal in the range of 50-100 mg/dm^3 for fish and 5-30 mg/dm^3 for plants, but there is a compromise zone of 50-80 mg/dm^3;
- Phosphates above 0.5-1.0 mg/dm^3 have a negative impact on the biocenosis of the system;

➤ Organic toxins are harmful even in trace concentrations.

➤ The oxygen level should not reach below 5 mg/dm^3 for the system to function properly.

In summary, the optimal concentrations of compounds in an aquaponic system should be maintained within a narrow range to ensure simultaneous safety for fish, nitrification efficiency and nutrient availability for plants. Given the variability between fish species, plant types and system architecture, individual adaptation of parameters is necessary. For example, in warm-water systems with tilapia, it is more appropriate to maintain nitrate at 60-80 mg/dm^3, while in systems with trout, the optimum may be 30-50 mg/dm^3. This flexibility should be applied to each parameter, which is key to developing adaptive and sustainable aquaponics models.

Forms of nitrogen and their impact on aquatic life and plants

The forms of nitrogen in aquaponic systems are important in maintaining the biological balance between aquatic organisms and plants. The main forms of nitrogen are ammonium, nitrite and nitrate, each of which has different effects on organisms and system function. Ammonium is an important form of nitrogen, but at high concentrations (>0.5 mg/dm^3) it can be toxic to fish, causing stress and metabolic disorders (Kloas *et al*., 2015; Wongkiew *et al*., 2017). W. Kloas *et al*. (2015) investigated the effect of ammonium concentration on fish and plant growth in aquaponic systems. The results indicate that excess ammonium inhibits the development of both components of the system, while controlled levels promote an optimal growth balance. The authors emphasise the need for continuous monitoring of the nitrogen cycle to maintain the efficiency of aquaponics. S. Wongkiew *et al*. (2017) presented a literature review on the impact of various nitrogen compounds on the functioning of aquaponic systems. The authors addressed the toxicity of ammonium and nitrite to fish and the possibility of nitrate accumulation in water, which can affect the quality of plant products. The review demonstrates the critical role of nitrogen metabolism management in ensuring the health of the system's biocomponents.

For optimal plant growth, the ammonium concentration should be in the range of 0.5-1.0 mg/dm^3. Z. Naeem (2023) investigated the negative impact of ammonia on fish health in aquaponic systems. The study determined that even slight increases in ammonia concentrations can cause stress, metabolic disorders, and increased mortality among fish. The author concluded that strict control of ammonia levels is necessary to maintain the viability of populations in closed aquatic systems. The results indicate that different species have different sensitivities to ammonium loading, which requires an individual approach to water composition management. The authors emphasise the importance of dynamic monitoring of concentrations to prevent a decrease in system performance. According to Y. Zou *et al*. (2016), at concentrations above 1.0 mg/dm^3, ammonium becomes toxic to fish and can inhibit plant growth. The authors determined that ammonium, nitrite and nitrate have different effects on plant growth and fish physiological status, with excess nitrite being particularly toxic to aquatic organisms. The results highlight the need for a delicate balance between nitrogen forms to ensure system sustainability and productivity. The optimal ammonium concentration in aquaponics systems should be limited to 1.0 mg/dm^3 to ensure the health of both fish and plants. The fish are the most sensitive component of the system to ammonium, as even a small exceedance of this concentration can cause serious stress.

Nitrites are toxic to fish even at low concentrations. A. Deswati *et al*. (2021) recommended maintaining nitrite levels in aquaponics systems at no more than 0.1-0.2 mg/dm^3, as exceeding these limits can cause respiratory disorders in fish. The study experimentally demonstrated that even a slight increase in nitrite levels in water causes hypoxia and reduced growth rates in fish, which directly affects the overall productivity of the aquaponics system. The authors established that proper regulation of the nitrogen cycle is crucial, as exceeding the permissible level of nitrites leads to serious physiological disorders in fish and inhibition of plant growth in the system. Nitrites are highly toxic even at minimal concentrations, so their levels should not exceed 0.1 mg/dm^3 to prevent harm to fish health. Fish are most sensitive to this form of nitrogen, which requires special attention when monitoring nitrites in the system.

According to S. Faliagka *et al.* (2024), nitrates are the main source of nitrogen for plants in aquaponics systems. Optimal concentrations for plant growth range from 50-150 mg/dm^3, which provides adequate nutrition without adverse effects on fish. Higher levels (>150-200 mg/dm^3) can cause toxic effects on fish, although plants can successfully utilise nitrate even at high concentrations (Alonso-López *et al.*, 2015; Zheng *et al.*, 2017). For healthy aquaponics systems, nitrate concentrations should be limited to 100 mg/dm^3 to ensure optimal plant growth and fish safety. While plants can cope well with higher concentrations, fish are more sensitive to toxic levels of nitrate.

The forms of nitrogen in aquaponics systems have different effects on the biological components of the system. The most sensitive component to changes in nitrogen concentrations is fish, while plants can use nitrogen in the form of nitrate efficiently at higher concentrations:

- Ammonium: for fish, the concentration should not exceed 0.5 mg/dm^3, and for plants, the optimal level is 0.5-1.0 mg/dm^3;
- Nitrites: toxic at concentrations above 0.1 mg/dm^3, so their level must be strictly controlled;
- Nitrates: optimal concentrations for plants are 50-150 mg/dm^3, and for fish, up to 100 mg/dm^3.

In general, to maintain the health of an aquaponic system, it is important to maintain a balance between different forms of nitrogen, regularly monitor their levels and take into account the specific requirements of each component of the ecosystem.

Water temperature and nitrification rate

Nitrification is an important biochemical process in aquaponic systems that ensures their stability and health. It is a two-step process of biological oxidation of ammonium (NH_4^+) to nitrite (NO_2-) and then to nitrate (NO_3-). The process is carried out through the activity of specific groups of bacteria, such as *Nitrosomonas* (converting ammonium to nitrite) and *Nitrobacter* (converting nitrite to nitrate). Water temperature is an important factor affecting the speed and efficiency of nitrification, as it affects the activity of nitrifying bacteria. Within the optimum temperature range, these bacteria work efficiently to convert ammonium into nitrate, which can be used by plants for growth. Experimental studies show that the optimal temperature range for effective nitrification is 20-30°C, with temperatures below 10°C or above 35°C significantly reducing bacterial activity (Hochman *et al.*, 2018). However, the data on the effect of temperature on nitrification varies depending on the specific conditions.

Studies by numerous authors confirm that the optimum temperature for the nitrification process is in the range of 20-30°C, which is most effective for *Nitrosomonas* and *Nitrobacter* activity. Y. Zou *et al.* (2016), based on modelling, determined a difference in results when the temperature is changed above 30°C, which can cause an inhibition of the activity of nitrifying bacteria, which is confirmed by both experimental and theoretical studies. In the context of the above-mentioned studies, temperature is a critical factor that determines the speed of the nitrification process in aquaponic systems. Based on them, it is possible to establish that the optimal temperature range for nitrification is 20-30°C. The results of experimental studies are mostly consistent with the models, but there are some discrepancies under extreme conditions (high temperature, water pollution).

Y. Huang *et al.* (2024) reviewed the influence of temperature on nitrification processes in aquaponic systems. The authors determined that the optimum temperature for the activity of nitrifying bacteria is between 25-30°C, which ensures the highest rate of ammonium oxidation and stability of biofilters. If the temperature deviates from these limits, microbiological processes decelerate, which can lead to the accumulation of toxic nitrogen compounds. The study by J.P.H. Kinyage *et al.* (2016) experimentally confirmed the effect of water temperature on the efficiency of nitrification in aquaponics. The results demonstrated that at temperatures of 25-28°C, the highest level of ammonium conversion to nitrate is achieved, which has a positive impact on water quality and aquatic life. The deterioration of nitrification was recorded at temperatures below 20°C and above 32°C, which indicates the sensitivity of the microbial community to fluctuations in the thermal regime.

C. Deer *et al.* (2021) demonstrated that increasing the water temperature to 32-35°C can significantly reduce the activity of nitrifying bacteria, which leads to inhibition of the nitrification process. This contributes to the accumulation of toxic nitrogen compounds, which negatively affect the overall nitrogen cycle and the health of organisms, including fish. According to D.K. Papadopoulos *et al.* (2024), temperature instability, in particular sharp fluctuations, can significantly reduce the efficiency of nitrification. M.S. Akhtar *et al.* (2014) indicated that at temperatures below 18°C, nitrification processes almost stop, which limits the system's ability to maintain a stable nitrogen cycle.

In general, a temperature stability in the range of 25-30°C is an important condition for efficient and stable nitrification in aquaponic systems. Within this range, the nitrifying bacteria function optimally, providing a high rate of ammonium oxidation and maintaining a high level of water quality. High and low temperatures significantly reduce the efficiency of this process, which can have negative consequences for the system, including the accumulation of toxic nitrogen compounds.

Temperature control and accelerated nitrification

Based on the findings of J.R.M. Bracino *et al.* (2020) and A.V. Atienza *et al.* (2021), the methods of temperature stabilisation in aquaponic systems are systematised (Table 1):

Table 1. *Methods of temperature stabilisation in aquaponic systems*

Method type	Characteristic	Advantages	Limitations
Technical methods	Use of heaters, coolers, and tank insulation	Precise temperature control, stable nitrification processes	High energy costs, difficulty in maintaining in the face of significant external temperature fluctuations, and insulation costs
Natural methods	Adjustment of the water flow rate	Reduced temperature fluctuations, even temperature distribution	Low efficiency in case of significant changes in ambient temperature, impact on nutrient circulation
Biotechnological methods	Optimisation of conditions for the microbiota (increasing oxygen levels, maintaining optimal pH, biofilters)	Increase in nitrification efficiency, maintain stable microbial communities	Need for constant monitoring, limited effectiveness in case of sudden temperature drop or lack of oxygen

Source: compiled by the authors based on J.R.M. Bracino *et al.* (2020) and A.V. Atienza *et al.* (2021)

As a result, it is advisable to use a combination of these methods for effective temperature stabilisation in aquaponic systems, incorporating their advantages and limitations. Technical methods provide high accuracy, natural methods provide certain energy savings, and biotechnological methods maintain microbiota stability and contribute to the long-term functioning of the system.

To improve temperature stability in aquaponics systems, researchers have proposed various approaches, including the integration of multifunctional heating and cooling systems. These methods can reduce energy costs while maintaining a stable temperature throughout the day. However, such approaches can be limited by the influence of external factors, such as seasonal temperature fluctuations, which require additional resources to maintain stability.

Other researchers, such as S. Wahyuningsih *et al.* (2015), suggest the use of active filtration systems with natural materials to reduce ammonium pollution, which also contributes to improving nitrification efficiency. This method, compared to automated heating systems, is more cost-effective, but its efficiency can be reduced in conditions of significant temperature fluctuations. The use of heat storage systems and external cooling devices is also an important aspect of maintaining the optimal temperature in aquaponic systems (Khalil, 2018). However, these methods require additional investment in the installation of external devices and ensuring their stable operation in a changing climate.

An important area is the use of natural energy sources, such as solar energy, to power heating and cooling systems, which can reduce energy costs (Atlason *et al.*, 2017). However, this method may be less efficient in regions with limited access to solar energy or in winter. R. Sallenave (2016) and J.P. Mandap *et al.* (2018) highlighted the importance of maintaining a stable water temperature, as even small fluctuations, especially above 30°C, can cause stress to nitrifying bacteria, which reduces the efficiency of the process. Therefore, cooling systems and thermostatic controllers should be used to prevent overheating of the water.

Thus, different approaches to temperature stabilisation have their advantages and limitations. The integration of heating and cooling technologies with natural filtration systems can achieve optimal conditions for nitrification, but their effectiveness depends on specific conditions and requires a comprehensive approach to ensure temperature stability in aquaponics systems.

Conclusions

The optimal temperature range for nitrifying bacteria activity is 20-30°C. Within this range, the maximum rate of ammonium conversion to nitrate is observed, which is essential for maintaining stable water quality and plant health. At temperatures below 10°C, the activity of nitrifying bacteria decreases significantly, and at temperatures above 35°C, it almost stops, leading to the accumulation of toxic nitrogen compounds and disruption of the nitrogen cycle in the system.

Temperature stability is particularly important, as sharp temperature fluctuations can significantly reduce nitrification efficiency. Stable temperatures in the range of 25-30°C are the most optimal, as they promote high bacterial activity and the stability of the ecosystem. To maintain a stable temperature in aquaponic systems, it is necessary to use various methods, including technical, natural and biotechnological ones, to minimise the impact of extreme temperatures and ensure the effective functioning of the microbiota. Given these results, an important area is the development and implementation of systems that can be used maintaining optimal temperature conditions, in particular using combined heating, cooling and filtration technologies. The use of natural energy sources, such as solar energy, can reduce energy costs for temperature stabilisation, which is especially relevant for the sustainable development of aquaponic systems in different climatic conditions.

Further research could address the effect of temperature fluctuations on the long-term stability of nitrification and optimise temperature regimes for different types of aquaponic systems, incorporating the specific conditions of each region. In addition, more attention should be paid to the study of the adaptation mechanisms of nitrifying bacteria to temperature changes and their ability to recover from stress.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Вплив температурного режиму в аквапонічній системі на процеси нітрифікації

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Анотація. Аквапонічні системи, що поєднують аквакультуру та гідропоніку, забезпечують сталий обіг ресурсів, а температурний режим є ключовим чинником, який визначає ефективність нітрифікаційних процесів і загальну продуктивність таких екосистем. В даній статті проведено огляд наукових досліджень, опублікованих за період 2014-2022 що стосуються впливу температурного режиму на процеси нітрифікації та загальну ефективність аквапонічних систем. Проаналізовано понад 100 наукових джерел, зокрема статті з міжнародних наукових журналів, монографій та інші публікації, що охоплюють різні аспекти температурного впливу на біологічні процеси в аквапонії. Особливу увагу приділено дослідженням, які фокусувалися на температурних діапазонах, оптимальних для підтримки активності нітрифікаційних бактерій та здоров'я аквакультури, а також їх взаємодії з факторами, такими як рівень азоту в системі та продуктивність рослин. Дослідження показали, що температура є важливим фактором, який визначає швидкість нітрифікаційних процесів, продуктивність риб і рослин, а також стійкість екосистеми в цілому. Занадто висока температура може прискорювати процес нітрифікації, але також створює стрес для риб, що знижує їх життєздатність. Натомість низька температура може сповільнити процеси, але підвищити стійкість живих організмів. Цей огляд надав ґрунтовну оцінку сучасним підходам до контролю температурного режиму в аквапонічних системах та надав рекомендації для практичного застосування отриманих результатів в умовах різних кліматичних і технологічних ситуацій. Окрім того, обговорена перспектива розвитку нових підходів до оптимізації температури для забезпечення ефективності та стійкості аквапонічних систем у майбутньому

Ключові слова: аквапоніка; нітрати; фосфати; елементи живлення; азот амонійний; сом кларієвий

Received 11.12.2024 Revised 17.03.2025 Accepted 25.04.2025

Vol. 21, No. 2 2025

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 635.64: 631.85

DOI: 10.31548/dopovidi/2.2025.49

Effectiveness of phosphite fertilisers in tomato cultivation technology

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Abstract. This study aimed to determine the effectiveness of using fertilisers containing phosphite form phosphorus in tomato cultivation under irrigated conditions in the Left-Bank Forest Steppe region of Ukraine. Field trials were conducted during 2022-2024 at the Institute of Vegetable and Melon Growing of the National Academy of Agrarian Sciences of Ukraine, on typical low-humus heavy loamy chernozem developed from loess-like loam. It was found that in tomato cultivation, it was effective in reducing

Suggested Citation:

Kuts, O., Katerynchuk, O., Mykhailyn, V., Ilinova, Ye., & Soldatenko, A. (2025). Effectiveness of phosphite fertilisers in tomato cultivation technology. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 21(2), 49-60. doi: 10.31548/dopovidi/2.2025.49.

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the rate of recommended fungicides (Ridomil Gold, Luna Experience, Quadris, and the biopreparations MycoHelp and Fitocid) by 25%-50% when combined with the integrated application of the fertiliser Ecoline Phosphite (K) (10 days after transplanting – 1 L/ha; 20 days after the first application – 1.5 L/ha; 20 days after the second application – 1.5 L/ha; 20 days after the third application; 15 days after the fourth application; and 15 days after the fifth application – all at 2 L/ha). The proposed technological approaches resulted in an increase in tomato plant height by 4.3%-8.7%, the number of fruit clusters by 15.6%-20.0%, and a reduction in the development of Alternaria leaf blight to 60%-65% (compared to 82% in the control). Under this approach, crop yield increased by 4.9-8.8 t/ha, alongside an improvement in the content of soluble dry matter in the fruit (up to 3.6%-3.98%), total sugars (up to 2.49%-2.53%), and vitamin C (up to 25.48-25.82 mg/100 g). The most significant effect was observed with the application of 75% of the recommended fungicide rate in combination with Ecoline Phosphite (K), which also demonstrated strong economic performance: profit reached 311.1 thousand UAH/ha, profitability was 83.9%, and the lowest production cost was recorded at 5.69 UAH/kg

Keywords: *Solanum lycopersicum* L.; phosphorus nutrition; biometric parameters of plants; yield; biochemical composition of produce; profitability

Introduction

Investigating the effectiveness of phosphite fertilisers in tomato cultivation technology is pertinent given the necessity of enhancing crop productivity and improving fruit quality, particularly in light of increasing demands for environmental safety and economic efficiency in agricultural production. Tomatoes are a crop sensitive to mineral nutrition, with their nutrient requirement, especially phosphorus, increasing significantly during critical growth and development stages. Concurrently, traditional phosphorus fertilisers exhibit low availability to plants under unfavourable soil and climatic conditions, which limits the realisation of the crop's potential and negatively impacts fruit quality and yield. Phosphite forms of phosphorus offer several advantages, including high bioavailability, the capacity to activate physiological and biochemical processes, and the ability to increase plant resistance to diseases and stress factors. Using such fertilisers is considered a promising element in resource-saving technologies for cultivating vegetable crops, enabling a reduction in pesticide load by boosting plant immunity and decreasing the rates of chemical plant protection products applied. These issues are particularly relevant in the context of irrigated agriculture in the Left-Bank Forest-Steppe of Ukraine, where optimising tomato nutrition will contribute not only to increased yield but also to improved fruit quality indicators, enhanced economic returns from production, and the assurance of sustainable development in vegetable growing.

Global food security represents a key challenge confronting world agriculture. The necessity of feeding a steadily increasing population is compounded by significant threats to food crop yields arising from climate change. As there is no longer an abundance of available agricultural land, a 40%-50% increase in food production can only be achieved through sustainable agricultural intensification (Syromyatnikov *et al.*, 2024). Optimising nutrition systems provides the most substantial impact on boosting crop productivity, particularly for vegetable crops. According to O.V. Kuts *et al.* (2024), yield increments resulting from the application of various types of fertilisers range from 20% to 75%. The use of growth regulators also significantly influences the regulation of plant productivity levels. This is achieved through their positive effect on root architecture, which in turn enhances the conditions for plant nutrient uptake.

Phosphorus is one of the most vital elements required by all living organisms. In agrochemical contexts, humanity primarily utilises phosphorus in the form of phosphates (PO_4^{3-}). However, researchers such as B. Lagunas *et al.* (2019) have shown interest in the salts of phosphorous acid – phosphites (PO_3^{3}). They established that the application of phosphites offers multifaceted benefits compared to phosphates. Phosphites have been noted for their use as fertilisers, plant growth stimulants, and substances with fungicidal properties. Y. Xi *et al.* (2020) investigated that salts of phosphorous acid (phosphites) contain higher concentrations of phosphorus (52%) than traditional phosphate-based fertilisers (32%). As the most stable form of phosphorus in the environment is phosphates, phosphites undergo a gradual transformation after being applied to the soil. Soil microorganisms are capable of assimilating phosphite and transforming it into phosphates, obtaining energy and nutrients during this biological conversion.

Phosphites also exert a unique influence on plant metabolism, linked to their functional role as plant growth regulators. It is worth noting that, according to I. Panfili *et al.* (2019), plant growth stimulants are increasingly being integrated into various production systems to mitigate physiological stress and minimise undesirable environmental consequences. The authors observed that phosphite (an isostere of the phosphate anion) often acts as a potential biostimulant, as it has been shown to induce resistance to a variety of biotic and abiotic stresses, as well as enhance the yield and quality of agricultural produce.

Research by M.A. Mohammadi *et al.* (2021) indicated that phosphites are employed as a systemic fungicide to manage the prevalence of oomycetes and soil-borne diseases such as *Phytophthora*, *Pythium*, and *Plasmopara*. Generally, phosphites lead to a reduction in disease severity by promoting increased photosynthetic and enzymatic activity, decreasing the accumulation of reactive oxygen species (ROS), and modifying a large group of genes.

In this context, the present study aimed to establish the effectiveness of using fertilisers containing phosphorus in the phosphite form for tomato cultivation under irrigated conditions in the Left-Bank Forest-Steppe of Ukraine.

Materials and Methods

The research was conducted during the period 2022-2024 at the Institute of Vegetable and Melon Growing of the National Academy of Agrarian Sciences of Ukraine, located in the Left-Bank Forest-Steppe region of Ukraine. The soil of the experimental plot is classified as a typical lowhumus heavy loamy chernozem on loess-like loam. The agrochemical characteristics of the arable layer (0-25 cm) are as follows: salt extract pH – 6.1; sum of exchangeable bases – 29.0 mg-eq per 100 g of soil; hydrolytic acidity – 2.0 mg-eq per 100 g of soil; humus content – 4.0%; hydrolysable nitrogen – 109-116 mg/kg; mobile phosphorus – 183-212 mg/kg; and exchangeable potassium – 121-163 mg/kg of soil. Tomatoes of the Heizer variety were cultivated following bulb onions, utilising drip irrigation (7 applications of 50-100 m^3/ha) with a plant spacing of 70×35 cm. The research adhered to the Convention on Biological Diversity (1992).

The experimental design included the recommended tomato disease control system (a complex of fungicides and biopesticides) and combinations of reduced fungicide rates with the application of the complex fertiliser possessing fungicidal properties, Ecoline Phosphite (K):

1. No fungicides or preparations applied (absolute control)

2. Recommended fungicides (reference treatment): Ridomil Gold (2.5 kg/ha) 10 days after transplanting to the field + Luna Experience (0.75 L/ha) 20 days after the first application + Quadris (0.6 L/ha) 20 days after the second application + MycoHelp biopreparation (2 L/ha) 20-25 days after the third application + Phytocid biopreparation (2 L/ha) 15 days after the fourth application + MycoHelp (2 L/ha) 15 days after the fifth application

3. Recommended fungicides at a 25% reduced rate + Ecoline Phosphite (K): Ridomil Gold (1.88 kg/ha) + Ecoline Phosphite (K) (1 L/ha) 10 days after transplanting + Luna Experience (0.55 L/ha) + Ecoline Phosphite (K) (1.5 L/ha) 20 days after the first application + Quadris (0.45 L/ha) + Ecoline Phosphite (K) (1.5 L/ha) 20 days after the second application + Ecoline Phosphite (K) (2 L/ha) 20 days after the third application + Ecoline Phosphite (K) (2 L/ha) 15 days after the fourth application + Ecoline Phosphite (K) (2 L/ha) 15 days after the fifth application

4. Recommended fungicides at a 50% reduced rate + Ecoline Phosphite (K): Ridomil Gold (1.25 kg/ha) + Ecoline Phosphite (K) (1 L/ha) 10 days after transplanting + Luna Experience (0.38 L/ha) + Ecoline Phosphite (K) (1.5 L/ha) 20 days after the first application + Quadris (0.3 L/ha) + Ecoline Phosphite (K) (1.5 L/ha) 20 days after the second application + Ecoline Phosphite (K) (2 L/ha) 20 days after the third application + Ecoline Phosphite (K) (2 L/ha) 15 days after the fourth application + Ecoline Phosphite (K) (2 L/ha) 15 days after the fifth application.

The research was conducted according to the methodology for experimental work in vegetable growing (Bondarenko & Yakovenko, 2001). The accounting plot area was 21.0 m^2, with four replications. In the experiment, biometric parameters of tomato plants (plant height and number of trusses per plant) were recorded dynamically. Assessments of plant damage by Alternaria leaf blight were determined using a 5-point scale dynamically (in the second ten-day period of July and the third ten-day period of August). The scale was defined as follows: 0 – no damage; 1 – yellowing of 1-2 leaves; 2 – yellowing of 3-4 leaves; 3 – yellowing of half the plant; 4 – yellowing of the entire plant, which blackens and dries out. The prevalence of the disease was calculated using the formula:

$$P = \frac{a}{k} \cdot 100\%, \quad (1)$$

where P is the disease prevalence, %; a is the number of affected plants, units; k is the total number of assessed plants, units. The degree of disease development intensity was calculated using the formula:

$$C = \frac{\sum a \cdot b}{n \cdot k} \cdot 100\%, \quad (2)$$

where C is the degree (intensity) of disease development; a is the number of affected plants for each score, units; b is the damage score; n is the highest score on the assessment scale; k is the total number of assessed plants, units.

Total yield and marketable yield, along with marketability, were also determined. Biochemical parameters of the tomato fruits assessed included: total soluble solids content – refractometrically according to DSTU 7804:2015 (2016); total sugars content – according to DSTU 4954:2008 (2009); ascorbic acid (Vitamin C) content – according to DSTU 7803:2015 (2016); and acidity – titrimetrically according to DSTU ISO 6632-2001 (2002). Statistical analysis of the research results was performed using analysis of variance, with years treated as replicates.

Results

It was noted that both the use of the complex of recommended fungicides and the combination of reduced fungicide rates with the application of Ecoline Phosphite (K) fertiliser increased tomato plant height (Fig. 1). When reducing the fungicide rate and adding Ecoline Phosphite (K), this parameter did not change significantly. In these variants, tomato plant height in the third ten-day period of July increased by 6.8%-8.7%, and in the first ten-day period of September, by 4.3%-7.4%.

A positive effect of fungicides and Ecoline Phosphite (K) fertiliser on the formation of trusses on tomato plants, which is a component of crop yield, was also established (Fig. 2). By the end of the growing season, the number of trusses increased from 4.5 units/plant in the control to 5.25.4 units/plant with the application of fungicides and Ecoline Phosphite (K) fertiliser. A synergistic effect was observed when using the 50% fungicide rate in combination with Ecoline Phosphite (K) fertiliser.

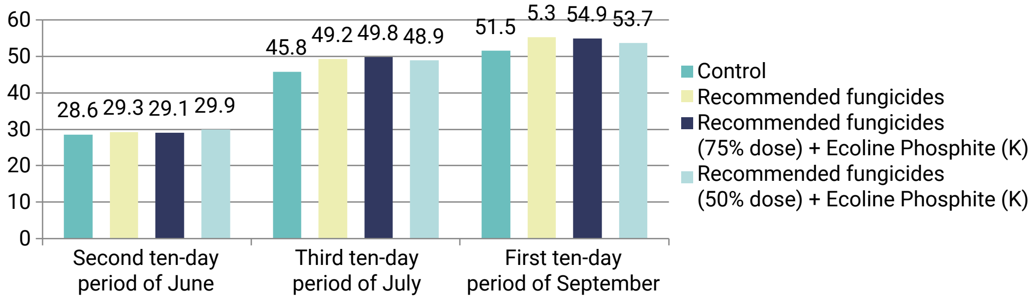

***Figure 1.** Effect of fungicides and Ecoline Phosphite (K) fertiliser on tomato plant height, cm (average for 2022-2024)*

Source: developed by the authors

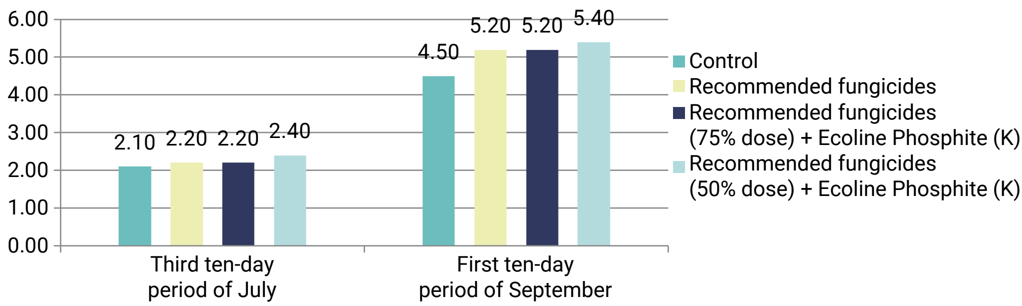

***Figure 2.** Effect of fungicides and Ecoline Phosphite (K) fertiliser on the number of tomato plant trusses, units/plant (average for 2022-2024)*

Source: developed by the authors

During the years of the study, Alternaria leaf blight (*Alternaria solani*) predominantly affected tomato plantings annually, while in 2023, late blight (*Phytophthora infestans*) developed in small foci, though this disease did not significantly impact plant development. Regarding the effect on Alternaria leaf blight development, the additional use of Ecoline Phosphite (K) fertiliser proved effective when the rate of recommended fungicides was reduced by 25%-50% (Table 1).

***Table 1.** Effect of fungicides and Ecoline Phosphite (K) fertiliser on the prevalence and development of tomato Alternaria leaf blight, % (average for 2022-2024)*

Variants	Second ten-day period of July		Third ten-day period of August	
	Spread	Development	Spread	Development
1. Control	100	9.6	100	82
2. Recommended fungicides	100	8.1	100	70
3. Recommended fungicides (75% dose) + Ecoline Phosphite (K)	100	7.8	100	65
4. Recommended fungicides (50% dose) + Ecoline Phosphite (K)	100	8.0	100	60

Source: developed by the authors

During the period of mass tomato fruiting, reducing the rate of recommended fungicides by 25% in combination with the use of Ecoline Phosphite (K) ensured a reduction in the degree of disease development to a level of 65%, and with a 50% reduction in the fungicide rate, it decreased to as low as 60%. Thus, the use of fertiliser containing phosphorus in the phosphite form acts as a substance with fungicidal properties, as well as an additional measure for optimising plant nutrition, which contributes to a better effect on tomato plants and a reduction in the degree of Alternaria leaf blight development.

Even though all tested variants resulted in a tomato yield increase of 4.5-9 t/ha, or 7.9%15.9%, the maximum impact on crop yield level was observed when combining fungicides at a 75% rate with the application of Ecoline Phosphite (K) fertiliser (Table 2). This variant also demonstrated the maximum level of marketable produce (96%).

Table 2. *Change in tomato yield using fungicides and Ecoline Phosphite (K) fertiliser (average for 2022-2024)*

Variants	Total yield, t/ha	Increase		Marketability, %
		t/ha	%	
1. Control	56.26	–	–	91.6
2. Recommended fungicides	60.72	4.48	7.9	93.7
3. Recommended fungicides (75% dose) + Ecoline Phosphite (K)	65.21	8.95	15.9	96.0
4. Recommended fungicides (50% dose) + Ecoline Phosphite (K)	61.19	4.93	8.8	94.0
$LSD_{0.95}$		5.37		

Source: developed by the authors

The variant combining fungicides at a 75% rate with Ecoline Phosphite (K) fertiliser also provided the maximum positive impact on the biochemical composition of the tomato produce (Table 3). Under this technological measure, a significant increase in total soluble solids to a level of 3.98% and total sugars to a level of 2.53% was noted. There was also a positive trend regarding the increase in vitamin C content in the fruits to a level of 25.48 mg/100 g. Reducing the fungicide rate by 50% in combination with the application of Ecoline Phosphite (K) fertiliser was also effective; this significantly increased the total sugar content in the fruits to 2.49% and showed a positive trend for the increase in vitamin C content in the fruits to a level of 25.82 mg/100 g.

Table 3. *Effect of fungicides and Ecoline Phosphite (K) fertiliser on the biochemical composition of tomato fruits (average for 2022-2024)*

Variants	Content in fruits, %			
	Soluble dry matter	Total sugar	Vitamin C, mg/100g	Acidity
1. Control	3.46	2.11	25.11	0.46
2. Recommended fungicides	3.61	2.43	24.67	0.45
3. Recommended fungicides (75% dose) + Ecoline Phosphite (K)	3.98	2.53	25.48	0.46
4. Recommended fungicides (50% dose) + Ecoline Phosphite (K)	3.60	2.49	25.82	0.46
$LSD_{0.95}$	0.30	0.22	1.88	0.04

Source: developed by the authors

The use of Ecoline Phosphite (K) fertiliser proved to be an economically advantageous technological measure (Table 4). Understandably, this technological approach increases costs due to the price of the fertiliser and the cost of harvesting the additional yield, but it reduces expenditure on recommended fungicides. Consequently, the total costs increase to a much lesser extent (by 19.6-30.5 thousand UAH/ha) than the additional profit generated by using Ecoline Phosphite (K) fertiliser with a reduced fungicide rate (by 72.3-136.3 thousand UAH/ha).

Table 4. *Economic efficiency of using Ecoline Phosphite (K) fertiliser for tomato cultivation (average for 2022-2023)*

Variants	Economic indicators				
	Marketable yield, t/ha	Total costs, thousand UAH/ha	Profit, thousand UAH/ha	Production cost, UAH/kg	Production profitability, %
1. Control	51.53	340.5	174.8	6.61	51.3
2. Recommended fungicides	60.72	360.1	247.1	5.93	68.6
3. Recommended fungicides (75% dose) + Ecoline Phosphite (K)	65.21	371.0	311.1	5.69	83.9
4. Recommended fungicides (50% dose) + Ecoline Phosphite (K)	61.19	360.6	251.3	5.89	69.7

Source: developed by the authors based on Minfin (n.d.)

This technological measure is particularly beneficial when the fungicide rate is reduced by 25%, leading to a high level of profitability (83.9%) and a reduction in production cost from 5.93 UAH/kg with the full fungicide rate to 5.63 UAH/kg.

Discussion

The use of phosphite fertilisers (Ecoline Phosphite (K)) primarily had a positive impact on the growth of certain biometric parameters of tomato plants, such as plant height and the number of trusses per plant. Higher rates of vegetative growth positively influence future plant productivity by increasing the photosynthetic apparatus and also facilitating faster recovery of leaves damaged by diseases (primarily Alternaria leaf blight).

Research indicating certain fungicidal properties of phosphite fertilisers (Ecoline Phosphite (K) providing a reduction in disease development to 65%, and with reduced rates to 50%-60%) is also supported by the scientific studies of other researchers. Similar results were obtained in studies by I. Fagundes-Nacarath *et al.* (2018) and L.C. Costa *et al.* (2020), where the use of phosphite fertilisers in bean cultivation reduced the negative consequences of *Sclerotinia sclerotiorum* development by decreasing photochemical dysfunctions. However, the action of phosphites on phytopathogens involves both direct and indirect effects. In the first instance, according to M.G. Yáñez-Juárez *et al.* (2018), phosphite ions, upon contact with pathogens, affect their growth and reproduction by influencing the expression of genes encoding compounds essential for various cell structures. Research by R. Garcia-Velasco *et al.* (2020) indicates that the application of phosphites inhibits the oxidative phosphorylation of oomycete metabolism, halts mycelial growth processes, and increases the activity of the pentose phosphate pathway, which significantly reduces enzyme activity.

In the research of O. Silva *et al.* (2013), phosphite was considered a biostimulant of systemic acquired resistance. Upon entering the plant cell, it activates biochemical and structural defence mechanisms (such as the production of polysaccharides, phytoalexins, or pathogenesis-related proteins) which limit the penetration and spread of pathogens within the plant organism. According to E. Liljeroth *et al.* (2016), phosphites inhibit the development of protozoa, oomycetes, fungi, bacteria, and nematodes, but their effectiveness depends on the ions bound to the phosphites (potassium phosphite, calcium phosphite, etc.) and the application methods (drenching and foliar feeding). The effectiveness of phosphite fertilisers is also influenced by the overall technological level of the farm and the intensity of the plant protection system against diseases involving fungicides and biopreparations.

The increase in tomato yield and the improvement in produce quality when using fertilisers containing phosphorus in the phosphite form are attributed to the reduced development of major tomato diseases and the optimisation of growth processes due to the stimulating effect of the fertiliser.

The mechanism by which phosphite affects plants is not yet fully understood; however, there is some evidence suggesting it is specific to roots and not solely related to a role as a pesticide or fertiliser. For instance, in greenhouse studies conducted by S. Rossall *et al.* (2016) on wheat, oilseed rape, sugar beet, and ryegrass, phosphites improved root biomass by approximately 30%. This enhanced the uptake of nutrients from the substrate, which are essential for developing a productive photosynthetic apparatus. Nevertheless, the fertiliser capacity of phosphites remains a subject of debate. According to F. Bertsch *et al.* (2009), phosphites can be absorbed via roots or leaves and transported through the xylem or phloem, but they cannot be directly utilised as a form of phosphate nutrition and therefore cannot serve as direct substitutes for phosphate fertilisers. However, the ability of soil microorganisms to oxidise phosphites to phosphates presents a possibility for their application as a source of phosphorus nutrition, as noted in the study of M. Manna *et al.* (2016). Microbial oxidation of phosphite is facilitated by the enzyme phosphite dehydrogenase. Consequently, certain *Bacillus* species and other microorganisms are capable of oxidising phosphite and hypophosphite to phosphate.

The mechanism by which phosphite acts on plants is not fully understood; however, there is some evidence to suggest it is specific to roots and not solely associated with a role as a pesticide or fertiliser. For example, in greenhouse studies by S. Rossall et al. (2016) involving wheat, oilseed rape, sugar beet, and ryegrass, phosphites improved root biomass by approximately 30%. This enhanced the uptake of nutrients from the substrate required for the development of a productive photosynthetic apparatus. Although the fertiliser capacity of phosphites is still debated. According to F. Bertsch *et al.* (2009), phosphites can be absorbed through roots or leaves and transported via the xylem or phloem, but they cannot be directly used as a form of phosphate nutrition and thus cannot be direct substitutes for phosphate fertilisers.

It should also be considered that, according to the results of some studies by E. Estrada-Ortiz *et al.* (2011), the effectiveness of phosphites as a partial source of phosphorus for plants is confirmed. In other studies, phosphites either have no significant effect on the growth and yield of agricultural crops or even negatively impact plant productivity. According to H. Thao *et al.* (2008), foliar and root applications of potassium phosphite did not improve the nutrition of spinach (*Spinacia oleracea* L.) and, conversely, strongly inhibited root growth under phosphate deficiency.

Given that in the present study, foliar applications of potassium phosphite contributed to both a reduction in tomato Alternaria leaf blight development with reduced fungicide rates and an increase in yield by 9%-16% due to a stimulating effect on tomato plant growth processes, a dual action of phosphite fertilisers in open-field tomato cultivation can be noted. However, the research programme did not allow for the quantification of the separate contributions of the fungicidal and stimulating effects of phosphite fertilisers on tomato yield. This is potentially related to the close interaction between plant growth processes, mechanisms for increasing plant resistance to phytopathogenic organisms, and the suppression of their development (Vdovenko *et al.*, 2024).

Similar to various studies by other researchers, phosphites demonstrated a positive trend in improving product quality, contributing to an increase in the content of soluble dry matter, total sugars, and vitamin C in tomato fruits. This is particularly important given the increase in crop yield. Frequently, an increase in the yield of vegetable crops is associated with a decrease in the content of biologically active compounds in the produce; hence, the yield level often correlates inversely with the content of vitamins and sugars in the produce.

The high economic indicators associated with the use of phosphite fertilisers are linked to two factors: the increase in tomato yield resulting from the stimulating and fungicidal action of the Ecoline Phosphite (K) product, and the savings achieved by reducing the amount of fungicides used (especially with a 50% rate reduction). However, despite the higher yield obtained when using the phosphite fertiliser in combination with 75% of the recommended fungicide rate, the most economically expedient option proved to be the application of Ecoline Phosphite (K) with only a 25% reduction in the fungicide rate, due to the overall economic benefit realised under those conditions. Furthermore, reducing the fungicide rate has an indirect, prolonged positive effect on agrobiocoenosis, reducing the chemical load and decreasing the likelihood of resistance developing in various species of phytopathogenic microorganisms.

Conclusions

Therefore, under irrigated conditions in the Left-Bank Forest-Steppe of Ukraine for tomato cultivation, reducing the rate of recommended fungicides (Ridomil Gold, Luna Experience, Quadris, biopreparations MycoHelp and Phytocid) by 25%-50% in combination with the comprehensive use of Ecoline Phosphite (K) fertiliser is effective. The recommended application schedule for Ecoline Phosphite (K) is 1 L/ha 10 days after transplanting, followed by 1.5 L/ha 20 days after the first application, 1.5 L/ha 20 days after the second, 2 L/ha 20 days after the third, 2 L/ha 15 days after the fourth, and a further 2 L/ha 15 days after the fifth application.

Observed benefits include an increase in tomato plant height by 4.3%-8.7% and the number of trusses by 15.6%-20.0%. Development of Alternaria leaf blight is reduced to a level of 60%-65% (compared to 82% in the control). Under this technological approach, crop yield increases by 4.98.8 t/ha, or 8.95%-15.9%. Fruit quality is also enhanced, with increased content of total soluble solids (up to 3.6%-3.98%), total sugars (up to 2.49%-2.53%), and vitamin C (up to 25.4825.82 mg/100 g).

The maximum impact was noted when using 75% of the fungicide rate in combination with the Ecoline Phosphite (K) application, which also yielded high economic indicators: a profit of 311.1 thousand UAH/ha, profitability of 83.9%, and the lowest production cost (5.69 UAH/kg).

The application of fertilisers containing phosphorus in the phosphite form has proven to be a promising measure for both optimising plant protection and improving tomato growth parameters, yield, and fruit quality under irrigated conditions. The results obtained confirm the ability of phosphites not only to act as inducers of systemic plant resistance but also as a factor contributing to the reduction of pesticide load without compromising the effectiveness of crop protection. Furthermore, their positive influence on the biochemical composition of the fruits was established, which is important for improving the nutritional value of the produce.

Future research perspectives include investigating the mechanisms of action of phosphite fertilisers on biochemical and physiological-molecular processes in tomato plants, particularly their effect on enzymatic activity and the antioxidant system. It would also be pertinent to conduct research into the possibility of complete or partial replacement of traditional phosphorus fertilisers with phosphite forms in conditions of limited available phosphorus in soils and to assess the longterm environmental safety of such application. A separate avenue for future research could focus on evaluating the effectiveness of phosphites under varying levels of water supply, which would allow for the adaptation of this technology to conditions of climate change and increasing water scarcity.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Ефективність фосфітних добрив в технології вирощування помідору

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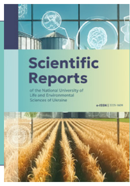
Анотація. Метою досліджень було визначення ефективності використання добрив з фосфітною формою фосфору за вирощування помідору в зрошуваних умовах Лівобережного Лісостепу України. Польові дослідження проводилися впродовж 2022-2024 років в Інституті овочівництва і баштанництва Національної аграрної академії наук України на чорноземі типовому малогумусному важкосуглинковому на лесовидному суглинку. Встановлено, що за вирощування помідору ефективним було зменшення норми рекомендованих фунгіцидів (Ридоміл голд, Луна екпірієнс, Квадріс, біопрепарати Мікохелп та Фітоцид) на 25-50 % в поєднанні з комплексним використанням добрив Еколайн фосфітний К (через 10 днів після висадки розсади 1 л/га + через 20 днів після першої обробки 1,5 л/га + через 20 днів після другої обробки 1,5 л/га + через 20 днів після третьої обробки + через 15 днів після четвертої обробки + через 15 днів після п'ятої обробки по 2 л/га). Вказані технологічні підходи забезпечили зростання висоти рослин помідору на 4,3-8,7 %, кількості китиць – на 15,6-20,0 %, зниження розвитку альтернаріозу до рівні 60-65 % (на контролі 82 %). За вказаного технологічного заходу урожайність культури зростала на 4,9-8,8 т/га, підвищувався вміст у плодах сухої розчинної речовини (до рівня 3,6-3,98 %), загального цукру (до 2,49-2,53 %), вітаміну С (до рівня 25,48-25,82 мг/100 г). Максимальний вплив зазначається за використання 75 % норми фунгіцидів у поєднанні з внесення Еколайн фосфітний К, що також має високі економічні показники: прибуток на рівні 311,1 тис. грн./га, рентабельність – 83,9 % та найменша собівартість продукції (5,69 грн./кг)

Ключові слова: *Solanum lycopersicum* L.; фосфорне живлення; біометричні параметри рослин; урожайність; біохімічний склад продукції; рентабельність

Received 06.01.2025 Revised 03.04.2025 Accepted 25.04.2025

Vol. 21, No. 2
2025



Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 636.4.034:636.082:637.5

DOI: 10.31548/dopovidi/2.2025.61

Technological solutions for improving the welfare of gestating sows in group housing

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Abstract. Modern pig breeding is focused on improving the welfare of sows by optimising housing conditions and introducing natural feed additives with hepatoprotective effects. The aim of the study was to determine the effect of the complex feed additive "Gepasorbex" on the behavioural reactions

Suggested Citation:

Lykhach, V., Lenkov, L., Lykhach, A., Reznichenko, V., & Faustov, R. (2025). Technological solutions for improving the welfare of gestating sows in group housing. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 21(2), 61-74. doi: 10.31548/dopovidi/2.2025.61.

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of gestating sows. The experiment was carried out under conditions of group housing of animals in industrial conditions of the private-rental enterprise "Victoria" (Mykolaiv region). The experiment was carried out on 62 heads of two-breed sows (Large White × Landrace), inseminated by boars of the terminal line "*Maxter*". The sows were divided into three groups: control (basic diet), experimental II (basic diet + 0.15% "Gepasorbex") and experimental III (basic diet + 0.15% commercial analogue). Behavioural responses were assessed using video monitoring (*Mobotix 6MP* network camera) for two weeks. It was found that the addition of the feed additive "Gepasorbex" to the diet contributed to a decrease in motor activity (186.5 min in experimental group II vs. 289.2 min in the control group, $p \leqslant 0.001$), an increase in rest time (by 4, 18-6.41 % more compared to the control, $p \leqslant 0.01$) and a decrease in stereotypical behaviour, in particular fictitious chewing (decrease by 120.2-131.1 min, $p \leqslant 0.001$) and hunger indication (by 109.0-111.8 min, $p \leqslant 0.01$). The use of "Gepasorbex" as a functional feed additive for gestating sows has demonstrated its effectiveness in improving their behavioural profile, which confirms the feasibility of using natural hepatoprotectors in programmes to improve animal welfare. The results of the study indicate that the inclusion of mycotoxin adsorbents in the diet helps to reduce stress reactions, increase the comfort of keeping and the overall welfare of sows. The data obtained can be used to optimise technological solutions in industrial pig production systems

Keywords: mycotoxin adsorbents; pig welfare; video monitoring; group housing; feed components; feed additive

Introduction

Modern pig farming is actively developing towards improving animal welfare and optimising feeding practices. One of the key aspects of effective sow management is creating comfortable conditions that align with welfare principles, as well as employing sensible feeding strategies. Natural feed additives, particularly those based on milk thistle and other botanical components known for their hepatoprotective and antioxidant properties, are attracting significant attention.

Keeping gestating sows in groups is a common and mandatory housing method that aligns with the concept of welfare and has a positive impact on the animals' social behaviour. During the production cycle, sows are regrouped after insemination through re-mixing, which can obviously lead to aggressive forms of internal interaction and restlessness within the groups (Lopez *et al.*, 2021).

As M. Priester *et al.* (2020) noted, a restricted feeding regime is used to prevent obesity in sows throughout the reproductive cycle – they are typically fed twice a day (at $8^{\underline{00}}$ and $16^{\underline{00}}$), which activates high feed motivation and reduces resting time. Researchers from Mexico, P. Islas-Fabila *et al.* (2024), stated that to meet energy requirements, the feeding allowance for pregnant sows varies around 2.4-2.6 kg, which constitutes approximately 50-60% of *ad libitum* intake.

According to M.C. Meunier-Salaun *et al.* (2001), the controlled feeding of pregnant sows contrasts with the natural form of feeding and can lead to the manifestation of atypical behaviours (stereotypies): bar biting; sham or vacuum chewing (chewing movements not associated with feed intake); sniffing or licking the floor or feeder in the absence of feed; time spent standing compared to lying down is used as an indicator of hunger, as sows do not appear satiated. It is worth noting that the feeling of satiety, which is insufficient with restrictive feeding of sows, and the reduction of hunger are the corrective factors by which positive changes can be introduced into sow feeding strategies.

In the convincing opinion of Korean researchers S. Do *et al.* (2023), diets for gestating sows enriched with fibre reduce active oral stereotypies, increase chewing and resting time, and decrease the rate of feed consumption. Furthermore, diets with the addition of milk thistle contain a number of biologically active substances that mitigate the negative consequences of hunger by reducing exploratory behaviour, and postprandial satiety is increased due to fibre consumption, raising the level of short-chain fatty acids in the blood and lowering the level of the digestive hormone ghrelin (Jensen *et al.*, 2015).

Thus, the available literature search suggests that the components of feed additives used for feeding gestating sows reduce the motivation to eat feed, provided that the animals' nutrient requirements are met, as in the specific experiment. According to the research results of R. Faustovet *et al.* (2022), the use of a complex feed additive based on milk thistle, active feed yeast, clinoptilolite, and selenium in the compound feed alters the feeding behaviour of fattening pigs, significantly improving their live weight gain and biochemical blood parameters, effectively neutralising the negative effects of mycotoxins without disrupting the vitamin balance in the body. V. Reznichenko *et al.* (2024) asserted that the complex feed additive "Gepasorbex" in the diet of sows during different periods of farrowing and lactation significantly improves their reproductive performance, promoting an increase in the reproductive index and offspring survival, creating a favourable nutritional environment that reduces the effects of feed toxins and stimulates the physiological mechanisms of growth and development in piglets.

Therefore, based on the aforementioned experimental results, it has been established that due to the saturation of diets with the components of the feed additive, there is a constant absorption of nutrients and greater microbial fermentation in the intestines, which, in fact, increases the satiety of sows. However, according to available information resources, there is insufficient material on the behaviour of sows during farrowing when using innovative feed additives. In this regard, the aim of the conducted research was to determine the nature of changes in the behavioural responses of gestating sows under the influence of the feed additive "Gepasorbex".

Materials and Methods

In groups of sows kept by the group method, the effect of the complex feed additive "Gepasorbex" on animal behaviour was evaluated in the conditions of industrial technology of the private-rental enterprise (hereinafter – PRE) "Victoria" in the Mykolaiv region according to the experimental scheme (Table 1). In total, 62 heads of two-breed sows (Large White (LW) × Landrace (L)) were used in the experiment in combination with boars of the "*Maxter*" terminal line.

Table 1. *Scheme of use of feed additives in diets of gestating and sow diets*

Group		*n*	Breed		Feeding conditions
			sows	boar	
I	control	19	LW × L	*Maxter*	BD* "Empty, sows"
II	experimental	22	LW × L	*Maxter*	BD "Empty, sows" + 0.15% by weight of feed "Gepasorbex" *
III	experimental	21	LW × L	*Maxter*	BD "Empty, sows" + 0.15% by weight of feed "Commercial analogue" **

Note: * – basic diet; ** – experimental feed additives were introduced into the diet directly in the farm's feed shop when making these recipes
Source: compiled by the authors

Sows were kept in group pens (with a stocking density of 2.1 m² per animal), and were fed 2.5-2.7 kg of feed per head per day using compound feed of the "Dry and Gestating Sows" type, with the following nutritional content: crude protein – 144.9 g/kg; metabolisable energy – 2914.7 kcal/kg. The basic diet (BD) consisted of compound feed produced in-house using premixes and protein-mineral-vitamin supplements manufactured by LLC "Tsekhave" (Ukraine) with the corresponding composition for "Dry and Gestating Sows" (%): wheat – 34.0; barley – 45.0; sunflower meal – 14.5; soya bean meal – 3.0; premix "Tsekhavit Sou Suporos" – 3.5; "Lactating Sows" (%): wheat – 43.5; barley – 30.0; sunflower meal – 10.0; soya bean meal – 11.5; premix "Tsekhavit Sou Laktatsiya" – 5.0.

The composition of 1 kg of the feed additive "Gepasorbex" (LLC "VetServisProdukt", Ukraine) contained the following active components (%): silicon dioxide – 60.2-70.8; aluminium oxide – 8-12; magnesium carbonate – 1.0-2.5; titanium dioxide – 0.8-0.15; selenium – 0.32-0.35; clinoptilolite – 4.2-4.5; active feed yeast – 8-10; milk thistle – 18-20%. The composition of the "Commercial Analogue" feed additive was: silicon dioxide (SiO_2), kaolinite clay, magnesium silicate, inactivated yeast (*Saccaromyces Cerevisiae*), sugar kelp (*Laminaria saccharina*), wild chicory and marigold extracts, dry matter – 954.0 g (Reznichenko *et al*., 2024). The main compound feed used for feeding the pigs in the experimental groups was recognised, according to laboratory tests by LLC "Expertnyi tsentr "Biolaites", as slightly toxic in terms of aflatoxin, ochratoxin, and zearalenone.

The monitoring of behavioural responses was carried out using a *Mobotix 6MP* network video camera (*MOBOTIX AG,* "*Langmeil*", Germany), equipped with "fisheye" lens, motion detection, and infrared illumination. Observations were conducted over two weeks during daylight hours (07:00 to 17:00) with three repetitions. For identification, each sow was marked with special tags, which allowed for the analysis of video footage. The duration (in minutes) of the main behavioural acts was assessed, such as: movement, resting (standing, sitting, ventral and lateral lying), feeding, chewing, exploratory activity, play behaviour, as well as the manifestation of stereotypies (sham chewing, signs of hunger, biting equipment) in accordance with generally accepted methods (Ibatulin & Zhukovskyi, 2017; Ladyka & Khmelnychiy, 2023).

The housing conditions of the experimental animals complied with the Departmental norms of technological design: Pig enterprises (complexes, farms, small farms) (2005) and the recommendations of genetic companies regarding housing. The rules for handling the experimental animals complied with Ukrainian legislation "Requirements for the welfare of farm animals during their keeping" (Order of the Ministry..., 2021). Ventilation was carried out using exhaust shaft fans and aerodynamic inlet valves and operated by creating negative pressure in the room. Manure removal from the room was carried out by means of a vacuum-gravity periodic action system from baths located under the slatted floor. All veterinary treatments were identical in both the experimental and control groups, according to the accepted scheme on the farm. The research results were processed using statistical methods (Kramarenko *et al*., 2019; 2024) with the use of computer equipment and applied software packages. The distribution of all variation series corresponded to the criteria of normality.

Results and Discussion

For the effective implementation of technological methods in industrial pork production, it is necessary to take into account the behavioural characteristics of animals. They help to predict future performance, promote pig welfare, optimise care and reduce labour costs. An important factor in the comfortable behaviour of gestating sows is their position in the pen and the frequency of changes in body position. Creating favourable conditions and reducing unnecessary motor activity facilitates animal observation, efficient feeding regulation and, most importantly, improves fertility. Monitoring of sow behaviour in the course of experimental studies made it possible to determine the key parameters of their behavioural acts, which are shown in Table 2.

Table 2. *Main indicators of behavioural repertoire of gestating sows as a result of the experiment*

Behavioural parameter	Definition
Movement	Changing the position of the sow's body or its individual parts through the locomotor system in order to interact with the environment.
Rest	A behavioural act aimed at acquiring a body position in the stall to restore the normal state of the body.
Standing	A static act of rest, when the ligaments of the supporting limbs are stretched, the rest of the body's muscles are consistently resting, and, therefore, no active locomotor activity takes place.
Sitting	The position of an animal in which a pair of hind limbs are relaxed on the floor, and the animal fixes the body position with its forelimbsц.
Ventral lying down	The animal's limbs are placed under the body while lying on the floor.
Lateral lying down	An animal lying on the floor has its limbs extended to the side.
Urination	Urinary act of elimination behaviour, the animal arches its back, spreads its pelvic limbs and squats slightly.
Defecation	The process of removing faeces from the body.
Foraging activity	It refers to feeding behaviour and consists of actually taking in the feed and chewing it in the mouth.
Imitation of chewing	Physical mobility of the oral cavity in the absence of food.
Indication of hunger	This is the behaviour of searching for and waiting for feed outside of feeding time.

Source: authors' development

In the course of video monitoring, it was found that the sows of the II experimental group spent the least time on mobility (186.5 min), followed by their counterparts of the III experimental group (196.8), which convincingly indicates stable hierarchical behaviour in group pens and the absence of operant reactions (Fig. 1). Significantly ($p < 0.001$) higher mobility was observed in sows of the first control group and, accordingly, outperformed their peers of the second experimental group by 102.7 min, and the third experimental group – by 92.4 min. Such increased locomotor activity has a number of dangers for animals (injuries, reduced productivity, risk of fetal loss, stress, aggression) and is a signal for pork production technologists to analyse and timely correct this act of behaviour in order to minimise undesirable effects on their productivity and welfare (Sun *et al.*, 2014).

The experimental sows of the II and III groups spent significantly ($p < 0.01$) more time on rest, respectively, by 4.18 % and 6.41 %, compared to the animals of the control group. There is an assumption that the presence of mycotoxin adsorbents in the diets of sows of the experimental groups reduces stress, physiological stress on the body, stabilises hormonal levels, and promotes the accumulation of energy for the body, which in turn leads to an increase in the period of rest of animals.

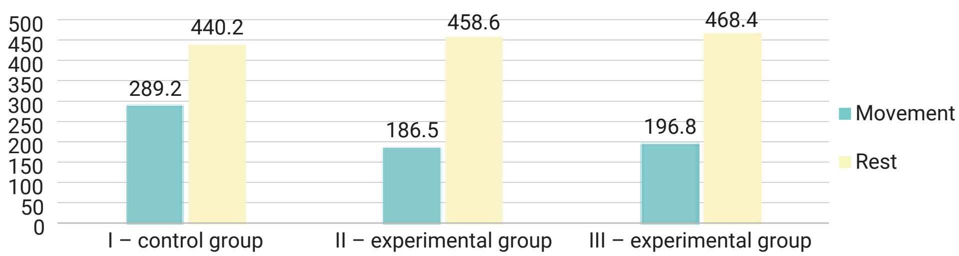

Figure 1. *Timekeeping of user actions of experimental sow groups during the experiment, min*

Source: authors' development

Sows, regardless of the group assignment, spent 13-15 s of time on urination during the experiment, and the number of urination acts was up to 6 times during video monitoring, which corresponds to the physiologically normal state of animals. Finally, the duration of the defecation act in gestation sows of different groups during the monitoring period was 5-7 s in 3-4 approaches, and the sows took a physiological posture during this act. It should be emphasised that the components of the rest indicator of gestation sows varied and depended on the purpose of the groups (Fig. 2). The timing of the components of the rest elements shows that sows of the II experimental group spent 40 min ($p < 0.05$) less time standing, and sows of the III experimental group spent 24 min less (difference not significant) standing compared to control sows. A possible explanation for the reduced standing time in sows of the experimental groups is an increase in postprandial satiety due to the presence of mycotoxin adsorbents in their diets and their powerful action in the intestine. The time spent on sitting by sows of the II-III experimental groups was higher and exceeded the same indicator of the I control group by 37.0-38.8 minutes ($p < 0.05$). An increase in the period of rest in the form of both ventral and lateral lying was characteristic of animals of the II and III experimental groups, which exceeded the sows of the control group by 11.7-12.5 min and 6.5-7.1 min, respectively.

Visualisation of the feeding behaviour of sows (Fig. 3) shows that the feeding activity of the II and III experimental groups of sows by the time spent on it was higher due to feed intake – 18.3-22.5 min compared to control counterparts, and by the time spent on chewing the feed, no significant difference was found in the groups.

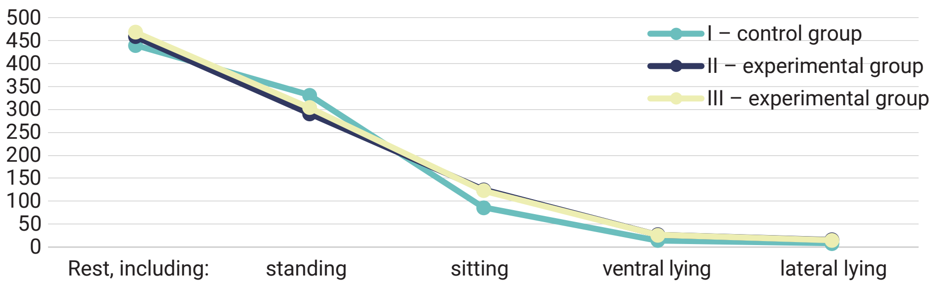

Figure 2. *Timekeeping of the components of behavioural acts of rest of experimental sow groups during the experiment, min*

Source: authors' development

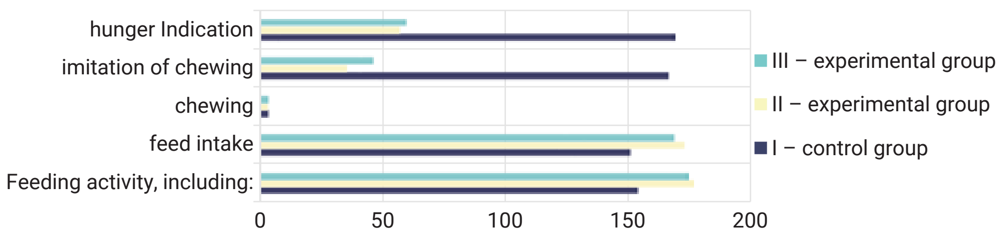

Figure 3. *Feeding behaviour of experimental groups of sows during the experiment, min*

Source: authors' development

Typically, gestating sows are fed in limited quantities, and they show high motivation to eat after their daily allowance is consumed, which leads to the development of stereotypic behaviour (regularly repeated movements that are morphologically identical and have no obvious function). In sows, stereotypical behaviour is often associated with feeding: imitation of chewing, indication of hunger, which confirms the connection with the motivation to feed. As can be seen from the experiment, sham or vacuum chewing was visualised to a greater extent in sows of the control group I, which spent significantly more time on this behavioural act – 131.1 min ($p < 0.001$) compared to the experimental group II and 120.2 min ($p < 0.001$) – to the experimental group III. Imitation of chewing is obviously associated with a combination of insufficient satiety and a disorder of feed search or intake behaviour, as in the case of sows of the control group I (Fig. 4).

Figure 4. *Stereotypical behaviour of sows – "imitation of chewin"*
Source: photo by the authors of the study

The stereopathy of gestating sows "hunger indication" is usually manifested in the search and expectation of feed outside the feeding time and is visualised by sniffing (Fig. 5), licking (Fig. 6) the feeder in the absence of feed. It should be noted that sows of the first control group spent the most time on this consumptive behavioural act – 168.6 min, which significantly exceeded the time spent by 111.8 min ($p < 0.01$) for the peers of the second experimental group and 109.0 min ($p < 0.01$) – respectively, for the sows of the third experimental group.

Figure 5. *Stereotypical behaviour of gestating sows – "hunger indication" in the form of sniffing the trough in the absence of feed*
Source: photo by the authors of the study

Figure 6. *Stereotypical behaviour of gestating sows – "hunger indication" in the form of licking the trough in the absence of feed*
Source: photo by the authors of the study

At the same time, the experiment increased the frequency of cases of non-feeding oral behaviour of sows of the first control group in the form of biting the rods of the group pen, which accounted for up to 17 minutes during the experimental timing (Fig. 7).

Figure 7. *Non-feeding oral behaviour of gestating sows in the form of biting the bars of a group pen*
Source: photo by the authors of the study

A time-and-motion study of the components of resting behaviour showed that the gestating sows in the second experimental group spent 40 minutes less time standing ($p < 0.05$), and their counterparts in the third experimental group stood for 24 minutes less (the difference was not statistically significant) compared to the control sows. An increase in the resting period, both in terms of ventral and lateral lying, was characteristic of the animals in the second and third experimental groups, which exceeded the control group sows in the time spent on this behavioural indicator by 11.7-12.5 minutes and 6.5-7.1 minutes, respectively.

In modern pig farming, effective management of technological processes involves not only optimising housing conditions but also considering the behavioural responses of animals as a key element in ensuring their welfare and productivity, as highlighted by researchers J.C. Jang & S.H. Oh (2022). The behaviour of gestating sows, in particular: locomotor activity, duration of rest, feeding motivation, and the manifestation of stereotypies, are closely related to the physiological state of the organism and reflect the degree of adaptation to housing and feeding conditions, as evidenced by the precision feeding programmes for gestating sows in the study by R.L. Domingos *et al*. (2024). The obtained results of the current experiment convincingly demonstrate that the use of the complex feed additive "Gepasorbex" in the diet of gestating sows positively affects their behavioural repertoire, reducing the level of stress load on the body and contributing to the maintenance of farrowing.

It was established that the lowest level of locomotor activity was observed in the sows of the second and third experimental groups, which likely indicates a stable social hierarchy and a low level of distress in group housing conditions. This aligns with the conclusions of the research by J.C. Jang & S.H. Oh (2022), who noted that increased locomotor activity can be a sign of anxiety, stress, and even the risk of foetal loss. Thus, the reduction of unnecessary movements in sows can be interpreted as a sign of improved physiological and psycho-emotional state of the animals when using the complex feed additive "Gepasorbex".

An increase in the duration of rest, particularly in the form of ventral and lateral lying, was characteristic of the animals in the second and third groups, which is consistent with the research by S. Huang *et al*. (2020), who pointed out the importance of minimising locomotor activity in gestating sows to prevent complications during farrowing. The decrease in standing time in the experimental animals is likely due to an increased level of postprandial satiety, which promoted physiological rest and reduced the risk of developing limb pathologies, consistent with the studies conducted by T. Kramer *et al*. (2023). As the authors M. Priester *et al*. (2020) stated, "feeding, pig farming and ethology no longer need to be considered separately", and therefore, the feeding activity of the gestating sows in the experimental groups should be considered.

The feeding activity of the sows that received the complex feed additive "Gepasorbex" was directed towards efficient feed consumption with a simultaneous reduction in the manifestations of stereotypical behaviour, in particular: sham chewing, indications of hunger, and aggressive reactions, which were most frequently recorded in the animals of the control group. The aforementioned phenomenon is typical for a restricted feeding regime, which is confirmed by the work of L. Vargovic *et al.* (2021), which noted that pregnant sows with high feed motivation demonstrate pronounced stereotypies in the case of feed deficiency or an unbalanced diet. The addition of mycotoxin adsorbents, in particular the multicomponent preparation "Gepasorbex", contributed to the stabilisation of the animals' mental profile, which is indirectly confirmed by a decrease in stress-associated behaviour. Similar results are presented in the studies by T. Feyer *et al.* (2021), who found that the use of sorbents in pig diets helps to improve behavioural responses and reduce aggression in group housing conditions.

The recording of behaviour within the framework of experimental monitoring also made it possible to establish a decrease in the manifestations of non-nutritive oral behaviour in the animals of the second and third experimental groups. In particular, the reduction in the time spent biting bars is a positive indicator of a decrease in frustration resulting from restricted access to feed or stress-inducing influences. This aspect was also considered in the study by S. Do *et al.* (2023), which noted that disturbances in feeding behaviour can be early signs of reduced welfare in pig farming. The occurrence of stereotypical behaviour reflects increased feed motivation after feeding and is interpreted as a sign of impaired welfare, and hunger and frustration in feeding motivation consequently increase aggression and competition for feed in group housing systems (Sapkota *et al.*, 2016; Shang *et al.*, 2019).

An additional argument in favour of using the "Gepasorbex" additive is its effect on reducing the risk of metabolic distress, which often accompanies intensive culling in pig farming. As R. Faustov *et al.* (2022) noted, mycotoxin adsorbents are capable not only of binding toxins in the gastrointestinal tract but also of reducing their systemic effects, lowering the activity of the hypothalamic-pituitary-adrenal axis. This indirectly contributes to a decrease in the production of cortisol – the stress hormone – which has a direct impact on the behaviour, appetite, and reproductive performance of sows. Considering the above, it becomes obvious that the improvement of behavioural responses in sows is not only an ethological but also a physiologically justified consequence of using a high-quality multicomponent additive in the diet (Slama *et al.*, 2019). It is also worth noting that the improvement of behavioural characteristics under the influence of "Gepasorbex" may also have a positive effect on rank relationships within groups in general. Reducing the level of aggression, competitive struggle for feed, manifestations of stress and frustration contributes to the formation of more stable social interactions between sows. This is particularly important in industrial housing conditions, where stocking density and limited space can be additional risk factors (Jang & Oh, 2022). Thus, the complex additive indirectly affects not only the individual behaviour of animals but also the harmonisation of relationships within the group, reducing the need for intervention by personnel.

Overall, the research results demonstrate that the use of the complex feed additive "Gepasorbex" allows not only to optimise metabolic processes (Krogh *et al.* 2016) in gestating sows but also significantly affects their behavioural acts. This has practical significance in the context of improving farrowing maintenance and increasing animal welfare. Thus, the use of a complex feed additive based on mycotoxin adsorbents is an effective tool for implementing the principles of humane treatment of animals and rational pig farming in intensive production conditions.

Further research will be aimed at a deeper study of the neuroendocrine mechanisms of the influence of feed additives on the behaviour of gestating sows, particularly in the context of stress-induced reactions and metabolic homeostasis. It is also advisable to involve broader biochemical markers that reflect the level of stress, satiety, and adaptive potential of animals in industrial conditions.

Conclusions

In commercial production pig farms, in order to adapt the methods of controlling limited dietary intake according to detailed regulations and the associated stereotypical behaviour in pregnant sows, it is necessary to apply the case of practical solutions to sow feeding with the use of complex feed additives of mycotoxin adsorbents. In our case, it is "Gepasorbex", which reduces the apparent motivation to feed gestating sows and improves their welfare.

Monitoring the behaviour of sows in group housing systems makes it possible to assess their welfare, predict productivity and minimise the risks associated with excessive physical activity, stress and injury. The study found that sows of the II and III experimental groups showed lower mobility, which indicates stable social behaviour, lack of operant reactions and a reduced likelihood of stress factors that can negatively affect the preservation of farrowing.

The addition of mycotoxin adsorbents to the diet helped to reduce the stress load on the body, which is confirmed by an increase in the duration of rest in sows of the experimental groups. Animals of groups II and III spent more time sitting and lying down, which had a positive effect on their general physiological condition. The physiological parameters of urination and defecation in all groups were normal, which confirms the absence of a negative effect of the studied factors on the functioning of the sows' body.

In the control group, more manifestations of stereotypical behaviour were recorded, including mock chewing, hunger indication and biting equipment, which indicates increased motivation to feed and the presence of stress factors. Instead, in the experimental groups, these behavioural deviations were observed much less frequently, which may be due to better saturation and stabilisation of the physiological state due to feed additives. Thus, the use of mycotoxin adsorbents in feeding helps to improve the overall welfare of sows, reducing stress and aggression in group housing systems.

In the future, a promising direction is to study the neurobiochemical mechanisms by which the feed additive "Gepasorbex" affects the behavioural reactions of gestating sows. In particular, it is advisable to monitor the levels of cortisol, serotonin, leptin and other biomarkers that reflect stress response, feeding motivation and adaptive capabilities of pigs. Of particular scientific value is the study of the impact of feed additives on the development and behavioural characteristics of offspring, including the assessment of viability, growth rates and stress resistance of newborn piglets, which will allow a more complete assessment of the long-term effectiveness of such dietary correction in gestating sows.

Acknowledgements

The authors would like to thank the Private-rental Enterprise "Victoria" for assistance in research and VetServiceProduct LLC for providing feed additives.

Funding

None.

Conflict of Interest

None.

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Технологічні рішення для покращення благополуччя поросних свиноматок при груповому утриманні

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Анотація. Сучасне свинарство орієнтується на підвищення благополуччя свиноматок шляхом оптимізації умов утримання та впровадження натуральних кормових добавок із гепатопротекторною дією. Метою дослідження було визначити вплив комплексної кормової добавки «Гепасорбекс» на поведінкові реакції поросних свиноматок. Експеримент проводився за умов групового утримання тварин у промислових умовах приватно-орендного підприємства «Вікторія» (Миколаївська область). Експеримент проведено на 62 головах двопородних свиноматок (велика біла × ландрас), запліднених кнурами термінальної лінії «*Maxter*». Свиноматки були розподілені на три групи: контрольну (основний раціон), дослідну II (основний раціон + 0,15 % «Гепасорбекс») та дослідну III (основний раціон + 0,15 % комерційного аналога). Оцінка поведінкових реакцій проводилася за допомогою відеомоніторингу (мережева камера *Mobotix 6MP*) протягом двох тижнів. Встановлено, що додавання кормової добавки «Гепасорбекс» до раціону сприяло зниженню рухової активності (186,5 хв у дослідній II групі проти 289,2 хв у контрольній, $p \leq 0,001$), збільшенню часу відпочинку (на 4,18-6,41 % більше, порівняно з контролем, $p \leq 0,01$) та зменшенню проявів стереотипної поведінки, зокрема фіктивного жування (зниження на 120,2-131,1 хв, $p \leq 0,001$) та індикації голоду (на 109,0-111,8 хв, $p \leq 0,01$). Застосування препарату «Гепасорбекс» як функціональної кормової добавки для поросних свиноматок продемонструвало ефективність у покращенні їхнього поведінкового профілю, що підтверджує доцільність використання натуральних гепатопротекторів у програмах підвищення рівня благополуччя тварин. Результати дослідження свідчать про те, що включення до раціону адсорбентів мікотоксинів сприяє зниженню стресових реакцій, підвищенню комфортності утримання та загального добробуту свиноматок. Отримані дані можуть бути використані для оптимізації технологічних рішень у системах промислового свинарства

Ключові слова: адсорбенти мікотоксинів; благополуччя свиней; відеомоніторинг; групове утримання; компоненти комбікормів; кормова добавка

Received 27.12.2024 Revised 31.03.2025 Accepted 25.04.2025

Vol. 21, No. 2
2025

Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 631.833:639.312

DOI: 10.31548/dopovidi/2.2025.75

Efficiency of potassium sulphate application for growing *Clarias gariepinus* in an aquaponics system

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Abstract. The study aimed to determine the effect of adding potassium sulphate (K_2SO_4) at a concentration of 500 mg/dm³ on the quality of the aquatic environment, growth of *Clarias gariepinus* and yield of lettuce in an aquaponics system. The experiment was conducted in two parallel lines: control (without K_2SO_4) and experimental (with the addition of K_2SO_4). The initial total weight of 19 fish in each line was 1330 g. In 57 days, the weight in the control line increased to 1995 g, and in the experimental – to 2888 g. The feed conversion was 2.5 in the control and 1.1 in the experiment. The specific growth rate (SGR) was 0.82%/day in the control and 1.74%/day in the experimental group. The potential yield of lettuce (4000 g/m²) was realised by 51.1% in the control and 87.5% in the experiment. In the control line, the main limiting factor was potassium deficiency (21.6-28.3 mg/l), and in the experimental line, the pH increased to 8.3 due to insufficient nitrogen uptake at 19.5°C (below the optimum for nitrification). In both lines, a significant increase in the content of mineral compounds (NO_3^-, NH_4^+, SO_4^{2-}, PO_4^{3-}) was recorded, but the water parameters remained within the range acceptable for aquaponics technologies. The results obtained indicate a positive effect of adding K_2SO_4 at a given concentration, which ensures an increase in fish and plant productivity, although it requires the incorporation of the ratio of green crops to fish biomass and

Suggested Citation:
Kolesnyk, T., & Maiboroda, Kh. (2025). Efficiency of potassium sulphate application for growing *Clarias gariepinus* in an aquaponics system. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 21(2), 75-90. doi: 10.31548/dopovidi/2.2025.75.

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water temperature. The addition of K_2SO_4 contributed to the increase in the biological efficiency of the aquaponic system while maintaining acceptable water quality

Keywords: lettuce; biomass growth; feed conversion; water quality; nitrate nitrogen; hydroponics module performance

Introduction

The African Clarius catfish (*Clarias gariepinus*) is an important aquaculture element due to its rapid growth, resistance to stressful conditions and ability to breathe atmospheric air, therefore resilient to high planting densities. In one cubic metre of water, 200-300 kg of adult fish can be grown, and under favourable conditions, catfish can reach a weight of 1.5-2 kg in six months (State Agency of Fisheries of Ukraine, 2021). B.Yu. Kovalenko *et al.* (2021) emphasised that catfish can adapt to different growing conditions, which is important for aquaponics systems, where effective management of the aquatic environment is critical for system stability. At the same time, N.M. Vdovenko *et al.* (2020) emphasised the importance of optimising feeding strategies to ensure high productivity and ecosystem stability.

A.M. Trofymchuk *et al.* (2021) provided a fish farming and technological rationale for recirculating aquaculture systems for African catfish, highlighting the importance of proper control of the aquatic environment to ensure optimal conditions for fish growth. This highlights the need for an integrated approach to managing aquaculture systems, where maintaining water stability and fish health are key factors for a successful system. Aquaponics, which combines aquaculture and hydroponics, is a sustainable system that allows for efficient use of resources and reduces the negative impact on the environment. Mineral elements are substantial in this system, in particular potassium, which is a key macronutrient for plant growth. Potassium sulphate (K_2SO_4) is a popular source of potassium in agriculture because it does not contain chlorine, which can be harmful to some crops.

However, the impact of potassium sulphate on the health and productivity of aquatic organisms, in particular the Clarius catfish, has not been sufficiently studied. Research demonstrated that an increased concentration of potassium sulphate in the aquatic environment can affect the physiological parameters of aquatic organisms. For instance, I.S. Babarchuk & Yu.V. Babich (2022) studied the effect of potassium sulphate on the haematological parameters of the mollusc *Planorbarius corneus*, which indicates the potential impact of this fertiliser on aquatic life. The efficient use of mineral fertilisers in aquaponics systems, in particular potassium sulphate (K_2SO_4), is an important aspect of research aimed at optimising these agroecological systems. According to H. Neerudu *et al.* (2023), potassium sulphate is a source of potassium, which is essential for normal plant growth and is also important for regulating water and salt balance in organisms, including aquacultured fish. Potassium is critical for chlorophyll synthesis, energy transfer and maintenance of cellular pressure, and therefore its deficiency or excess can have a significant impact on the performance of aquaponics systems.

Potassium is important not only for plant development but also for fish health, as evidenced by studies showing that potassium helps fish to better adapt to stressful conditions such as rising water temperatures and changes in water quality. The potential positive effect of potassium on fish is also supported by H. Nyadjeu *et al.* (2020) and L.C. Wenzel *et al.* (2021), studies on the African Clarius catfish, which demonstrated improved health and metabolism when added to feed. One of the most important areas of research is the study of the effect of potassium sulphate on the physiological parameters of fish, particularly the African *Clarias gariepinus*. The study by A. Granal *et al.* (2024) demonstrated that potassium has a positive effect on the ability of fish to adapt to stressful conditions, including increased water temperature. However, at excessive concentrations of potassium sulphate, there is an increase in toxicity, which can lead to a decrease in fish activity and negatively affect their ability to grow. In addition, studies demonstrated a positive effect of potassium on improving fish metabolism improving the condition of their skin and reducing stress levels in the event of sudden changes in water parameters.

F.X. Presas-Basalo (2021) highlighted the importance of a balanced supply of macro- and micronutrients in aquaponic systems. The study highlighted that potassium in high concentrations can affect the levels of other macronutrients, such as calcium and magnesium, which are important for normal physiology in both plants and fish. Furthermore, the system should include well-configured filtration to prevent the accumulation of toxic levels of salts. Other studies, such as by V.C. John *et al.* (2021), demonstrated that properly configured aquaponics systems using potassium sulphate can provide sustainable and efficient production of both fish and plants. The researchers noted that for the successful integration of potassium sulphate, environmental factors such as water temperature and pH must be incorporated, as these parameters directly affect the efficiency of potassium in both components of the system. In general, studies conducted by S.F.P. Duarte & B.S. Cerozi (2024) demonstrated that properly balanced potassium levels in aquaponics systems have a positive effect on the productivity of both fish and plants. However, more research is needed to determine the optimal concentrations of this element depending on the type of plants and fish species grown.

Overall, numerous studies demonstrated that potassium sulphate is promising for aquaponics systems, but more research is needed to determine the optimal concentrations of this element depending on the type of plants and fish species grown. Another important area is the development of new methods of water purification and monitoring of mineral levels, which can reduce the negative impact of high potassium concentrations on the environment. Thus, the relevance of this study lies in the need to study the effect of potassium sulphate on the cultivation of Clarius catfish in aquaponics systems.

The study aimed to evaluate the effectiveness of potassium sulphate in ensuring optimal conditions for the development of aquaponics organisms (Clarius catfish and lettuce). Study goals included:

- analysis and evaluation of changes in the state of the aquatic environment during 1 cycle of growing lettuce (57 days) without the addition of potassium sulphate and with the addition of potassium sulphate at a concentration of 0.50 g/dm^3;
- analysis and evaluation of the development of Clarius catfish in the experimental line of the aquaponics system (with and without the addition of 0.50 g/dm^3 of potassium sulphate) by metrics: average fish weight, feed conversion rate, specific fish growth rate, assessment of the impact of potassium sulphate on fish physiological parameters.

The research relevance is determined by the novelty of the comprehensive study of the effect of potassium sulphate on the cultivation of Clarius catfish in aquaponics systems, which will increase the efficiency and sustainability of such systems.

Materials and Methods

The experimental study was conducted at the National University of Water and Environmental Engineering in the educational and scientific laboratory of cyclic water of agroecosystems in 2024 and aimed to analyse the effect of adding potassium sulphate (K_2SO_4) to fresh water of an aquaponic system with Clarias catfish (aquaculture module) and lettuce (hydroponics module) at a concentration of 0.5 g/dm^3 on the chemical parameters of water and productivity of *Clarias* *gariepinus* in an aquaponic system. The study was conducted based on the Convention on Biological Diversity (1992).

Experiment. Two parallel aquaponics systems were used in the experiment: a control system (without potassium sulphate) and an experimental system (with potassium sulphate). In the aquaculture module of each line (a 1 m^3 tank with a water level of 0.8 m^3), 19 Clarus catfish with an average initial weight of 50 g/individual were grown, with a total fish biomass of 950 g/tank. In the hydroponics module, leaf lettuce was grown on a planting area of 1 m^2 with a planting density of 57 plants/m^2.

Water quality analysis. Water quality was tested at the start of the experiment (13 November 2024) and at the end of the experiment (8 January 2025). To determine the content of macroelements in water, a Lasa agro 1900 spectrophotometer (manufacturer: STEP Systems GmbH, country of manufacture: Germany) was used, and to determine the pH of water and the concentration of potassium ions, an ion meter I-160 MI (manufacturer: NPF Tensor, country of manufacture: Russia) with appropriate selective electrodes. This equipment provided accurate measurements of the concentration of the main chemical elements affecting the state of the aquatic environment in the aquaponics system. In addition, the following methods were used to study water quality: measurement of nitrate ion concentration by the photocolorimetric method MM No. 081/12-0651-09 (2010); measurement of the mass concentration of ammonium ions by the photocolorimetric method with Nessler's reagent MM No. 081/12-0651-09 (2010), measurement of the mass concentration of sulphates by titrimetric method MM No. 081/12-0653-09 (2010).

Two important physiological indicators were calculated to assess the efficiency of fish feed assimilation and fish development: Specific Growth Rate (SGR) and Feed Conversion Ratio (FCR). FCR is an important indicator of the efficiency of fish farming in aquaponic systems (Nyadjeu *et al.*, 2020):

$$\text{FCR} = \frac{\text{Consumed feed mass (g)}}{\text{Biomass growth (g)}}. \qquad (1).$$

The FCR determines the amount of feed required to produce a unit of biomass gain. The calculation of these metrics determines how efficiently fish use feed and how fast they grow in conditions where potassium sulphate is added compared to control conditions. SGR is another important indicator that can estimate the growth rate of fish over a certain period (Dos Santos, 2018):

$$\text{SGR} = \frac{(\ln W_t - \ln W_0) * 100}{t}, \qquad (2)$$

where W_t – fish mass at the end of the experiment, g; W_0 – initial fish mass, g; t – experiment duration, days; *ln* – natural logarithm.

To determine statistically significant differences between the mean values of the two experimental variants, the least significant difference (LSD_{05}) was calculated (Ushkarenko *et al.*, 2013). These calculations determined: number of degrees of freedom for variants, replicates, and error; total number of observations; correction factor; total sum of squares; sum of squares for replicates, variants, and error; variance for line and error; Fisher's test; and relative error.

Results and Discussion

The results of the study of Clarius catfish development in the aquaponics system showed that at the end of the experiment (57 days), the total weight of fish in the control line reached 1995 g/basin, while in the experimental – 2888 g/basin (Table 1).

The increase in the total biomass of Clarie catfish during the study period in the control line was +665 g/basin, in the experimental line +1558 g/basin, which exceeded the control indicator by 134%, which indicates a very positive effect of adding potassium sulphate at a concentration of 0.50 g/dm^3 on the development of Clarus catfish. At the same time, the average weight of one Clarus catfish in the control line at the end of the experiment was 105 g/individual, and in the experimental line, 170 g/individual.

Dispersion analysis showed statistically significant differences between the average fish weights in the control and experimental lines. The smallest significant difference (LSD_{05}) was 21.6 g/individual, which indicates the reliability of the differences.

Table 1. *Growth and feed conversion parameters in Clarius catfish*

Metric	Controller	Experimental	LSD_{05}	Absolute increase relative to control	Relative increase, % to control
Average weight of fish at the beginning of the experiment, g/individual	70	70	-	0	0
Number of fish, individuals/pool	19	19	-	0	0
Total weight of feed consumed during the experiment, g/pool	1670	1670	-	0	0
Average fish weight at the end of the experiment, g/specimen	105	152	21.6 g/specimen	47	+44.8
Total fish weight at the start of the experiment, g/basin	1330	1330	-	0	0
Total fish weight at the end of the experiment, g/basin	1995	2886	-	893	+44.8
Increase in total fish weight during the experiment, g/basin	665	1558	-	893	+134
FCR (feed conversion ratio)	2.51	1.08	-	-1.44	-57.3
SGR (specific growth rate), %/day (for 57 days)	0.71	1.36	-	0.65	91.2

Source: compiled by the authors

The feed conversion ratio (FCR) in the control line was 2.51, while in the experimental line, the FCR decreased to 1.07. According to the scientist J. Breinballe (2010), the average optimal values of the feed conversion ratio of Clarius catfish range from 1.2 to 1.5. Thus, the obtained values of FCR indicate a low level of feed assimilation by fish of the control line and a very high level in fish of the experimental line. Thus, the addition of potassium sulphate to the water at a concentration of 0.50 g/dm^3 increased the efficiency of feed assimilation by Clarius catfish by 57.3%. The specific growth rate of fish (SGR) during the study period in the control line was 0.71 %/day, in the experimental line, 1.36%/day, respectively, which indicates an acceleration of growth of Clarius catfish under the influence of potassium sulphate (0.50 g/dm^3) by 91.2%.

An important benchmark for the level of water pollution in an aquaponics system is the water quality standard. The search for relevant standards in Ukrainian and foreign regulatory documents demonstrated that in Ukraine, there are only fishery water quality standards for ponds, while EU countries also have relevant standards for surface water sources (Directive 2000/60/EC..., 2000; Order of the Ministry..., 2022). For aquaponics systems, no standards were found that would regulate the maximum permissible concentrations (MPC) of pollutants, but based on the study of various literature sources, some technological standards for water quality in recirculation plants for samarium were summarised in Table 2.

To determine the reasons for the acceleration of Clarius catfish development under the influence of potassium sulfate addition to water to set its concentration in the aquatic environment at 0.50 g/dm^3, the main parameters of water quality were analysed at the beginning and end of the experiment in the control and experimental lines of the aquaponics system (Fig. 1) and a graph of the average daily water temperature dynamics (Fig. 2).

Table 2. *Consolidated technological standards for water quality of closed water supply systems for rearing juvenile Clarius catfish*

No.	Metric	Units of measurement	Technologically permissible fluctuation limits	Source of information on the value of the indicator's technological limits
1	pH	Unit, pH	6-8.5	A. Peteri *et al.* (2015)
2	Salt content	mg/dm³	10	A. Peteri *et al.* (2015)
			25-27	A. Peteri *et al.* (2015)
			>0.0	A. Peteri *et al.* (2015)
5	$N\text{-}NH_3$	mg/dm³	<0.34	A. Peteri *et al.* (2015)
6	$N\text{-}NH_4^+$	mg/dm³	<80	A. Peteri *et al.* (2015)
7	NO_2^-	mg/dm³	<8.0	A. Peteri *et al.* (2015)
8	NO_3^-	mg/dm³	<100 for fish weighing up to 10 g, for fish weighing more than 10 g – not regulated	A. Peteri *et al.* (2015)
9	$N\text{-} (NH_4^+ + NO_3^-)$	mg/dm³	<100	J. Breinballe (2010)
10	CO_2	mg/dm³	<15	J. Breinballe (2010)
			<10	A. Peteri *et al.* (2015)
11	H_2S	mg/dm³	<2.0	A. Peteri *et al.* (2015)
12	BSC	mg/dm³	<20	J. Breinballe (2010)
13	$P\text{-}PO_4^{3-}$	mg/dm³	<20	J. Breinballe (2010)

Source: compiled by the authors

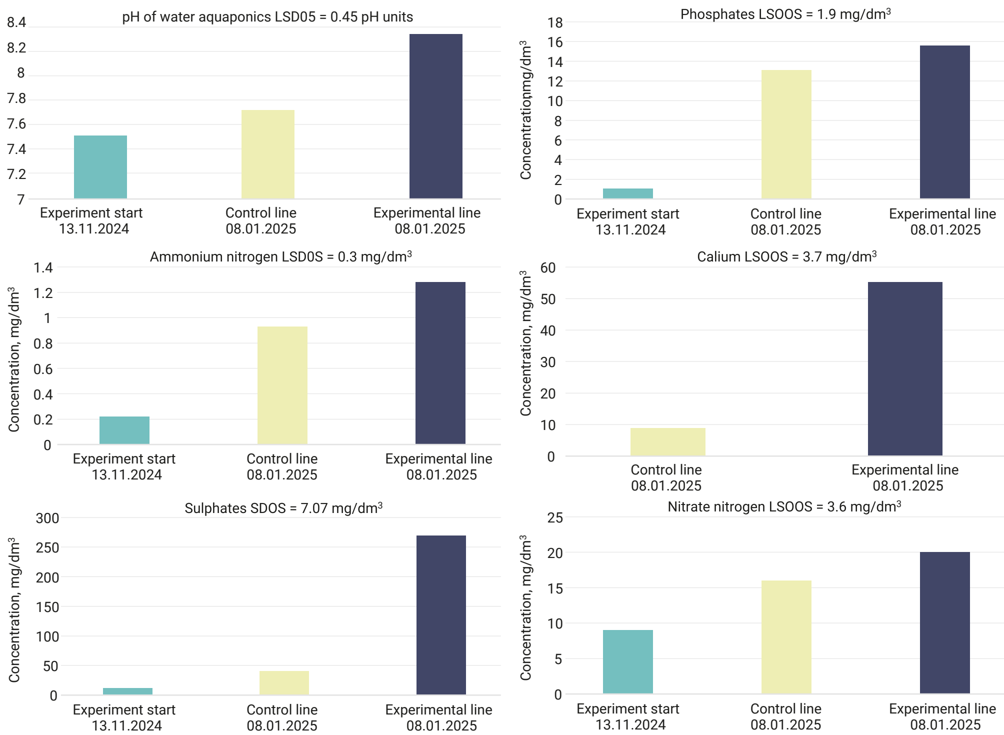

Figure 1. *Comparison of the chemical composition of water at the beginning and end of the experiment*

Source: compiled by the authors

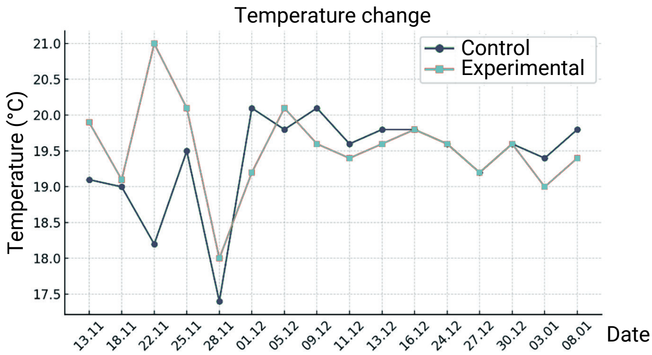

Figure 2. *Dynamics of water temperatures during the experiment*
Source: compiled by the authors

The results of the analysis of changes in the redox conditions of the water environment (pH) of the control line during the experiment period (57 days) demonstrated an increase in pH from 7.5 to 7.7 pH units (+2.67% of the initial value), which is an insignificant increase, while in the experimental line the pH of the water increased to 8.3 pH units (+10.7% of the initial level). In the control line, the pH increased from 7.5 to 7.7, and in the experimental line, from 7.5 to 8.3. Such changes can be caused by several factors (Poloviy *et al*., 2024):

➤ Ammonium nitrogen (NH_4^+) and nitrate (NO_3-) can increase the acidity of water, but their metabolic transformation, especially through nitrifying bacteria, can lead to a decrease in acidity. However, the addition of potassium sulphate can change the ion balance in the water, resulting in a slight increase in pH;

➤ Algae photosynthesis and bacterial processes can reduce CO_2 concentrations in the system, leading to an increase in pH. This may also be the result of increased algae and bacterial activity under the influence of potassium, which reduces CO_2 concentrations in aquaponics systems, as confirmed by other studies.

At the beginning of the experiment (one day after the addition of potassium sulphate in concentration and mixing of water in the system), the pH of the experimental line increased to 7.9 pH units (+0.4 pH units relative to the control line), at the end of the experiment, the pH of the experimental line exceeded the corresponding indicator of the control line by + +0.6 pH units (+8.0%). During the study period, there were significant fluctuations in water pH in both the experimental and control lines (Fig. 3).

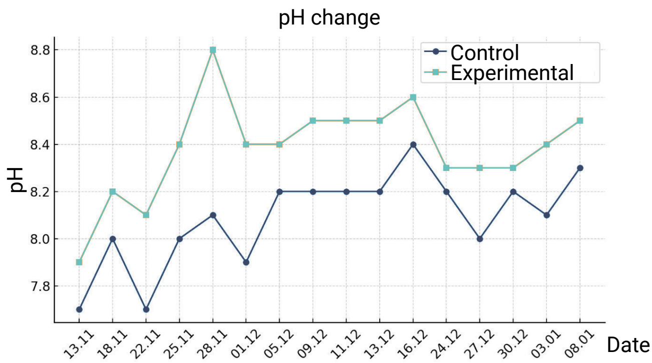

Figure 3. *Water pH dynamics during the experiment*
Source: compiled by the authors

In the control line, the temperature ranged from 17.4°C to 20.1°C, which is within the optimal range for Clarius catfish (18-28°C), as demonstrated in Figure 2. The drop in temperature to 17.4°C on 28 November was due to changes in external climatic conditions and the switching off lighting, which slowed the metabolic activity of the fish and reduced their ability to release ammonia. The temperature in the experimental line ranged from 18°C to 21°C, with sharper fluctuations.

Analysing the diagram of the course of average daily temperatures during the study period (Fig. 3), then on 28.11.2024, a clear inversely proportional relationship between temperature and pH is notable, in which a sharp decrease in water temperature causes a sharp increase in pH, especially in the experimental line (pH = 8.8 units. pH), which is due to the deterioration of nitrifying bacteria, slowing down the development of lettuce plants and, as a result, the accumulation of ammonium nitrogen as a product of fish vital activity. In general, during the experiment, the pH of the water did not exceed the technological standards for Clarius catfish (Table 1), except for the date 28.11.2024, when the pH of the experimental line reached a maximum (8.8 pH units) due to a sharp decrease in water temperature to 18°C, which is normal for lettuce, but a factor inhibiting the development of Clarius catfish and especially nitrifying bacteria. After increasing the temperature from 18 to 20.1°C, the pH of the water in the experimental line decreased from 8.8 pH units to 8.4 pH units and came to the technological norm, not leaving it at the end of the experiment.

Monitoring the potassium and sulphate content in the water of the experimental and control lines and comparing them with the balance of sulphate ions and potassium ions added with potassium sulphate to the experimental line at a concentration of 0.50 g/dm^3, the difference in potassium concentrations between the experimental and control lines is +46.3 mg/dm^3 in favour of the experimental line, and the difference in sulphate concentrations is 229 mg/dm^3 in favour of the experimental line is notable. The ratio of the increase in potassium ion concentration to sulphate ion concentration in the experimental line relative to the control line is 4.95 times in favour of sulphate ion. At the same time, the ratio between potassium ions and sulphate ions in the water of the experimental line at the beginning of the experiment (at a potassium sulphate concentration of 0.50 g/dm^3) was 1.23. Thus, a significant shift in this ratio at the end of the experiment (+302% of the initial value) is notable in favour of sulphate ions. To determine the reasons for this shift, it is necessary to analyse other water quality indicators, which will correlate with the processes of fish and plant development and water quality. It should be noted that the fish diet and feeding rates in both lines remained unchanged during the study period (30 g of feed per 19 fish per day), and the feed quality was also the same: Aller Aqua Classic, 4 mm fraction.

An important indicator of water quality is the content of ammonium nitrogen and nitrate nitrogen in water, which together is the sum of nitrogen from mineral compounds. These mineral nitrogen compounds in water occur as a result of the gradual conversion of organic nitrogen compounds (nitrogen amides, urea nitrogen) first to ammonium nitrogen, then to nitrate and nitrite nitrogen, and then to amino acid nitrogen in plant organisms and microorganisms living in water through assimilative denitrification (Nugraha *et al*., 2020). But there is also another way of denitrification – dissimilatory denitrification, in which nitrates are reduced to gaseous nitrogen compounds (NO, N_2O, N_2), which indicates unproductive losses of nitrogen that could be used in the synthesis of organic compounds of the plant organism and effective microorganisms. The processes of transformation of nitrogen compounds in aquaponic systems are temperature-dependent: when the temperature rises to 25-30°C, the activity of nitrifying bacteria (Nitrosomonas and Nitrobacter) increases, which contributes to more intensive oxidation of ammonium (NH_4^+) to nitrite (NO_2-) and further conversion to nitrate (NO_3-), whereas at low temperatures (<15°C), the rate of nitrification slows down significantly, which can lead to the accumulation of toxic forms of nitrogen in the aquatic environment.

In an aquaponic system, the main consumer of nitrogen compounds is plants, which consequently purify water from toxic nitrogen compounds. At the same time, nitrate nitrogen accounts for 75…95% of the total nitrogen consumption by plants, and ammonium nitrogen accounts for the rest. Therefore, an increase in the ratio between ammonium and nitrate nitrogen in favour of the former in aquaponics water indicates insufficient nitrogen consumption by plants in general, resulting in the accumulation of the ammonium form of nitrogen.

According to the results of studies of changes in the content of mineral nitrogen compounds in the water of the studied aquaponics system lines (Fig. 1), it is evident that at the beginning of the experiment, the total content of mineral nitrogen compounds in both lines was 9.22 mg/dm^3, with ammonium nitrogen accounting for 2.39% and nitrate nitrogen accounted for 97.6%. At the end of the experiment (58 days after the start of the experiment), the content of nitrogen in mineral compounds in the control line increased to 16.9 mg/dm^3 (+7.71%), with the proportion of ammonium nitrogen increasing to 5.49% (+3.11%) and the proportion of nitrate decreasing accordingly. This indicates insufficient assimilation capacity of leaf lettuce plants per 1 m^2 and the need to increase the area of lettuce plantings relative to the total fish biomass (1995 g) by approximately 17%. Overall, during the study period, the specific nitrogen concentration in water per 1 kg of live fish biomass changed from 0.165 mg/(dm^3·kg)to 0.466 mg/(dm^3·kg), or +182% of the initial value. In the experimental line, during the study period, the increase in the specific nitrogen concentration in water per 1 kg of live fish biomass changed from 0.165 mg/(dm^3·kg) to 0.443 mg/(dm^3·kg), or +168% compared to the initial value. This indicates nitrogen accumulation in both lines and an insufficient area of leaf lettuce plantings. These indicators also indicate improved nitrogen assimilation of mineral compounds by plants of the experimental line by 14% under the influence of potassium sulphate at a concentration of 0.50 g/dm^3.

Considering the yield of green mass of leaf lettuce at 2043 g/m^2 in the control line and 3498 g/m^2 in the experimental line, respectively, it is possible to conclude that under the influence of potassium sulphate at a concentration of 0.50 g/dm^3, the lettuce yield increased by 71.2% with a 134% increase in fish biomass relative to the control line. Thus, the overall productivity of the aquaponics system increased in both the aquaculture module and the hydroponics module. The relative excess of the aquaculture module's productivity growth over the hydroponics module by 62.8% indicates the high potential for overall productivity growth of the aquaponics agroecosystem under the influence of potassium sulphate, which in this experiment was not fully realised, primarily due to insufficient planting area and insufficiently high water temperature, which did not contribute to the active life of nitrifying bacteria and increase the availability of total nitrogen for plants, which would have made it possible to increase the level of water purification from nitrogen compounds even with the available plant area of 1 m^2.

The phosphate content in the aquaponics system of both lines at the beginning of the experiment was 1.04 mg/dm^3. At the end of the experiment, the phosphate content in the control line increased to 13.1 mg/dm^3 (+1160% compared to the initial value), while in the experimental line, this indicator increased to 15.6 mg/dm^3 (+1400%). Such a catastrophic increase in phosphate content is the result of fish life and the high-water solubility of fish excrement in slightly alkaline water. According to J. Breinballe (2010), the technological standard for phosphorus content in water is less than 20 mg/dm^3, which is less than 61 mg/dm3 when converted to phosphates. Considering the average specific waste generation rates per 100 kg of feed consumed, which average 4.5-5 kg of nitrogen and 1.3-1.5 kg of phosphorus

(Babarchuk & Babich, 2022) under conditions of uniform consumption of both nutrients by plants, a maximum phosphate concentration of 9-10 mg/dm^3 in the experimental line and 5.5-6 mg/dm^3 in the control line would be expected. Therefore, it is possible to conclude that leaf lettuce does not cope with the task of uniform water purification in aquaponics systems and is not an ideal crop for this system. In the future, it will be necessary to seek additional ways to improve biological water purification in aquaponics systems, apart from the cultivation of leaf lettuce.

The most interesting indicator is the potassium content in the water of the control and experimental lines, since this study was designed to increase the intake of potassium as a macronutrient for plants. According to the hypothesis, the additional intake of potassium in the form of potassium sulphate (0.50 g/dm^3) should have balanced the composition of the water in terms of the content of nutrients for leaf lettuce and increased the total nitrogen removal from the water, which would increase the level of water purification for fish and increase the lettuce yield (since the waste products of catfish, similarly to all other fish, have a low potassium concentration). According to research by T. Kleiber *et al.* (2013), the dry weight of leaf lettuce leaves contains 3.64-5.15% nitrogen, 8.13-9.11% potassium and 0.57-1.31% phosphorus. Therefore, when forming the yield of leaf lettuce per unit of nitrogen removed by the lettuce harvest, plants remove 1.8-2.2 units of potassium and 0.16-0.25 units of phosphorus.

Potassium, as a macronutrient, maintains the correct balance of ions in fish organisms and is involved in many metabolic processes. Its deficiency can cause slower growth and development of fish. Potassium is an important element for many physiological processes, including the regulation of metabolism, which can contribute to the faster growth of fish. Higher levels of potassium also improve cell membrane function and enzymatic activity, which has a positive effect on growth rates.

Analysis of potassium content in the control line water (without potassium sulphate addition) at the end of the experiment showed that the potassium content was 8.89 mg/dm^3, while in the experimental line (with potassium sulphate added), the potassium content was 55.2 mg/dm^3 (+46.3 mg/dm^3 or +521% compared to the control). Comparing the relative increase in potassium content to the control (+521%), the relative increase in nitrogen content of mineral compounds to the control (+26%), and the relative increase in sulphate ions to the control (+567%) in the water of the experimental line at the end of the study period, it is possible to conclude that the area of leaf lettuce (1 m^2 per total fish biomass of 2.88 kg/m^2) is insufficient to ensure a high degree of water purification from nitrogen compounds. In the control line water, the potassium to nitrogen ratio is 0.53, in the experimental line water it is 2.59, while in lettuce plants it is within the range of 1.8-2.2. Thus, there is a large potassium deficiency in the control line, and it is this deficiency that is the main limiting factor for yield, which explains the low level of lettuce leaf yield in the control (2.43 kg/m^2). There is no potassium deficiency in the experimental line, and the maximum yield potential of leaf lettuce is only % realised. The increase in lettuce yield in the experimental line did not reach its potential level. The water in the experimental line contains 26% more nitrogen in mineral compounds, combined with high concentrations of potassium and phosphorus, which do not limit yield. Despite the optimal ratio of nitrate and ammonium nitrogen for the plant, leaf lettuce does not consume the available nitrate form of nitrogen. There is only one explanation for this: at pH >7.5 (as in the experimental line), the assimilation of nitrogen compounds by plants drops sharply. At pH > 7.5, the activity of nitrifying microorganisms gradually decreases, and after the threshold level of pH = 8.6, it drops sharply, which significantly complicates the processes of water purification and nitrogen consumption by plants.

Given the experimental data analysed above and revisiting the cause of the imbalance between the sulphate ion to potassium ion ratio in the experimental line water at 4.54 and the control line water at 4.88 in favour of sulphate ion (+7.43% to the control), it is possible to unequivocally explain this increase in the ratios in both lines by the uneven removal of potassium and sulphur by lettuce plants in favour of potassium and the gradual accumulation of sulphates caused by the decomposition of fish waste products. Considering that the increase in sulphate content in the water of the experimental line during the experiment was +258 mg/dm^3, while in the control line the corresponding increase was only +28.8 mg/dm^3 (where no potassium sulphate was added), it is possible to conclude that that the addition of potassium sulphate causes a significant increase in the sulphate content in water. However, the total concentration of sulphates increased in both lines, indicating a significant accumulation of sulphates due to the biochemical transformation of fish waste products. At the same time, there are no technological standards for the sulphate content in the water of aquaponics systems. Taking into account the fact that when potassium sulphate was added to a concentration of 0.50 g/dm^3 in the water of the experimental line, assuming the same formation of waste products as in the experimental line (since the same amount of feed was fed in both lines), the predicted increase in sulphate content was expected to be +316 mg/dm^3 compared to the actual (+25 8 mg/dm^3), which is 22.5% higher than the actual value, it can be concluded that due to the intake of potassium in the form of potassium sulphate, sulphates are consumed more intensively. However, excessive accumulation of sulphates can be dangerous for fish. Therefore, it is necessary to conclude that it is advisable to add potassium sulphate and to establish the maximum permissible concentration of this salt that is not harmful to fish. In addition, potassium chloride should be considered as an additional source of potassium in aquaponics systems. However, this issue also requires further research, as chlorides in excessive concentrations can harm plants and fish.

A. Bittsanszky *et al.* (2016) determined that the source of potassium had a significant effect on the growth rate of lettuce, photosynthetic activity and the efficiency of macronutrient uptake in closed aquaponic systems. In particular, the addition of potassium sulphate (K_2SO_4) improved the absorption of calcium, magnesium and nitrates, and increased the overall yield of green crops due to a better ionic balance in the root nutrition zone. As noted by Q. Du *et al.* (2019), potassium stimulates chlorophyll synthesis and accelerates photosynthesis in plants, which can increase crop productivity in aquaponic systems. In particular, optimal concentrations of potassium improve the growth of leafy crops such as lettuce and spinach and can also improve plant resistance to pests and diseases. However, excessive concentrations of potassium in water can cause salinity, excessive levels of which can be toxic primarily to plants, but also to fish, which can lead to poor fish development. Other studies, such as the work of V. Kumar & P. Singh (2023), also highlight the importance of potassium in regulating the immune system of fish and their overall health in aquaponics systems, which affects the overall productivity of these ecosystems.

Thus, the research demonstrated that the use of potassium salts, in particular potassium sulphate, in aquaponics systems was a reasonable agrotechnological technique for increasing plant yields, improving fish growth and stabilising the quality of the water environment. The greatest effect was observed when potassium nutrition was combined with adequate temperature conditions and effective biofiltration. The use of such approaches helps to create optimal conditions for the development of both plants and fish, which increases the overall efficiency of the aquaponic system. In addition, this approach minimises the use of chemical fertilisers, which reduces the negative impact on the environment. As a result, potassium nutrition is becoming an important tool in achieving sustainable and efficient production in aquaponics systems. These results indicate the feasibility of integrating potassium salts into aquaponics processes to achieve high productivity and environmental sustainability.

Conclusions

Under optimal conditions of water temperature in the aquaponics system and light intensity in the hydroponics module at 2500 Lx/m^2 during 57 days of the experiment, the biomass increase of 19 individuals of Clarie catfish in the control line of the system was +1195 g, in the experimental line, under the influence of potassium sulphate addition until its concentration in water reached 500 mg/l, the total biomass increase of Clarie catfish during the experiment was +2886 g (+44.6% compared to the control), which indicates the high efficiency of potassium sulphate addition to the system water in stimulating the development of Clarie catfish.

The high stimulating effect of adding potassium sulphate (500 mg/dm^3) to the water of the aquaponics system on the feed conversion efficiency of Clarian catfish was confirmed, which is estimated at 57.0% lower feed conversion ratio compared to the control (without potassium sulphate addition) and 91.5% higher growth rate of Clarie catfish relative to the control. The addition of potassium sulphate (500 mg/dm^3) to the aquaponics system water increased the productivity of the hydroponics module with a planting area of 1 m^2, also ensuring an increase in the green mass of leaf lettuce to 3498 g/m^2 in the experimental line compared to the control line (2043 g/m^2) or +71.2% compared to the control. The potential yield of leaf lettuce (4000 g/m^2) was realised in the control line by 51.1% and in the experimental line by 87.5%. Analysis of water quality in terms of pH, nitrogen content of mineral compounds, phosphates, sulphates and potassium showed that the main limiting factor for lettuce yield and fish productivity was a potassium deficiency in the system at a level of 21.61-28.3 mg/l, while in the experimental line of the system, the main limiting factor was an increase in pH to 8.3, which prevented the assimilation of nitrogen compounds by lettuce plants, The reason for this was the insufficiently high average water temperature (19.5°C compared to the optimum temperature for microorganisms of the nitrification cycle of 25°C), which slowed down the processes of nitrification and assimilation of nitrogen compounds by plants.

Overall, the water quality in the control line of the aquaponics system during the 57-day experiment was within the technological standards but deteriorated due to an increase in ammonium nitrogen content by 323%, nitrate nitrogen by 77.8%, sulphates by 248%, phosphates by 1160%, at a pH level of 7.7. The water quality in the experimental aquaponics system (with the addition of 500 mg/dm^3 of potassium sulphate) during the same period of the experiment deteriorated due to an increase in ammonium nitrogen content by 482%, nitrate nitrogen by 122%, sulphates by 2223%, and phosphates by 1400% at a pH level of 8.3. The main factors contributing to the deterioration of water quality in the experimental line compared to the control line were an increase in pH to 8.3 units This was due to insufficient planting area for leaf lettuce (1 m^2 per 2886 g of total biomass of 19 individuals of Clarian catfish) and insufficiently high-water temperature (19.5°C compared to the optimal 25°C).

Further research could optimise the area of lettuce plants, modelling nitrogen conversion processes with changing water temperatures, optimising potassium sulphate doses and finding additional ways to purify water from water-soluble phosphates to ensure maximum development of Clarius catfish and maximum yields of lettuce. The impact of increased potassium concentrations on long-term effects on fish health, as well as the optimal aquaponics conditions for achieving high productivity at different planting density levels, should be addressed.

Acknowledgements

The authors express their sincere gratitude to the individuals who contributed to the establishment of the Laboratory of Circular Water

Agroecosystems at the National University of Water and Environmental Engineering, which became the basis for the research presented in this article. Special thanks are extended to Professor Harsha Ratnavira, Associate Professor Zakhar Maletskyi, Senior Lecturer Alla Kucherova, Associate Professor Serhii Konontsev, and Rector of NUWEE Viktor Moshynskyi. The authors also acknowledge all participants of the TENOR project and NUWEE staff who supported the creation of the "Circular Water Agroecosystems" Laboratory.

Funding

This research was made possible through the support of the TENOR project (Towards the circular EcoNomy in Organic faRming). The authors are grateful to the managers, experts, and organisations involved in funding the project, which enabled the establishment of the educational and research laboratory at NUWEE.

Conflict of Interest

None.

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Ефективність застосування сульфату калію для вирощування *Clarias gariepinus* в системі аквапоніки

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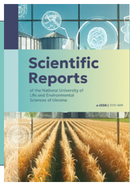
Анотація. Метою дослідження було визначення впливу додавання сульфату калію (K_2SO_4) у концентрації 500 мг/дм³ на якість водного середовища, ріст сома кларієвого (*Clarias gariepinus*) та врожайність листового салату в умовах аквапонічної системи. Дослід проводили у двох паралельних лініях: контрольній (без K_2SO_4) та експериментальній (з додаванням K_2SO_4). Початкова загальна маса 19 особин риб у кожній лінії становила 1330 г. За 57 діб маса в контрольній лінії зросла до 1995 г, а в дослідній – до 2888 г. Конверсія корму склала 2,5 у контролі та 1,1 у досліді. Питома швидкість росту (SGR) була на рівні 0,82 %/день у контролі та 1,74 %/день у дослідній групі. Потенціал врожайності салату (4000 г/м²) реалізовано на 51,1 % у контролі та на 87,5 % у досліді. У контрольній лінії головним лімітуючим фактором був дефіцит калію (21,6-28,3 мг/л), а в дослідній – зростання pH до 8,3 через недостатнє засвоєння азоту при температурі 19,5 °C (нижче оптимуму для нітрифікації). В обох лініях зафіксовано істотне зростання вмісту мінеральних сполук (NO_3^-, NH_4^+, SO_4^{2-}, PO_4^{3-}), однак водні параметри залишалися в межах прийнятних для технологій аквапоніки. Отримані результати свідчать про позитивний ефект від додавання K_2SO_4 у заданій концентрації, що забезпечує зростання продуктивності риб і рослин, хоча потребує врахування співвідношення площі зелених культур до біомаси риби та температурного режиму води. Додавання K_2SO_4 сприяло підвищенню біологічної ефективності аквапонічної системи за одночасного збереження прийнятної якості води

Ключові слова: салат листовий; приріст біомаси; конверсія корму; якість води; азот нітратний; продуктивність модуля гідропоніки

Received 13.12.2024 Revised 11.03.2025 Accepted 25.04.2025

Vol. 21, No. 2
2025



Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 633.11:632.4

DOI: 10.31548/dopovidi/2.2025.91

The degree of dominance of resistance trait against pathogens in F_1 winter wheat

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Abstract. One of the most effective and at the same time environmentally friendly measures of integrated protection of wheat against diseases is the development of resistant varieties through breeding adapted to specific agroclimatic conditions. The purpose of the present study was the phytopathological evaluation of winter wheat collection samples on artificial infection backgrounds

Suggested Citation:
Murashko, L., Kyrylenko, V., Gumeniuk, O., Suddenko, Yu., & Novytska, N. (2025). The degree of dominance of resistance trait against pathogens in F_1 winter wheat. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 21(2), 91-105. doi: 10.31548/dopovidi/2.2025.91.

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in the field and to determine the dominance of resistance of F_1 hybrids to *Puccinia recondita* and *Tilletia caries*. The study was conducted during 2023, 2024 in a selection crop rotation on natural and artificial infection backgrounds and in the laboratory of the winter wheat breeding laboratory of the V.M. Remeslo Myronivka Institute of Wheat of the National Academy of Agrarian Sciences of Ukraine according to generally accepted methods. 189 collection numbers of winter wheat were studied against artificial infectious backgrounds of brown rust and stinking smut. The study found that the varieties protected by resistance genes Arthur 71 (*Lr9*), McNair 2203 (*Lr9*), Agrus (*Lr19*), Century (*Lr24* + *Lr42*), TAM-200 (*Lr24* + *Lr43*), V1275 (*Lr19*), VR89Bo22 (*Lr19*) were immune to the pathogen *Puccinia recondita;* immunity to *Tilletia caries* was reflected by winter wheat varieties Rada (SVK), Famulus (DEU), SHARK/F4. 105W21 (USA), Reia (UKR), Ekspromt, Erythrospermum 24210, and Line 46 (UKR). When studying the composition of the population of *Puccinia recondita*, it was found that the average efficiency was shown by genes *Lr10*, *Lr13*, *Lr25*, and *Lr34* (gene of age resistance) at the 5-10% degree of damage to the lines. The genes *Lr9* and *Lr19* stably maintained strong resistance and continued to be highly effective. In terms of resistance to *Puccinia recondita*, superdominance (heterosis) was found in five (14.72% of the total number of hybrid combinations) hybrid combinations Beres/Blueboy II, Beres/TAM-200, Matuo/TAM-200, Tobarzo/TAM-200, Matuo/Blueboy II. It was noted that the local population of the pathogen *Tilletia caries* is avirulent or slightly virulent to resistance genes: Bt6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21. The study of the genetics of resistance to this disease showed that among F_1 hybrid combinations, 41.63% showed partial positive dominance (PPD). No overdominance to the pathogen of stinking smut was found

Keywords: brown rust; resistance gene; variety; line; stinking smut of wheat; background

Introduction

Development of high-yielding varieties of soft winter wheat *Triticum aestivum* L. is a major task of modern breeding. These varieties should be capable of demonstrating maximum grain yields, effectively utilising their genetic potential in various agroecological conditions. At the same time, minimising the gap between biological (potential) and economic (actual) productivity caused by adverse biotic factors continues to be a vital task. Fungal diseases are a substantial source of crop losses, which can reach 15-50% depending on the virulence of the pathogen and specific weather conditions. These diseases have a particularly strong impact on wheat varieties susceptible to them, causing severe damage to producers (Topko *et al*., 2021; Kayim *et al.,* 2022). M. Lunzer *et al*. (2023) noted that among the common and harmful diseases of wheat, the most significant are powdery mildew (*Erysiphe graminis* DC. f. sp. *tritici* Em. Marchal), stinking smut (*Tilletia caries* Tul.), brown rust (*Puccinia recondita* Rob. et Desm f. sp. *tritici* Eriks.), and leaf septoriosis (*Septoria tritici* Rob.et.Desm.). L.A. Murashko *et al.* (2022) noted that in certain epiphytotic years in Ukraine, crop damage led to a decrease in yield by 25-30% or more.

A.G. Bashlay & V.A. Vlasenko (2020) noted that *Tilletia caries*, which causes the emergence of a black mass instead of grain, reduces seed germination and crop density due to the death of affected plants, is most evident in late winter crops and early spring wheat crops. E. Ritzer *et al.* (2021) identified several specialised forms of smut that affect only some wheat species: *Tilletia vulgaris* – affects *Triticum aesticum* (*vulgare*), weakly – *Triticum compactum* and very weakly – *Triticum durum, Triticum dicoccum, Triticum monococcum,* and *Triticum timopheevi; Tilletia dicaccus* – affects *Triticum diccocum, Triticum aesticum*. The pathogen *Puccinia recondita* is an obligate parasite capable of forming infectious urediniospores, provided that the affected leaf tissues stay viable. T. Krępski *et al.* (2024) found that uredinospores are dispersed by air currents, infecting host plants even at considerable distances, which can reach hundreds of kilometres from the initial focus.

O.E. Markovska *et al.* (2021) found that brown leaf rust, caused by the fungus *Puccinia recondita* f. sp. tritici Rob. ex Desm, is the most widespread rust disease affecting wheat. Under Ukrainian conditions, the pathogen develops according to a shortened vegetation cycle with the involvement of plants of the genus *Thalictrum* spp. as an intermediate host. N.I. Sauliak *et al.* (2024) proved that this disease most intensively affects the leaves of winter wheat, and less often its leaf sheaths and stems. A. Palamarchuk *et al.* (2018) noted that the pathogen overwinters as a mycelium, whose spores can effectively withstand low temperatures during the winter period.

The study of the heritability of wheat resistance to certain diseases is a key task of breeding. M.O. Samoilik (2024) found that breeding experts annually review and update the list of genotypes used as basic material for further selection. The data on the resistance of these genotypes to various diseases has a dual significance: it not only contributes to solving current practical problems in the field of breeding but also serves as a key tool for predicting its effectiveness in the longer term. It is the systematic analysis and use of such data that ensures the development of varieties that can meet the growing demands of agronomy and successfully adapt to new environmental challenges.

According to H. Lisova *et al.* (2023), data on the donor properties of individual varieties that are used once, repeatedly, or permanently as parental forms are particularly valuable. This information, as well as information on the structural composition of existing hybrid populations in terms of their resistance or susceptibility to various diseases, including *Puccinia recondita* and *Tilletia caries*, can substantially contribute to the efficiency of breeding resistant winter durum wheat varieties.

The purpose of the present study was to conduct phytopathological evaluation of winter soft wheat collection samples under artificial infection load caused by pathogens in the field environment. Furthermore, the task was to determine the level of dominance of resistance to *Puccinia recondita* and *Tilletia caries* in first-generation hybrids under artificial infection with pathogens.

Materials and Methods

Experimental studies were conducted during 2023-2024 in breeding crop rotations on a natural background, artificial infection environment, and in laboratory conditions. The study was conducted at the Winter Wheat Breeding Laboratory of the V.M. Remeslo Myronivka Institute of Wheat of the National Academy of Agrarian Sciences of Ukraine (MIW). To achieve maximum efficiency in fulfilling productivity objectives and optimising the selection and accounting processes, a sparse sowing method was used. Specifically, the intervals between plants in a row were 5 cm, the inter-row distance was 30 cm, and the length of each row was 1 metre. The object of research included collection samples of winter bread wheat obtained from the National Centre of Plant Genetic Resources of Ukraine and other breeding centres. In the collection nurseries, 189 collection accessions of winter soft wheat were studied using artificial infectious backgrounds of *Puccinia recondita* and *Tilletia caries*. The artificial infection background of the brown rust pathogen was used to study 78 collection samples. The composition of the *Puccinia recondita* population was studied on a series of isogenic lines of spring wheat variety Thatcher. In the collection nursery of resistant forms to *Tilletia caries*, 111 cultivar samples were studied.

In August and November 2023, the average monthly air temperatures exceeded the long-term average by 1.2° Cand 1.7°C, respectively, while in September and October they were lower by 1.6°C and 0.5°C, respectively, which contributed to the development of stinking smut. Excessive precipitation during this period (84.4 mm in August and 117.5 mm in September) led to waterlogging of the topsoil. In 2022, winter wheat plants stopped growing on 15 November at an average daily air temperature of +4.0°C, which gradually decreased to 3.8°C (16.11); 1°C (17.11); -0.6°C (18.11). In November, there was 80.9 mm of precipitation, which was 40.8 mm greater than the long-term average. The resumption of winter crops vegetation in 2024 was noted on 21 March at an average daily air temperature of +9.0°C with a subsequent gradual increase. In the spring-summer wheat growing season, the average monthly temperatures were 0.5-0.2°C below the long-term average, with only 0.4°C higher in June.

In April, an excessive moisture supply was observed, the excess of precipitation from the norm was 40.0 mm, which contributed to the growth of brown rust, and then during the period from May to June a rather acute shortage of precipitation was observed, especially in May – only 21.0 mm (the long-term average was 51.4 mm). The spring (April-June) period favoured the development of the brown rust pathogen. Accordingly, the level of hydrothermal coefficient (HTC) was low: April – 0.89, May – 0.46, June – 0.67. Winter wheat was infected with the pathogen *Puccinia recondita* in the booting phase of the plant according to the method (Babayants & Babayants, 2014). To create an artificial infection background, the local population of the pathogen was used, and the Myronivska 10 cultivar was used as an infection accumulator.

The artificial infection background of *Tilletia caries* was created according to the method of seed inoculation a few days before sowing. The Polka cultivar (HUN) was used as a susceptible variety, and sowing was conducted in the beginning of the first decade of October (Demidov *et al.*, 2023). The resistance of winter wheat plants to pathogens was assessed according to generally accepted methods (Tribel *et al.*, 2010; Demidov *et al.*, 2023). The degree of phenotypic dominance in hybrid combinations for this quantitative trait was calculated according to the following formula (Griffing, 1950):

$$h_p = (F_1 - MP)/(BP - MP), \quad (1)$$

where h_p is the degree of dominance, F_1 is the average value of the indicator for first generation hybrids, *MP* is the average value of the indicator for both parental forms, *BP* is the average value of the parental form with a more pronounced development of the trait. The value of the degree of dominance (h_p) can range from -∞ to +∞ (Tribel *et al.*, 2010). For ease of analysis, the data were classified according to the scale (Beil & Atkins, 1963):

- positive overdominance (heterosis) (PD) ($h_p > +1$),
- partial positive dominance (PPD) ($+0.5 < h_p \leqslant +1$),
- intermediate inheritЦance (II) ($-0.5 \leqslant h_p \leqslant +0.5$),
- partial negative inheritance (PNI) ($-1 \leqslant h_p < -0.5$),
- negative dominance (depression) (ND) ($h_p < -1$).

The study was conducted following the Convention on Biological Diversity (1992). The study included an analysis of the presence of effective resistance genes and their role in the formation of plant immunity. Genetic control of resistance was determined using a series of crosses and assessment of phenotypic dominance of the trait.

Results

The average development of *Puccinia recondita* over two years was 15.9%, and the development of the pathogen ranged within 0-80%. The varieties protected by the known resistance genes Arthur 71 (*Lr9*), McNair 2203 (*Lr9*), Agrus (*Lr19*) Century (*Lr24 + Lr42*), TAM-200 (*Lr24 + Lr43*), V1275 (*Lr19*) (USA), VR89Bo22 (*Lr19*) (FRA) were immune to brown rust (Table 1). High resistance (2-5%) against brown rust was found in 24 (30.8%) samples: Osage (2%), Agrus (3%), Blueboy II (5%) (USA), Bu 22 (CZE), and others.

The genes *Lr10, Lr13, Lr25,* and *Lr34* (age resistance gene) showed average efficiency – the degree of damage to the lines was 5-10%. The genes *Lr9 and Lr19* stayed sTable and highly effective (Table 2). The resistance genes found in winter wheat varieties showed high efficiency: Rendezvous *(Lr37*) (ANG), Century (*Lr42*), TAM-200 (*Lr43*), Arthur-71, McNair 2203, Flex (USA), VR89Bo 22 (CZE), and others.

Table 1. *Donors of resistance against Puccinia recondita with known resistance genes*

Sample	Origin	Resistance genes	Damage intensity, %
Myronivska 10 (vulnerable cultivar)	UKR	-	80
Arthur 71	USA	*Lr9*	0
McNair 2203	USA	*Lr9*	0
Agrus	USA	*Lr19*	3
Flex	USA	*Lr19*	0
V1275	USA	*Lr19*	0.5
Osage	USA	*Lr24*	2
Blueboy II	USA	*Lr10, Lr24*	5
VR89Bo22	FRA	*Lr19*	0
Rendezvous	ANG	*Lr37*	0
Bu 22	CZE	*Lr3, Lr26*	5
203-238	BOL	*Lr9, Lr26*	0
Century	USA	*Lr42+Lr24*	0
TAM-200	USA	*Lr43+Lr24*	0

Source: developed by the authors of this study

Table 2. *Intensity of Puccinia recondita Lr infection in spring wheat Thatcher series lines*

Line series resistance gene	Type of seedling immunity in laboratory conditions, %	Degree of damage in the field phase of milk ripeness, %
Lr1	0.5	8.5
Lr2a	0	45.1
Lr2c	0	50.7
Lr3	0	51.2
Lr3bg	1	15.4
Lr3ka	0.5	25.1
Lr9	1	45.7
Lr10	1	40.6
Lr11	0.5	50.5
Lr12	0.5	0
Lr13	1	52.1
Lr14	0.5	50.9
Lr14a	0.5	62.1
Lr14b	0	60.3
Lr19	0	46.1
Lr23	0.5	63.4
Lr24	0	53.7
Lr25	1	8.1
Lr26	0	60.5
Lr29	0.5	63.8
Lr30	0	46.1
Lr32	1	45.3
Lr34	0	40.7
LrEch	0	8.2

Source: developed by the authors of this study

The following genes were found to be ineffective*:* *Lr1*, *Lr2a*, *Lr2c*, *Lr3*, *Lr3bg*, *Lr3ka*, *Lr11*, *Lr12*, *Lr14*, *Lr14a*, *Lr14b*, *Lr23*, *Lr26*, *Lr29*, *Lr30*, *Lr32*, *LrEch*. The degree of damage to Thatcher lines with the above genes in the years of study was 15-60%. To investigate the genetic control of resistance traits against *Puccinia recondita* and *Tilletia caries* in winter wheat varieties, a series of crosses was conducted in 2023. To determine the genetics of the resistance trait in a series of sources of resistance to *Puccinia recondita* (Beres, Matyo, Tobarzo, Polka), a series of crosses were conducted: donors with the vulnerable cultivar Myronivska 65, donors with each other and test varieties carrying effective resistance genes Arthur 71 (*Lr9*), Flex (*Lr19*), Blueboy II (*Lr10, Lr24*), Century (*Lr24+Lr42*), TAM 200 (*Lr24+Lr43*) (USA), Rendezvous (*Lr* 37) (ANG) (Table 3).

Table 3. *The degree of phenotypic dominance of resistance trait against Puccinia recondita in F_1, 2024*

Cross	Intensity of plant damage, %			Degree of phenotypic dominance (h_p)/type of dominance
	♀	F_1	♂	
Beres / MYR 65	0	1.0	40.0	0.95 / PPD
Matuo / MYR 65	0	10.0	35.0	0.4 / II
Tobarzo / MYR 65	0	8.0	30.0	0.5 / PPD
Polka / MYR 65	1.0	30.0	40.0	-0.48 / II
Beres / Matuo	0	0.5	0.5	-1.3 / D
Beres / Tobarzo	0	1.0	0	0.15 / II
Beres / Polka	0	2.0	0	0.35 / II
Beres / Arthur-71	0	1.0	0	0.45 / II
Beres / Fleks	0	0.5	0	-0.88 / PNI
Beres / Blueboy II	0	0	5.0	1.52 / PO
Beres / Rendezvous	0	0	0	0.67 / PPD
Beres / Century	0	1.0	0	0.58 / II
Beres / TAM-200	0	1.0	0.2	1.65 / PO
Matuo / Tobarzo	0	0	0	0.27 / II
Matuo / Polka	0	0.1	0	-0.20 / II
Matuo / Arthur-71	0	0	0	-0.54 / II
Matuo / Fleks	0	0	0	-0.93 / PNI
Matuo / Blueboy II	0	0	5.0	1.38 / PO
Matuo / Rendezvous	0	5.0	0	0.57 / PPD
Matuo / Century	0	1.0	0	-3.01 / D
Matuo / TAM-200	0	0	0.1	1.82 / PD
Tobarzo / Polka	0	0	0	-0.71 / PNI
Tobarzo / Arthur-71	0	1.0	0	0.38 / II
Tobarzo / Fleks	0	0.1	0	0.32 / II
Tobarzo / Blueboy II	0	0.5	1	0.63 / PPD
Tobarzo / Rendezvous	0	0	0	0.57 / PPD
Tobarzo / Century	0	0	0.1	1.0 / PPD
Tobarzo / TAM-200	0	0	0.1	5.01 / PO
Polka / Arthur-7	0.5	1.0	0	-3.12 / D
Polka / Fleks	0.5	0.5	0	-1.08/ D
Polka / Blueboy II	0.5	1.0	0	0.9 / PPD
Polka / Rendezvous	0	0	0	0.73 / PPD
Polka / Century	0.5	1.5	0	- 5.1 / D
Polka / TAM-200	0.5	1.5	0.1	- 4.0 / D

Note: PO – positive overdominance, PPD – partial positive dominance, II – intermediate inheritance, PNI – partial negative inheritance, D – depression (negative dominance), MYR – Myronivska

Source: developed by the authors of this study

In terms of resistance to *Puccinia recondita*, dominance (heterosis) was established in five (14.72%) hybrid combinations – Beres/Blueboy II, Beres/TAM-200, Matuo/TAM-200, Tobarzo/TAM-200, Matuo/Blueboy II (Table 3). Partial positive dominance was observed in nine (26.47%) hybrids, intermediate inheritance – in 11 (32.35%), partial negative inheritance – in 8.82%, and depression was observed in six (17.64%) hybrid combinations. Beres, Tobarzo, and Matuo varieties, which were involved in the crossing as a mother form, better transmitted the trait of resistance against *Puccinia recondita* pathogen.

The damage to plants by *Tilletia caries* over two years ranged within 0-70%, and the average development was 35.6%. High resistance to this pathogen was demonstrated by the accessions protected by effective resistance genes: Sel.M 65-3157 (*Bt9*), Sel.M. 66-23 (*Bt10, 11*) (USA), Lutescens 6028 (*Bt12, 13*), Erythrospermum 5221 (*Bt14*) (UKR, MIW), Ferrugineum 220/85 (*Bt15, 16*), Erythrospermum 4318/88 (*Bt17*), Erythrospermum 60-89 (*Bt18, 19*), Ferrugineum 124-88 (*Bt20, 21*) (UKR, SGI) (Table 4). In the study of collection accessions against *Tilletia caries*, 13 immune (0%), 17 highly resistant (1-5%), 16 resistant (10-15%), 26 slightly susceptible (20-30%), and 39 susceptible (over 40%) winter wheat samples were identified. The average development of the disease caused by *Tilletia caries* in the collection nursery was 67.3%. The varieties Rada (SVK), Famulus (DEU), SHARK/F4.105W21 (USA), Reya (UKR), Ekspromt, and lines Erythrospermum 24210, Line 46 (UKR) showed immunity to *Tilletia caries* (Table 5).

Table 4. *Characteristics of Tilletia caries resistance donors with known resistance genes (average for 2023-2024)*

Cultivar, line	Resistance gene	Origin	Damage intensity, %
			Stinking smut
Polka (vulnerable cultivar)	*St*	HUN	56.3
Turkeu CI 1558-B	*Bt4*	USA	5.2
Sel. 34-32	*Bt5*	USA	3.9
RiO Ci 10064	*Bt6*	USA	6.8
P.I. 178210	*Bt8*	USA	5.1
Sel.M. 65-3157	*Bt9*	USA	0
Sel. M. 66-23	*Bt10, 11*	USA	0
Lutescens 6028	*Bt12, 13*	UKR	0
Erythrospermum 5221	*Bt14*	UKR	0
Ferrugineum 220 / 85	*Bt15, 16*	UKR	0
Erythrospermum 4318 / 88	*Bt17*	UKR	0
Erythrospermum 60-89	*Bt18, 19*	UKR	0
Ferrugineum 124-88	*Bt20, 21*	UKR	0

Source: developed by the authors of this study

Table 5. *Intensity of damage to the best samples of winter wheat of the collection nursery by the pathogen Tilletia caries (average for 2023-2024)*

Cultivar, line	Country of origin	Damage intensity, %
Polka (vulnerable cultivar)	HUN	45.9
Rada	SVK	0
Famulus	DEU	0
SHARK/F4105W21	USA	0
Reia	UKR	0
Warwick SRW	CAN	1.6

Table 5. *Continued*

Cultivar, line	Country of origin	Damage intensity, %
Erythrospermum 24210	UKR	0
Line 46	UKR	0
UN 49	TUR	5.6
Mukhran	GEO	5.9
Nyva	UKR	1.8
Ekspromt	UKR	0
Nezabudka	UKR	5.1
Fermerka	UKR	5.4

Source: developed by the authors of this study

When investigating the population of the stinking smut pathogen, the study found that the local population was avirulent or slightly virulent to resistance genes: *Bt6*, *8*, *9*, *10*, *11*, *12*, *13*, *14*, *15*, *16*, *17*, *18*, *19*, *20*, *21*. To determine the genetics of the resistance trait in a series of sources of resistance to *Tilletia caries* (Erythrospermum 24210, Ekspromt, Line 46 (UKR)), a series of crosses of donors with the vulnerable variety Polka (HUN), donors with each other and test varieties carrying effective resistance genes was conducted (Table 6).

Table 6. *Degree of phenotypic dominance of resistance trait against Tilletia caries in* F_1*, 2024*

Combination	Plant damage, %			Degree of phenotypic dominance (h_p) / type of dominance
	♀	F_1	♂	
Erythrospermum 24210 / Polka	0	3.6	41.5	0.82 / PPD
Ekspromt / Polka	0	11.4	31.0	0.26 / II
Line 46 / Polka	0.1	14.0	40.0	0.3 / II
Erythrospermum 24210 / Ekspromt	0	0	0	0.1 / II
Erythrospermum 24210 / Line 46	0	0	1.6	1.0 / PPD
Ekspromt / Line 46	0	1.2	1.6	-0.5 / II
Ekspromt / Sel. M.65-3157	0	0	0	0.12 / II
Ekspromt / Sel. M 66-23	0	0	0	0.25 / II
Ekspromt / Ferrugineum 220/85	0	0	0	0.45 / II
Ekspromt / Erythrospermum 4318 / 88	0	0.5	1.5	0.33 / II
Ekspromt / Erythrospermum 60-89	0	1.4	2.2	-0.27 / PNI
Ekspromt / Ferrugineum 124-88	0	0.8	1.7	0.05 / II
Erythrospermum 24210 / Sel. M.65-3157	0	0	0	0.8 / PPD
Erythrospermum 24210 / Sel. M 66-23	0	0	0	0.71 / PPD
Erythrospermum 24210 / Ferrugineum 220 / 85	0	0	0	0.6 / PPD
Erythrospermum 24210 / Erythrospermum 4318 / 88	0	0	1.5	1.0 / PPD
Erythrospermum 24210 / Erythrospermum 60-89	0	1.4	2.4	-0.16 / PNI
Erythrospermum 24210 / Ferrugineum 124-88	0	0.5	2.1	0.52 / PPD
Line 46 / Sel. M.65-3157	0.1	0	0	1.0 / PPD
Line 46 / Sel. M. 66-23	0.1	0	0	1.0 / PPD
Line 46 / Ferrugineum 220 / 85	0.1	0	0	1.0 / PPD
Line 46 / Erythrospermum 4318 / 88	0.5	1.2	1.5	-0.2 / PNI
Line 46 / Erythrospermum 60-89	0.3	1.2	1.2	-0.04 / PNI
Line 46 / Ferrugineum124-88	0.1	2.3	1.8	-1.42 / D

Note: PPD – partial positive dominance, II – intermediate inheritance, PNI – partial negative inheritance, D – depression (negative dominance)
Source: developed by the authors of this study

The analysis of the results obtained during the evaluation of the degree of phenotypic dominance of resistance to *Tilletia caries* in F_1 of soft winter wheat, created based on diverse parental forms, demonstrated a wide range of inheritance types. Specifically, several characteristic patterns could be identified within this sample: from partial positive dominance and intermediate inheritance to partial negative dominance and negative dominance. Such distribution of inheritance indicated a complex genetic mechanism that regulated resistance to the pathogen, as well as a major influence of both parental genotypes and the environment on the formation of dominant traits in first-generation hybrids. Based on the degree of phenotypic dominance in 2023, the study found that among F_1 hybrid combinations, 41.63% showed partial positive dominance against *Tilletia caries*. Intermediate inheritance of the trait was found in 37.5% of hybrids, partial negative inheritance was found in 16.7% of hybrid combinations, and depression was found in 36.37%.

The highest partial positive dominance was found in hybrid combinations using the resistance donor Sel. M. 65-3157 (*Bt 9*), Sel. M. 66-23 (*Bt10*, *11*): Erythrospermum 24210/Sel. M.65-3157, Erythrospermum 24210/Sel. M 66-23, Line 46/Sel. M.65-3157, Line 46/Sel. M. 66-23. Erythrospermum lines 24210 and Line 46, which were involved in the cross as the mother form, better transmitted the trait of resistance against *Tilletia caries* pathogen. One of the key causes of substantial yield losses, which can range from 15% to 50% depending on the level of pathogen virulence and climatic conditions in a given year, is fungal infection. These pathogens have a considerable impact, specifically, on the yield of wheat varieties, as noted by O.V. Barabolya & S.V. Borovko (2024). The findings of A. Palamarchuk *et al.* (2018), who assessed the extent of the affected areas, indicated that the most common diseases were septoriosis (43.69%) and powdery mildew (44.32%). Diseases such as root rot (29.83%) and brown leaf rust (22.65%) were intermediate in terms of prevalence, while helminthosporium (9.76%) was recorded in only a small number of regions. As for the intensity of these diseases, the average value for powdery mildew was 3.71%, for septoriosis – 3.21%, for root rot – 2.92%, for brown leaf rust – 2.57%, and for helminthosporium the lowest value was recorded – 0.85%.

D. Datta *et al*. (2006; 2007) suggested that leaf rust (*Puccinia triticina* Eriks.) occurs in all regions of wheat (*Triticum aestivum* L.) cultivation in the world. The cultivation of resistant varieties is the most effective, environmentally friendly, and cost-effective method of rust control. It is vital that the genetic base of rust resistance in cultivated varieties is expanded and that lines with more than one effective resistance gene are developed. The genetic material they created with combined resistance *Lr9* + *Lr24* was developed by combining host-pathogen interaction and a molecular marker. D. Pal *et al.* (2024) confirmed that identifying and introducing wheat varieties with diverse resistance is the best way to control all types of rust. The researchers used the *Lr9*, *Lr19*, and *Lr24* markers to authenticate the presence of specific genes in the selection for brown rust resistance. Analogous studies were conducted by A. Hanzalova *et al.* (2022), who for 10 years (1995-2004) studied the virulence of leaf rust in Slovakia on Linex (NIL) with genes *Lr1*, *Lr2a*, *Lr2b*, *Lr2c*, *Lr3a*, *Lr9*, *Lr10*, *Lr11*, *Lr15*, *Lr17*, *Lr19*, *Lr21*, *Lr23*, *Lr24*, *Lr26*, and *Lr28*. Based on the findings of field trials, the highly resistant to leaf rust varieties Arida (*Lr13*, *Lru*), Eva (*Lr3*, *Lru*), and Solara (*Lru*) were developed.

The high efficiency of the identified resistance genes of the *Puccinia recondita* population was evidenced by the findings of studies by many foreign scientists. According to J. Kolmer (2013), foliar rust caused by *Puccinia triticina* is the most common rust of wheat worldwide. The researchers noted that many different races of *P. triticina* are detected annually in the USA, which differ in virulence and leaf rust resistance genes in different wheat lines. Molecular markers have been used to characterise rust populations in the United States and around the world. S. Xu *et al.* (2024)

conducted a comparative study of twenty-three improved spring wheat (*Triticum aestivum* L.) lines from the Ottawa Research and Development Centre (ORDC) and four known varieties. The study covered agronomic performance at eight sites in Eastern Canada (Ottawa CEF-C1, Ottawa CEF-C2, St. Isidore, Harrington, Palmerston, Princeville, Kincardine, Beloeil) and Fusarium head blight (FHB) resistance. The reaction of the lines to six races of leaf rust (LR) was studied under vegetative conditions using the Morocco variety as a control to assess the development of the disease. The findings revealed that most of the tested lines did not show noticeable differences compared to the four control varieties. At the same time, ECSW05 and ECSW48 were distinguished by greater yields, moderate resistance to FHB and resistance to most of the studied LR races. They can serve as a valuable source of LR resistance for further breeding programmes in the region.

T. Bakhshi *et al*. (2024) found that varieties with combinations of race-neutral resistance genes stayed resistant for many years, even though the races of the leaf rust population were constantly changing. O.V. Babayants *et al*. (2006) confirmed the data on resistance genes, indicating that genotypes containing any or all of these four genes *Bt10*, *Bt11*, *Bt12*, and *Btp* can be used as a source of resistance to *Tilletia caries*. A.M. Mourad *et al*. (2022) found that four isolates carrying the *Bt10*, *Bt11*, *Bt12*, and *Btp* genes conferred resistance to Turkish and Nebraska species of stinking smut. Genotypes carrying any or all these four genes can be used as a source of resistance. In the study by Ž. Liatukas & V. Ruzgas (2008), among the tested genotypes with known resistance genes *Bt1-15*, Z, only two resistance genes provided full efficiency in PI 554120 and Jaila 305, which carry Bt8, and in Eryth-5221, which carries *Bt14*. Other single resistance genes considered effective (infection up to 10.0%) were *Bt5*, *9*, *11*, *12*, *13м 15*, *Z*. E.V. Alekseienko & E.I. Kirchuk (2022) found that breeding lines originating from *Lr* gene carriers derived from Western European wheat varieties demonstrated a significant advantage over the standard variety in terms of average brown rust resistance scores. This advantage was observed regardless of the crossing schemes used. A series of crossing combinations were analysed in the study, which resulted in the identification of several promising breeding lines, such as L.17018, L.18016, L.21919 and L.16718. These lines could serve as valuable genetic sources to improve the trait of brown rust resistance in winter wheat.

T.I. Mukha & L.A. Murashko (2019) studied 170 collection accessions of winter wheat originating from different ecological and geographical regions. Among them, 13 samples with a strong level of resistance to the pathogen Fusarium ear blight were identified. Of particular note were two samples that showed immunity to stinking smut. The damage of the studied samples by the pathogen *Fusarium graminearum* ranged from 1.0% to 3.2%, while the comparable control variety Natula had a damage that reached 18.0%. Other winter wheat samples showed genotype-dependent resistance to 2-5 different diseases. The most noteworthy were varieties with resistance to five major diseases, including ear blight, stinking smut, root rot, powdery mildew, and brown rust. This group included the varieties Rhea, Rada, and Warwik SRW. Furthermore, the study identified accessions that showed resistance to four of these diseases, including Famulus, Zlatina 2, Catalus, and TX9801170/Sophisticated. These findings highlighted the significance of breeding to increase the immunity of winter wheat to a wide range of pathogens and improve its adaptive potential. Fermerka, MV-VERBUNKOS, and Dromos were resistant to three diseases.

Overall, the findings obtained suggested a significant variability in the resistance of winter wheat accessions to the main pathogens of brown leaf rust and smut, which was explained by both the presence of effective resistance genes and the specificity of their inheritance in hybrid combinations. The study found that among the tested sources there were both immune and highly resistant samples capable of providing reliable plant protection under conditions of spread of pathogens of different virulence. The data obtained on the phenotypic dominance of the resistance trait in hybrid combinations allowed identifying promising combinations of parental forms for further breeding. Thus, the results of the study created a scientifically sound basis for the development of winter wheat varieties with complex resistance to dangerous fungal diseases and preparation of recommendations for breeding programmes.

Conclusions

The study found that the average development of *Puccinia recondita* in the collection nursery was 15.9%, while the average development of *Tilletia caries* was 35.6%. Twenty-four (30.8%) collection accessions were found to be immune to brown rust, and varieties protected by the known resistance genes Arthur-71 (*Lr9*), McNair 2203 (*Lr9*), Agrus (*Lr19*), Century (*Lr24* + *Lr42*), TAM-200 (*Lr24* + *Lr43*), V1275 (*Lr19*) (USA), VR89Bo22 (*Lr19*) (FRA), immunity to *Tilletia caries* – varieties Rada (SVK), Famulus (DEU), SHARK/F4. 105W21 (USA), Rhea, Ekspromt (UKR) and lines Erythrospermum 24210, Line 46 (UKR). The study found that highly effective genes *Lr9*, *Lr19* retain sTable resistance, and genes contained in winter wheat varieties are also highly effective: Rendezvous (*Lr37*) (ANG), Century (*Lr42*), TAM-200 (*Lr43*), Arthur-71, Mc Nair 2203, Flex (USA), VR89Bo 22 (FRA). High resistance against the pathogen *Tilletia caries* was observed in the cultivars protected by effective resistance genes: Sel. M 65-3157 (*Bt9*), Sel. M. 66-23 (*Bt10*, *11*) (USA), Lutescens 6028 (*Bt 12*, *13*), Erythrospermum 5221 (*Bt14*) (UKR), Ferrugineum 220/85 (*Bt15*, *16*), Erythrospermum 4318/88 (*Bt17*), Erythrospermum 6089 (*Bt18*, *19*), Ferrugineum 124-88 (*Bt20*, *21*) (UKR).

The study proved that in terms of resistance to the pathogen *Puccinia recondita*, superdominance (heterosis) was established in five (14.72%) hybrid combinations: Beres/Blueboy II, Beres/TAM-200, Matuo/TAM-200, Tobarzo/TAM-200, Matuo/Blueboy II. Based on the degree of phenotypic dominance, it was found that among F_1 hybrid combinations, 41.63% showed partial positive dominance: Erythrospermum 24210/Polka, Erythrospermum 24210/Line 46, Erythrospermum 24210/Sel. M.65-3157, etc., against *Tilletia caries*, no overdominance was found. The prospect of further research is to analyse the efficiency of the breeding process of creating winter soft wheat varieties immune to pathogens by using highly resistant source material.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Ступінь домінування ознаки стійкості проти збудників хвороб у F_1 пшениці озимої

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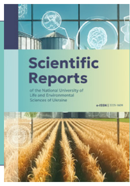
Анотація. Одним із найефективніших і водночас екологічно безпечних заходів інтегрованого захисту пшениці від хвороб є розробка резистентних сортів через селекцію, адаптовану до специфічних агрокліматичних умов. Мета роботи – фітопатологічна оцінка колекційних зразків озимої пшениці на штучних інфекційних фонах у польових умовах та визначення домінування стійкості гібридів F_1 до *Puccinia recondita* і *Tilletia caries*. Дослідження проведені впродовж 2023, 2024 рр. у селекційній сівозміні на природньому, штучному інфекційному фонах та лабораторних умовах лабораторії селекції озимої пшениці Миронівського інституту пшениці імені В. М. Ремесла Національної академії аграрних наук України за загальноприйнятими методиками. На штучних інфекційних фонах бурої іржі та твердої сажки вивчено 189 колекційних номерів пшениці озимої. Встановлено, що імунністю до збудника *Puccinia recondita* володіли сорти, захищені генами стійкості Arthur 71 (*Lr9*), McNair 2203 (*Lr9*), Agrus (*Lr19*) Century (*Lr24+Lr42*), TAM-200 (*Lr24+Lr43*), V1275 (*Lr19*), VR89Bo22 (Lr19), імунність до *Tilletia caries* відобразили сорти пшениці озимої Rada (SVK), Famulus (DEU), SHARK/F4.105W21 (USA), Рея (UKR), Експромт, лінії Еритроспермум 24210 та Лінія 46 (UKR). При вивчення складу популяції *Puccinia recondita* встановлено, що середню ефективність проявили гени: *Lr10*, *Lr13*, *Lr25* та *Lr34* (ген вікової стійкості) за ступеня ураження ліній – 5-10 %. Стабільно зберігали високу стійкість і продовжували залишатися високоефективними гени *Lr9*, *Lr19*. За стійкістю проти збудника Puccinia recondita наддомінування (гетерозис) встановлено у п’яти (14,72 % від загальної кількості гібридних комбінацій) гібридних комбінаціях Beres / Blueboy II, Beres / TAM-200, Matuo / TAM-200, Tobarzo / TAM-200, Matuo / Blueboy II. Зазначено, що місцева популяція збудника *Tilletia caries* авірулентна або слабко вірулентна до генів стійкості: Bt6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21. Дослідження генетики ознаки стійкості до даного захворювання засвідчило, що серед гібридних комбінацій F_1 41,63 % проявили частково позитивне домінування (ЧПД). Наддомінування до збудника твердої сажки не виявлено

Ключові слова: бура іржа; ген стійкості; сорт, лінія; тверда сажка; фон

Received 25.11.2024 Revised 19.02.2025 Accepted 25.04.2025

Vol. 21, No. 2
2025



Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 633.34:631.53.01:581.1/.2

DOI: 10.31548/dopovidi/2.2025.106

Physiological and biochemical aspects of pre-sowing treatment of soybean (*Glycine max* (L.) Merr.) seeds

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Abstract. Soybean is one of the most in-demand crops, with its production increasing; however, climate change affects yield, necessitating the application of biopreparations to enhance plant resilience to stress conditions. This study aimed to investigate the effects of pre-sowing seed treatment with an inoculant and a phytohormonal preparation on the physiological and biochemical parameters of

Suggested Citation:
Chaika, T., Korotkova, I., Shevnikov, M., Liashenko, V., & Horbenko, O. (2025). Physiological and biochemical aspects of pre-sowing treatment of soybean (*Glycine max* (L.) Merr.) seeds. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 21(2), 106-119. doi: 10.31548/dopovidi/2.2025.106.

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soybean plants and their yield under organic farming conditions. A field study conducted in 2022-2024 examined the impact of pre-sowing seed treatment with the inoculant Legume Fix and the phytohormonal preparation Violar on leaf area, proline content, malondialdehyde levels, photosynthetic pigments, and yield under various weather conditions in an organic farming system. It was established that pre-sowing seed treatment increased leaf area by an average of 13.4% with Legume Fix and by 19.3% with Violar. It was established that the highest increase in proline content (as a protective response) was observed in the hot conditions of 2024, with seed treatment using Violar (41.2%) and Legume Fix (26.5%). Over the study period, the lowest MDA concentrations in soybean plants were recorded following seed treatment with Violar and Legume Fix, averaging 7.57 and 9.33 µg/g fresh weight, respectively, which was 37.4% and 22.9% lower than in the control plants. Treatment with Violar resulted in an increase in Chl *a*, Chl *b*, and total Chl (*a* + *b*) content by an average of 18.9%, 13.3%, and 17.2%, respectively, compared to the control, while inoculation with Legume Fix led to increases of 7.4%, 3.4%, and 6.2%, respectively. Pre-sowing seed treatment with Legume Fix and Violar resulted in a higher yield than the control plants, with average increases of 13.2% and 20.6%, respectively. The obtained results may be recommended for organic farming to enhance crop yield

Keywords: leaf area; proline; malondialdehyde; photosynthetic pigments; organic farming; weather conditions

Introduction

The study of the physiological and biochemical aspects of pre-sowing seed treatment is important for understanding the processes that occur in seeds during preparation for sowing, as it allows for the determination of optimal treatment methods to improve their germination energy, resistance to stress conditions, and increase yields. Such treatments can affect the biochemical processes that occur in seed cells, including enzyme activity, protein synthesis, and processes related to the energy supply of germination. Studying the physiological responses of seeds to treatment helps to develop effective technologies that stimulate plant growth and development, and improve their adaptation to adverse conditions such as droughts or low temperatures, which is particularly relevant in the context of climate change. This knowledge also makes it possible to reduce the use of chemical fertilisers and pesticides, which is important for sustainable agriculture and environmental conservation.

According to J. Bosanquet (n.d.), soybean (*Glycine max* (L.) Merr.) is one of the most soughtafter legume crops in the global market, which ranks it sixth among the most widespread crops in terms of production volume and fourth in terms of economic value and production area. This growth is accompanied by a 5% increase in global soybean consumption due to demand in the feed, food, and industrial sectors (IGS: Global soybean production in 2024/25 MY to break record, 2024).

In Ukraine, despite abnormal heat and drought in 2024, soybean production reached a record 6.0 million tonnes, an increase of 15.4% compared to 2023. Soybean production in the EU increased by only 0.3% compared to the previous year due to the negative impact of weather conditions in Central European countries (Ukraine soybean area, yield and production, n.d.). V. Voora *et al.* (2022) stated that in Europe, ongoing climate change and the high demand for genetically unmodified soybeans in domestic markets are contributing to the idea of introducing soybeans into typical organic farming systems. Considering the research of JJ.L. Rotundo *et al.* (2024), the EU market is the largest sales market for domestic soybeans (47% of total exports), so Ukrainian producers seek to adhere to the European Green

Deal, one of the important directions of which is the introduction of organic production.

According to research by M.B. Hrabovskyi *et al.* (n.d.), the profitability of growing organic soybeans in Ukraine is high, and although its yield is lower compared to traditional technology, lower production costs and a higher selling price make such production more profitable. At the same time, the presence of climatic risk, especially the uneven impact of precipitation and high temperatures, requires the introduction of technological innovations to increase its yield. However, it is difficult to obtain high yields and quality soybean seeds, despite the proper soil properties, even in organic farming conditions, due to water scarcity and prevailing high temperatures.

Scientists M.S. Hossain *et al.* (2024) noted that despite its adaptability, soybeans also face challenges from climate variability, including unpredictable precipitation patterns that threaten growth and yield. The degree of effect depends on when the period of high temperatures occurs and how intense the water deficit is. Such changes in weather conditions can cause a decrease in soybean yields of up to 40%. Research by A.C.S. Nakagawa *et al.* (2020) showed that when soybeans are exposed to high temperatures during the seed-filling stage, their yield decreases and the seed composition changes. Studies by L. Ogunkanmi *et al.* (2022) indicated that the most detrimental effect on soybean yield (a decrease of 42-64%) is the combined effect of high temperature and drought compared to their individual effects.

According to M.N. Khan *et al.* (2019), one of the promising directions for managing the process of forming stable agroecosystems of legumes, primarily soybeans, is the use of preparations that allow protecting the physiological state of plants from excessive temperature effects and precipitation deficits. According to research by I. Korotkova *et al.* (2023), the most commonly used technological measures at present are the priming of seeds with various biostimulants, hormonal preparations and osmoprotectants, which have already been tested on crops such as wheat, corn and chickpeas.

While there is plenty of research on the individual benefits of microbial and phytohormonal treatments for soybean seeds, there is less focus on comparing their effectiveness, especially in organic farming. Pre-sowing inoculation with bacterial preparations is a vital part of organic growing. According to S. Brambilla *et al.* (2022), various symbiotic and non-symbiotic rhizobacteria are used as bioinoculants to boost plant growth and development through mechanisms like nitrogen fixation, siderophore production, and phytohormone synthesis.

This study aimed to assess the role of pre-sowing inoculation and phytohormonal seed treatment in organic farming systems in mitigating the effects of extreme temperatures during the growing season by evaluating their impact on the physiological and biochemical parameters of plants and overall yield.

Materials and Methods

The field studies were conducted at the experimental field of Poltava State Agrarian University (Khudoliivka Village, Kremenchuk District, Poltava Region) during 2022-2024. The region is known for its ecological purity due to the nearby forest massifs and Sudebske Lake. The soil of the experimental plots is residual-saline chernozem on loess deposits with a moderate level of nitrogen and phosphorus availability and high potassium. For soil analysis, 5 samples were taken from a depth of 0-20 cm of the experimental plot. A composite soil sample was prepared by mixing the collected samples. The sample was air-dried, crushed, and passed through a 2 mm sieve. The content of nitrogen, phosphorus, potassium, and pH in the soil samples (0-20 cm) was determined using a Palintes SK500 multiparameter photometer: pH_{KCl} – 6.3; humus – 5.2%; total nitrogen – 58.6 mg/kg; phosphorus (P_2O_5) – 78.3 mg/kg; potassium (K_2O) – 138.4 mg/kg. The total area of the land plot was 0.3 ha, and the accounting area was 0.1 ha.

The experiments employed standard agricultural practices for the cultivation zone. Its predecessor was spring barley. Soybean sowing was carried out at optimal times according to the climatic conditions of the year of research to a depth of 5 cm, with a row spacing of 38 cm and a seeding rate of 700 thousand seeds/ha. The technological soil cultivation, taking into account the peculiarities of growing plant crops using organic technology, included autumn ploughing, spring harrowing with a heavy harrow to retain moisture, cultivation with a stubble implement, pre-emergence and post-emergence harrowing with a Striegel mesh harrow (Hatzenbichler, Austria), and two inter-row cultivations to control weeds. To protect crops from pests, trichogramma (100-200 thousand individuals/ha) was manually applied three times at 50 points per hectare: before sowing, one month later, and as needed, depending on the level of crop infestation.

The object of the study was the early-ripening soybean variety Khorol of Ukrainian selection, originator – Soybean Research Institute LLC. The experiment was repeated three times. The placement of variants was randomised. For soybean seed inoculation, the bacterial preparation Legume Fix (Legume Technology Ltd, United Kingdom) and the preparation with a complex of phytohormones Violar (Ukraine) were used. Seeds were inoculated using the dry method 30 minutes before sowing at a rate of 1.25 kg of inoculant per 500 kg of seeds. The biopreparation Violar was used for pre-sowing seed treatment (0.5 L/t) and for spraying during the budding-early flowering stage (10 mL/ha). In the control variant, soybean seeds and plants were treated with an equivalent amount of water. The content of proline and malondialdehyde (MDA) in soybean leaves was determined by the method of M.K. Fatema *et al.* (2017).

Optical density measurements were performed using a ULAB 108 UV spectrophotometer. The leaf area was calculated using the Easy Leaf Area software (Easlon & Bloom, 2023). Knowing the leaf area per plant and multiplying this by the plant density per hectare, the leaf apparatus area of plants per specific area was obtained, expressed in m^2/ha. The research was conducted following the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973).

Material for the determination of photosynthetic pigments was processed fresh immediately after collection. Pigments were extracted with 96% ethanol. Spectrophotometric measurement of the optical density of ethanol extracts for the determination of chlorophyll *a* (Chl *a*) and chlorophyll *b* (Chl *b*) content was carried out without prior separation at the absorption maxima of Chl *a* – 665 nm, Chl *b* – 649 nm using a ULAB 108 UV spectrophotometer (ULAB, China). The calculation of pigment content in the obtained extracts was carried out using the method of A.R. Wellburn (1994) according to formulas (1-2):

$$C_{chl\,a} = [(13.95D_{665} - 6.88D_{649}) \cdot V]/m, \quad (1)$$

$$C_{chl\,b} = [(24.96D_{649} - 7.32D_{665}) \cdot V]/m, \quad (2)$$

where $C_{chl\,a}$, $C_{chl\,b}$ are the concentration of Chl *a* and Chl *b* in mg/g of fresh weight; D_{665} and D_{649} are the optical density of the alcohol extract of pigments at wavelengths $\lambda = 665$ nm and $\lambda = 649$ nm, respectively; *m* is the sample weight, mg; *V* is the volume of ethanol, cm^3. MS Excel was used for the graphical display of the research results. The significance of the experimental data was assessed using analysis of variance (ANOVA) to calculate the least significant difference (LSD_{05}).

Results and Discussion

An analysis of the dynamics of soybean leaf area formation during 2022-2024 allowed for an assessment of the impact of weather conditions during the crop's growing season (Fig. 1).

The provided data shows that in 2022 and 2023, temperature and moisture levels were more favourable for soybean growth and development. However, in 2024, excessively high temperatures and low relative air humidity were observed due to insufficient atmospheric precipitation and uneven distribution throughout the growing season, which limited the leaf area formation of the crop.

In the hot year of 2024, the leaf area of soybean plants was lower than in the previous years, 2022 and 2023, for all experimental variants (Fig. 2): 16.5-22.1% lower in the control; 13.6-21.3% lower with Legume Fix inoculation; and 16.1-21.2% lower with Violar phytohormonal treatment. In the current studies, the proline and MDA content were used as stress biomarkers, the overcoming of which was facilitated by the use of Legume Fix inoculant and Violar phytohormonal preparation (Fig. 3).

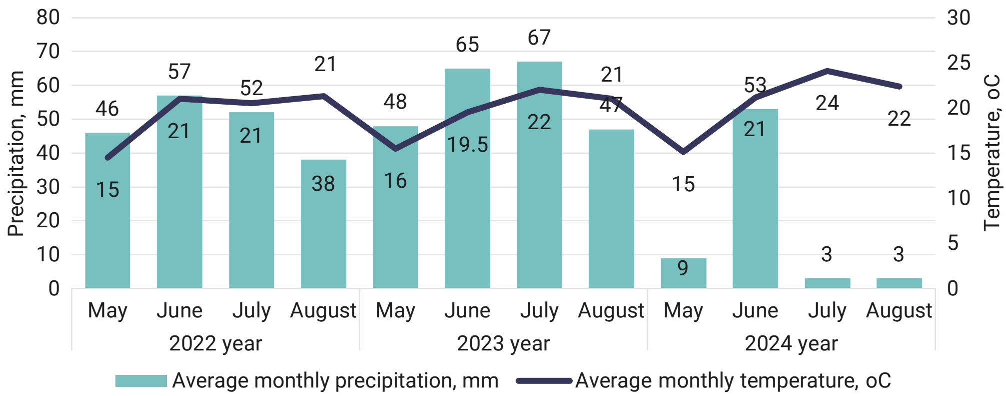

Figure 1. *Average monthly air temperature and precipitation during the soybean growing season*
Source: compiled by the authors

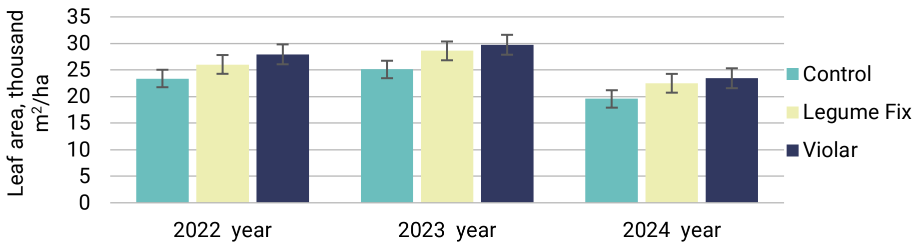

Figure 2. *Dynamics of leaf area formation of soybean plants of the Khorol variety under different pre-sowing treatment technologies, thousand m²/ha*
Note: average for 2022-2024
Source: compiled by the authors

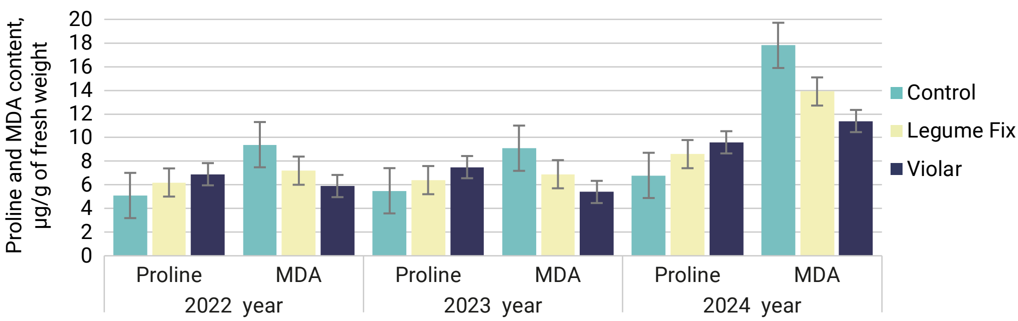

Figure 3. *Proline and MDA content in soybean plants of the Khorol variety under different presowing treatment technologies, µg/g of fresh weight*
Source: compiled by the authors

The proline content in plants in the control was the lowest for all years of research. Indicators of high temperature in 2024 correlated with the maximum proline content (9.6 μg/g of fresh weight); when seeds were treated with the phytohormone Violar, the proline content increased by 41.2% and 26.5% when inoculated with Legume Fix compared to the control. Soybean plants grown in more favourable weather conditions in 2022-2023 also had increased proline content, but the excess over the control when treated with Violar averaged ~22.6% and with Legume Fix ~18.7%. Control plants showed the highest MDA content, indicating the level of response to oxidative stress compared to other treatments (Fig. 3). Soybean plants grown from treated seeds were more resistant to adverse temperature conditions due to a decrease in MDA levels. The MDA content in plants treated with the phytohormone Violar was lower than the content in control plants by ~36% and with Legume Fix inoculation by ~22% in 2024, which differed from previous years with extremely indicators of high temperature with moisture deficit during the growing season.

In 2022-2023, the lowest concentration of MDA in soybean plants was observed when seeds were treated with Violar, with the MDA concentration averaging ~5.65 μg/g of fresh weight, which is 38.9% less than the MDA content in control plants. Legume Fix inoculation also showed an effective action in overcoming temperature stress; the MDA content in plants decreased to an average of ~7.05 μg/g of fresh weight, which is ~23.8% less than in control plants. Therefore, priming soybean seeds with Violar demonstrates better results compared to the effect of Legume Fix. The level of MDA in plants from seeds treated with Violar was almost 20% lower relative to the MDA level with Legume Fix treatment in 2022-2023 and 18% in 2024. A significant increase in proline levels in plants was observed as a result of treating soybean seeds with Violar and Legume Fix. This protective response was absent when seeds were treated with water (control), where the lowest proline levels were recorded for all years of research.

To determine the effect of pre-sowing seed treatment with Legume Fix and Violar on the functioning of the photosynthetic apparatus of soybean plants under different weather conditions, an analysis of the dynamics of chlorophyll Chl *a* and Chl *b* content was performed, and the sum of their forms was calculated since the efficiency of the pigment system affects the yield of soybean crops and depends on environmental conditions (Table 1).

Table 1. *Chlorophyll a and b content in leaves of the Khorol soybean variety at the flowering stage depending on pre-sowing treatment technology*

Technology	Chl *a*			Chl *b*			Chl (*a* + *b*)		
	2022	2023	2024	2022	2023	2024	2022	2023	2024
Control (water)	1.12	1.17	0.78	0.46	0.48	0.34	1.58	1.66	1.12
Legume Fix	1.17	1.23	0.88	0.47	0.49	0.36	1.64	1.73	1.24
Violar	1.29	1.44	0.93	0.51	0.56	0.38	1.80	2.00	1.30
LSD_{05}		0.098			0.034			0.134	

Note: average for 2022-2024
Source: compiled by the authors

In the current study, pre-sowing treatment of soybean seeds with the experimental preparations improved the physiological parameters of plants and promoted an increase in chlorophyll content, which activated the photochemical functions of chloroplasts, increasing the efficiency of photosynthesis. The data in Table 1 shows an increase in the total Chl (*a* + *b*) content using Legume Fix and Violar, depending on the years of research, compared to the control by 3.510.7

and 14.1-21.0%, respectively. The total Chl (*a* + *b*) content in soybean plants using Legume Fix and Violar compared to control plants in 2024 increased by 10.7 and 16.1%, respectively, while in 2022-2023, it increased by an average of 4.0 and 17.5%, respectively. A comparison of the concentration of Chl *a* and Chl *b* in plants grown from seeds treated with Violar showed their maximum level in all years of research. The content of Chl *a* and Chl *b* exceeded the control by an average of 18.9 and 13.3%, respectively, and by 7.4 and 3.4%, the content of chlorophylls in plants from seeds inoculated with Legume Fix.

It should be noted that the content of photosynthetic pigments in the leaves of soybean crops in the more favourable year of 2023 increased, which may be due to the treatment of seeds with biological preparations. Thus, in 2023, compared to 2022, when using Legume Fix and Violar, an increase in Chl *a* content was observed by 5.1% and 11.6%, respectively, and the excess over the control was 5.1-23.1% under the action of both preparations. The increase in Chl *b* content in 2023 compared to 2022 correlated with an increase in Chl *a* levels. The concentration of Chl *b* in soybean leaves when using Violar was higher than its concentration in 2022 by 9.8%; the concentration of Chl *b* when using Legume Fix exceeded this indicator and the control by 4.3%. Despite a decrease in Chl *a* and Chl *b* content in all research variants in 2024, when plant growth was inhibited by high temperature. Compared with the content in plants grown in previous years, when using Violar, the Chl *a* content increased relative to the control by 19.2%, which confirms the effectiveness of its action in overcoming the temperature factor. However, the Chl *b* content when using Violar exceeded control plants in 2024 by 11.8%, and in the more favourable years of 2022-2023 – by 10.9-16.7%. When soybean seeds were inoculated with Legume Fix in 2024, the Chl *a* content in plants increased most significantly – by 12.8%, and Chl *b* – by 5.9% relative to control plants. A similar correlation was observed in 2022-2023 – the increase in Chl *a* was 4.5-5.1%, and Chl *b* only 2.1%.

Soybean yield in the control variant was determined at the level of 1.9-2.4 t/ha depending on the year (Fig. 4), while using Legume Fix and Violar – 2.1-2.8 and 2.3-3.0 t/ha, respectively. The experimentally determined increase in Chl (*a* + *b*) content relative to the control by 5.5% with Legume Fix inoculation and by 17.2% with the use of Violar phytohormonal preparation led to an increase in soybean yield by an average of 13.2-20.6%. At the same time, a direct correlation with a strong relationship was determined between the Chl (*a* + *b*) content and yield for all research variants: control – $r = 0.986$, when using Legume Fix inoculant – $r = 0.983$, Violar biopreparation – $r = 0.988$.

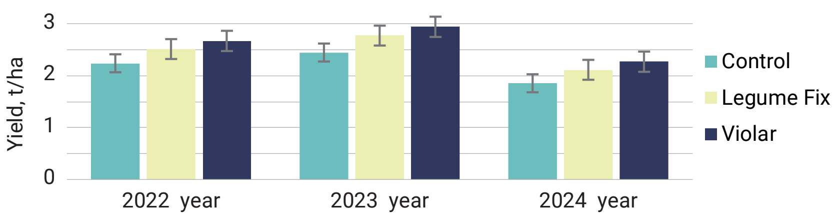

Figure 4. *Dynamics of soybean yield of the Khorol variety with pre-sowing seed treatment using different technologies, t/ha*

Note: average for 2022-2024

Source: compiled by the authors

The yield increase obtained in the current study correlates with the results of V. Tsygankova *et al.* (2017) – the use of Violar in the cultivation of spring wheat contributed to an increase in Chl *a*, Chl *b* and Chl (*a* + *b*) content by 20.0, 40.0 and 19.2%, respectively, which contributed to an increase in grain yield by 20.3%. According to the results of the present research, the use of Violar led to an increase in Chl *a*, Chl *b* and Chl (*a* + *b*) content relative to the control by an average of 18.9, 13.3 and 17.2%, and yield – by 20.6%.

The effectiveness of the Legume Fix application is reflected in the study by H.L. Hadzovskyi *et al.* (2020), where inoculated soybean seeds were supplemented with foliar feeding of complex chelated micronutrients. As a result, the increase in Chl *a*, Chl *b* and Chl (*a* + *b*) content in the leaves of plants of two soybean varieties was 5.8-8.2, 1.1-16.8 and 6.8-7.8%, respectively, and yield – by 6.0-8.0%. According to research by T.O. Chaika *et al.* (2023), the use of Legume Fix in organic farming contributed to an increase in soybean seed yield by 12.4-16.1%, and according to S.S. Nimenko & M.B. Grabovskyi (2023), by 14.8-22.2%. The authors D.B. Lobell & G.P. Asner (2003) proved that with each 1°C increase in temperature, soybean yield decreases by an average of 17%. A. Puteh *et al.* (2013) and K. Jumrani & V.S. Bhatia (2018) note that high-temperature stress during mid-reproductive growth is more detrimental to crop and seed size than that occurring at early or late stages of reproductive development.

Bacterial preparations play a strategic role in mitigating the harmful effects of reactive oxygen species (ROS) through the production of various phytohormones that provide plant resistance. The result of inoculation depends primarily on the strains of bacteria included in the preparations and weather conditions. According to a study by M.S. Sheteiwy *et al.* (2021), inoculation of soybean seeds with *Bradyrhizobium* led to a decrease in ROS levels by an average of ~15% and an increase in proline content by ~20% compared to the control.

Oxidative damage caused by adverse temperature conditions can be reduced by inoculation with phyllosphere bacteria, strains of *Bacillus amyloliquefaciens*, *Azospirillum brasilense*, *Rhizobium leguminosarum*, *Mesorhizobium cicero*, *Trichoderma* sp., which form colonies in root zones and enhance plant growth under various circumstances, as was shown in rice plants (Seleiman *et al.,* 2021; Mokrienko *et al.*, 2024).

However, there are suggestions that bacterial preparations might be less effective under high temperatures. However, microorganisms do not necessarily die under the influence of high temperatures; they can enter a dormant state. Rehydrating dry soil promotes the stimulation of bacterial growth and the activation of respiration, as reflected in studies by P. Iovieno & T. Baath (2008) and A. Meisner *et al.* (2015).

Articles by X. Zhang *et al.* (2013) and M. Cardarelli *et al.* (2022) have shown that bacterial inoculation can positively affect the maintenance of photosynthetic pigments in plants under conditions of insufficient moisture. Seed bacterization contributes to an increase in Chl (*a* + *b*) content, which is explained by a direct relationship between chlorophyll concentration in leaves and nitrogen fixation intensity, which significantly depends on the symbiotic properties of nodule bacteria that determine plant nitrogen nutrition. According to research by O. Lastochkina *et al.* (2020), the use of *B. subtilis* induced an increase in Chl *a* and Chl *b* levels up to 1.52 and 1.46 times, respectively, compared to non-inoculated seeds due to an increase in proline levels, which provides neutralisation of ROS production in plants under drought conditions. At the same time, C. Pagano & M. Miransari (2016) and E. Yusnawan *et al.* (2019) proved that depending on the strain used, different results can be obtained regarding soybean development and yield.

According to research by S.G. Jaybhaye *et al.* (2024) and A. Koziuchko *et al.* (2024), presowing treatment of seeds with biologically active substances (phytohormones, vitamins, amino acids, etc.) plays an important role in increasing soybean productivity. Biologically active substances create a favourable microbiological and biochemical environment around germinating seeds, which stimulates growth, increases the resistance of seedlings to adverse weather conditions, and also activates beneficial soil microflora W.F. Abobatta & D.K.A. Al-taey (2023). When growing common beans (*Phaseolus vulgaris* L.) under drought conditions, seed inoculation with *Bacillus velezensis* and foliar treatment with acetylsalicylic acid significantly increased Chl *a* levels by 25.5% and Chl *b* by 37%, which increased yield by ~30% compared to plants without inoculation (Zamani *et al.,* 2024).

Thus, the highest levels of Chl *a* and Chl *b* can be achieved under conditions of combined use of bacterial preparations in pre-sowing seed treatment and phytohormonal preparations, which indicates the possibility, within certain limits, of managing the photosynthetic process in legume crops. Thus, the experimental results and subsequent analysis highlight the phytohormonal preparation Violar as an effective means for inducing soybean plants to overcome adverse climatic conditions and form high yields under organic farming technologies.

Conclusions

In organic farming, inoculating seeds with bacterial preparations and priming them with phytohormone-containing substances significantly impacts soybean development and yield under harsh growing conditions (high temperatures and lack of precipitation). Quantifying parameters like leaf area and chlorophyll content, based on growing conditions and pre-sowing seed treatment, provides valuable insight into yield-boosting factors. Also, measuring MDA and proline levels when using these treatments helps assess their role in enhancing plant resilience to adverse weather.

The results showed that all methods of soybean seed treatment led to an increase in leaf area, photosynthetic pigment content, and their total while reducing MDA levels and increasing proline content. However, pre-sowing treatment with the Violar phytohormonal preparation was more effective than the Legume Fix bacterial inoculant. The MDA content in plants grown from Violartreated seeds was almost 20% lower in 2022-2023 and 18% lower in 2024 than after using Legume Fix. A significant increase in proline levels was observed both with Violar treatment (averaging ~40% relative to the control) and with Legume Fix inoculant use (~22%). The content of chlorophylls Chl *a* and Chl *b* in plants whose seeds were treated with Violar exceeded the control by an average of 18.9% and 13.3%, respectively, while with Legume Fix inoculation, these indicators increased by 7.4% and 3.4%. The experimentally established increase in the total chlorophyll content Chl (*a* + *b*) relative to the control by 5.5% when using Legume Fix and by 17.2% with Violar treatment, which contributed to an increase in soybean yield by an average of 13.220.6%.

A statistically confirmed strong direct relationship between these indicators and yield, which on average increased relative to the control by 13.2% (2.47 t/ha) when using Legume Fix and 20.5% (2.63 t/ha) when using Violar. This study demonstrates the possibilities of various approaches to soybean seed preparation (using bacterial and phytohormonal preparations) for cultivation using organic farming technologies, comparing their effectiveness. Future research is planned to be devoted to assessing the effect of their combined use in overcoming inevitable climate changes that pose a serious threat to soybean production and the development of effective adaptation measures.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Фізіолого-біохімічні аспекти передпосівної обробки насіння сої (*Glycine max* L. Merr.)

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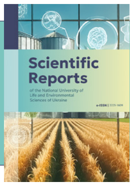
Анотація. Соя є однією з найбільш затребуваних культур, і її виробництво зростає, але зміни клімату впливають на врожайність, що вимагає впровадження біопрепаратів для підвищення стійкості рослин до стресових умов. Мета роботи полягала у дослідженні впливу передпосівної обробки насіння сої інокулянтом і фітогормональним препаратом на фізіолого-біохімічні показники рослин і їх врожайність в умовах органічного землеробства. У польовому дослідженні, проведеному в 2022-2024 роках, проаналізовано вплив передпосівної обробки насіння сої інокулянтом Legume Fix та фітогормональним препаратом Віолар на площу листкової поверхні, вміст проліну, малонового діальдегіду та фотосинтетичних пігментів і врожайність в умовах органічного землеробства за різних погодних умов. Встановлено, що за передпосівної обробки насіння збільшується площа листкової поверхні в середньому на 13,4 % за використання Legume Fix і на 19,3 % – за обробки Віолар. З'ясовано, що найбільше підвищення проліну в рослинах (як захисна функція) спостерігалось у спекотному 2024 році за обробки насіння сої Віолар (41,2 %) та Legume Fix (26,5 %). За роки досліджень у рослинах сої спостерігали найменшу концентрацію MDA за обробки насіння Віолар і Legume Fix - в середньому 7,57 і 9,33 мкг/г сирої маси, відповідно, що на 37,4 і 22,9% менше, ніж в контрольних рослинах. За обробки Віолар вміст Chl *a*, Chl *b* і Chl (*a* + *b*) перевищував контроль у середньому на 18,9; 13,3 і 17,2 %, відповідно, а за інокуляції Legume

Fix – на 7,4; 3,4 і 6,2 % відповідно. Визначено, що за передпосівної обробки насіння сої Legume Fix і Віолар отримано більшу врожайність відносно контрольних рослин в середньому на 13,2 і 20,6 % відповідно. Отримані результати можуть бути рекомендовані для органічного землеробства з метою підвищення врожайності культури

Ключові слова: площа листкової поверхні; пролін; малоновий діальдегід; фотосинтетичні пігменти; органічне землеробство; погодні умови

Received 10.12.2024 Revised 07.03.2025 Accepted 25.04.2025

Vol. 21, No. 2
2025



Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 631.5:631.816:633.17(1-17)(251.1)(477)

DOI: 10.31548/dopovidi/2.2025.120

Influence of agronomic practices on the photosynthetic activity of grain sorghum hybrids in the Northern Steppe of Ukraine

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Abstract. The study of the photosynthetic activity of grain sorghum is crucial for enhancing its productivity under the conditions of the Northern Steppe of Ukraine, characterised by unstable moisture levels and significant temperature fluctuations. This research aimed to determine the influence of hybrids, plant density, and the application of the plant growth regulator Appetaizer on the indicators of photosynthetic activity in grain sorghum. The research was conducted over the period 2022-2024 on experimental plots in the Dnipropetrovsk Region. Winter wheat served as the preceding crop, and cultivation practices followed the standard techniques for the region (except for the investigated elements and a row spacing of 45 cm). The methods employed included: field observations of the phenological phases of growth and development of the crop, as well as the impact of the studied factors on the photosynthetic activity of grain sorghum; tabular methods for the systematisation, arrangement, and presentation of the data obtained; and graphical methods for data visualisation. The study established that, in terms of photosynthetic potential, the optimal combinations were found to be: the hybrid ES Alize at a density of 170 thousand plants/ha with the application of the plant growth regulator (PGR) (392.7 thousand m^2/ha*days); hybrids ES Alize and ES Foehn at a density of 200 thousand plants/ha under control conditions (407.2 and 398.4 thousand m^2/ha*days respectively); the ES Foehn hybrid at the same density with the application of the PGR (404.0 thousand m^2/ha*days); and hybrids ES Alize and ES Foehn at a density of 230 thousand plants/ha under control conditions

Suggested Citation:

Sukhina, D., & Novytska, N. (2025). Influence of agronomic practices on the photosynthetic activity of grain sorghum hybrids in the Northern Steppe of Ukraine. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 21(2), 120-133. doi: 10.31548/dopovidi/2.2025.120.

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(400.0 and 415.7 thousand m^2/ha*days respectively), as well as ES Alize with the application of the PGR (403.2 thousand m^2/ha*days), demonstrated optimal results. In terms of net photosynthetic productivity, the best results were recorded for the Albanus hybrid at a density of 170 thousand plants/ha – both without PGR (4.67 g/m^2 per day) and with PGR (4.70 g/m^2 per day); for the Albanus (4.77) and ES Monsoon (5.07) hybrids at 200 thousand plants/ha under control conditions, as well as with PGR (4.89 and 5.12 g/m^2 per day, respectively); and at 230 thousand plants/ha – for the Albanus (4.78) and ES Monsoon (4.69) hybrids under control conditions, and with PGR (4.78 and 4.82 g/m^2 per day, respectively). Thus, the photosynthetic activity of sorghum was influenced by plant density, hybrid, and the effect of the studied growth regulator. The results obtained will enable agricultural producers to select optimal combinations of plant density, sorghum hybrids, and the appropriateness of using growth regulators to enhance the photosynthetic activity and yield of crops

Keywords: photosynthetic potential; net photosynthetic productivity; phenological phases; plant nutrition; biostimulant; grain sorghum

Introduction

Rational cultivation of grain sorghum necessitates considering the specifics of regional soil and climatic conditions, as these factors determine the efficiency of the plants' photosynthetic apparatus, upon which yield formation directly depends. In the context of climate change and increasing moisture deficit, research into sorghum photosynthetic productivity in the Northern Steppe of Ukraine – a zone characterised by unstable moisture, high temperatures, and frequent occurrences of abiotic stress – becomes particularly relevant. Given sorghum's ability to adapt to arid conditions, identifying the most productive hybrids in combination with optimal agricultural practices, namely plant density and the application of growth regulators, offers the potential to significantly enhance the efficiency of the crop's photosynthetic potential utilisation. Therefore, studying these aspects is of considerable importance for developing adaptive grain sorghum cultivation technologies aimed at ensuring stable high productivity even under climatic constraints (Polevoy *et al*., 2020; Prysiazhniuk *et al*., 2022).

According to Y. Al-Salman *et al.* (2024), global climate change trends over recent decades have expanded the potential growing region for grain sorghum, which is attracting attention from the scientific community due to its low requirements for soil and climatic conditions and its plasticity towards abiotic factors. Researchers D. Wang *et al.* (2022) investigated that grain sorghum belongs to plants with C4-type photosynthesis, which are characterised by lower water losses through transpiration due to CO_2 fixation in mesophyll cells and subsequent transfer to bundle sheath cells where photosynthesis occurs. This type of photosynthesis is more productive compared to C3 photosynthesis under high light intensity and temperature conditions.

The drought tolerance of this crop using different concentrations of PEG 6000 (polyethylene glycol) was confirmed in studies by M. Stefanov *et al.* (2023), who noted better plant recovery at PEG concentrations of 20% and 25%. Concurrently, R.G. Ávila *et al.* (2023) found that water deficit negatively impacts the photosynthetic parameters of grain sorghum plants, although the application of plant growth regulators increases plant resilience. S.Y. Davidenko (2023) argued that the insufficient realisation of the genetic potential of grain sorghum plants is linked to violations of cultivation technological protocols, including those that determine the plant's feeding area and its shape, and consequently regulate competition between plants in agrophytocoenoses.

According to R.E. Grishchenko *et al.* (2020), one of the most dynamic indicators of plant photosynthetic activity is leaf area. The capacity of the assimilatory apparatus and the duration of its function are crucial factors for photosynthetic productivity, influencing yield and grain quality indices. Research by L.A. Pravdyva *et al.* (2023) highlighted the positive impact of applying a growth regulator on the leaf area of grain sorghum, its photosynthetic potential, and net photosynthetic productivity, as well as the important role of crop nutrition in enhancing photosynthetic productivity. The authors established that the use of a regulator promotes increased leaf area development, activates photosynthetic processes, and improves the overall physiological state of plants, enabling more effective utilisation of the crop's potential under stress conditions. L. Pravdyva & V. Doronin (2020) analysed the influence of mineral nutrition on grain sorghum photosynthetic productivity. It was determined that the application of mineral fertilisers contributes to an increase in leaf area, a rise in photosynthetic potential, and an increase in net photosynthetic productivity, which collectively improve the crop's yield.

According to O.S. Tytarenko & L.M. Karpuk (2022), the photosynthetic parameters of crops are an exceptionally important component for determining the effectiveness of grain sorghum cultivation technology elements, as in cultivated plants, yield formation efficiency directly depends on the speed and quality of photosynthetic processes. They also noted a significant influence of applying micronutrients and growth regulators on the course of photosynthetic processes.

Therefore, studying the photosynthetic activity of crops depending on hybrid composition, plant density, and the application of growth regulators is a necessary condition for further improvement of grain sorghum cultivation agricultural practices to realise its biological potential. This study aimed to determine the photosynthetic efficiency of grain sorghum hybrids of different maturity groups depending on plant density and growth regulator application under the conditions of the Northern Steppe of Ukraine.

Materials and Methods

Field research was conducted between 2022 and 2024 on the fields of Zoria LLC in the village of Havrylivka, Synelnykove District, Dnipropetrovsk Region. According to the zonal distribution, the district belongs to the northern part of the steppe zone of Ukraine, characterised by insufficient and unstable moisture and arid weather conditions. The soils at the research site are ordinary chernozems with a high humus content. Soil nutrient reserves were 260-270 kg/ha of mineral nitrogen, 240-260 kg/ha of phosphorus, and 860-880 kg/ha of potassium. The humus content during the research years fluctuated between 4.48% and 4.55%. The agricultural practices in the experiment were generally accepted for the Steppe zone of Ukraine, except for the sowing method (row spacing was 45 cm) and the experimental factors. The preceding crop was winter wheat. The experimental design involved the study of three factors. The research was conducted following the Convention on Biological Diversity (1992).

The first factor comprised grain sorghum hybrids of French breeding from the company Lidea, belonging to different maturity groups: early-maturity – Albanus; mid-early – Kalatur, ES Foehn, and ES Monsoon; and late-maturity – ES Alize. The early-maturity hybrid Albanus (FAO maize equivalent 300-350) has a vegetation period of 92-100 days. Plant height is 115-116 cm. The grain is white, with a 1,000-grain weight of 25.9-29.0 g. Grain protein content is 12.6%-13.0%, and starch content is 74.3%-74.8%. The mid-early hybrid Kalatur (FAO maize equivalent 400-450) has a vegetation period of 108-109 days. Plant height is 114-120 cm. The grain is white, with a 1,000 grain weight of 25.4-29.5 g. Grain protein content is 12.4%-12.8%, and starch content is 74.0%-74.8%. The mid-early hybrid ES Foehn (FAO maize equivalent 380-450) has a vegetation period of 108-111 days. Plant height ranges from 107 to 120 cm. The grain is red, with a 1,000 grain weight of 24.7-30.0 g. Grain protein content is 12.0%-12.8%, and starch content is 73.8%-74.3%. The mid-early hybrid ES Monsoon (FAO maize equivalent 320-400) has a vegetation period of 103-108 days. Plant height is 105-114 cm. The grain is white, with a 1,000grain weight of 26.2-26.5 g. Grain protein content is 11.4%-12.8%, and starch content is 71.8%-73.9%. The late-maturity hybrid ES Alize (FAO maize equivalent 400-480) has a vegetation period of 117-120 days. Plant height is 107-120 cm. The grain is red, with a 1,000-grain weight of 26.9-28.4 g. Grain protein content is 10.2%-11.6%, and starch content is 74.6%-76.4%.

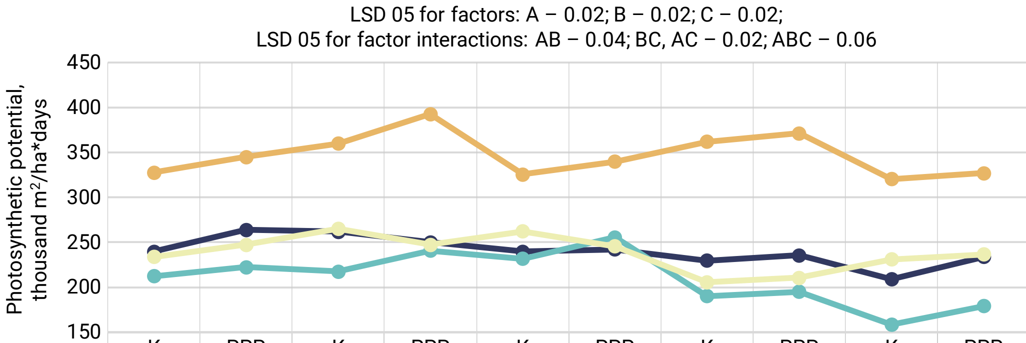
The second factor investigated was plant density, which was set at 170, 200, and 230 thousand plants per hectare. The third factor investigated was the double application of the plant growth regulator Appetaizer, which stimulates physiological processes and improves plant nutrition under stress conditions. The formulation of the Appetaizer growth regulator is an aqueous solution (AS). The active ingredients are sea algae extract (GA-142) – 952 g/L, zinc salts (1%), and manganese salts (1%). The first application was carried out at the 4-5 leaf stage on the experimental variants at a rate of 0.5 L/ha with a working solution volume of 150 L/ha. To ensure high-quality application of the product per the manufacturer's recommendations, an air injection double fan nozzle IDKT 04 with a droplet size of 350-480 VMD μm was used.

The second application of the growth regulator was conducted at the 7-8 leaf stage with a product application rate of 0.5 L/ha and a working solution volume of 150 L/ha. Applications were performed in the evening at air temperatures ranging from +15°C to +20°C, relative air humidity of 20%-30%, and wind speed of 3-4 m/s. The total area of the experimental plot was 8 ha. The accounting area of a variant plot was 600 m^2 (6×100 linear metres), and the total area was 673.2 m^2 (6.6×102 linear metres). The variants were arranged systematically in three tiers (30 variants). The experiment had four replications. Photosynthetic activity of plants was determined by the following indicators: leaf area – using the "cutting" method; photosynthetic potential of the crop (PP) and net photosynthetic productivity (NPP) – according to the methodology of A.O. Nichiporovich. Statistical analysis of the research results was performed using the analysis of variance method for multifactorial experiments with the aid of Microsoft Excel software.

Results and Discussion

During the field research conducted between 2022 and 2024, the dates of the onset of phenological growth and development stages of grain sorghum hybrids were recorded, the leaf areas of the variants were determined depending on the studied factors, and the photosynthetic potential of the crops (PP) and net photosynthetic productivity (NPP) were calculated. From the obtained data, average values over the 3 years were determined to reflect the effectiveness of the agricultural practices.

During the plant stages of stem elongation to panicle emergence, in the control variants at a plant density of 170 thousand plants/ha, the highest photosynthetic potential was observed in the late-maturity hybrid ES Alize (217.8 thousand m^2/ha*days) and the early-maturity hybrid Kalatur (212.6 thousand m^2/ha*days), while the lowest value was recorded for the mid-early hybrid ES Monsoon (320.3 thousand m^2/ha*days) (Fig. 1). An increase in photosynthetic potential occurred in all variants with the application of the growth regulator; the minimum difference was +2.52% for the Albanus hybrid, and the maximum was +13.12% for the ES Monsoon hybrid. A significant difference was also recorded for the ES Alize (+10.59%) and ES Foehn (+10.38%) hybrids. During the panicle emergence to flowering stages of grain sorghum development, the highest photosynthetic potential was observed in the ES Alize (265 thousand m^2/ha*days) and ES Foehn (262.4 thousand m^2/ha*days) hybrids. The minimum value during this period was for the Albanus hybrid – 205.7 thousand m^2/ha*days.



	Kalatur K	Kalatur PPP	ES Alize K	ES Alize PPP	ES Foehn K	ES Foehn PPP	Albanus K	Albanus PPP	ES Monsoon K	ES Monsoon PPP
C-SE	239.9	264.0	261.8	250.1	239.9	242.0	229.6	235.8	209.0	233.7
SE-PE	212.6	222.3	217.8	240.8	231.7	255.8	190.2	195.0	158.5	179.3
PE-F	234.0	247.5	265.1	247.5	262.4	245.5	205.7	210.6	231.0	236.5
F-WR	327.8	345.0	360.0	392.7	325.5	339.8	362.1	371.5	320.3	327.0

Plant density, 170 thousand plants/ha

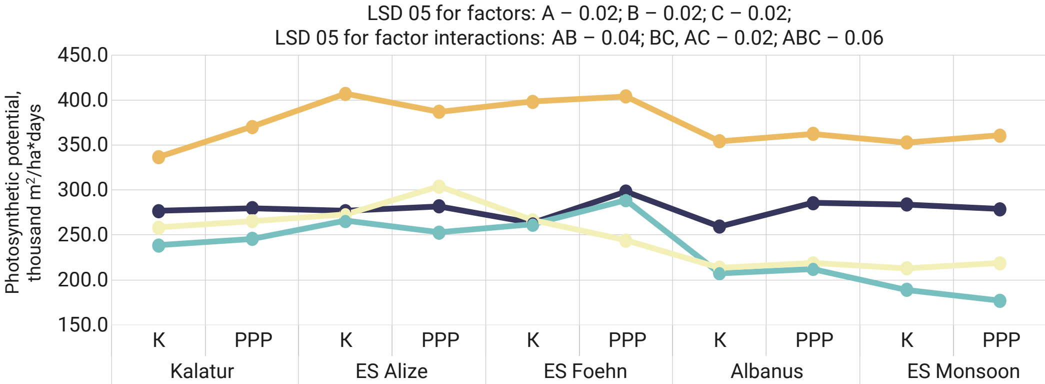
Figure 1. *Photosynthetic potential of crops at a density of 170 thousand plants/ha during the main phenological growth and development stages of the plants*

Note: C – control; PGR – plant growth regulator; SE – seedling; SE – stem elongation; PE – panicle emergence; F – flowering; WR – waxy ripeness

Source: developed by the authors

The application of the growth regulator at this stage had a somewhat differentiated effect – on the ES Alize and ES Foehn hybrids, the photosynthetic potential decreased by 6.42%-6.64% compared to the control, but increased by 5.77% for the Kalatur hybrid and by 2.38%-2.41% for the ES Monsoon and Albanus hybrids. This phenomenon was likely due to the genetic characteristics of the hybrids, particularly their maturity group, which in turn characterises the process of ontogenesis with specific features of biometric parameter development (formation of leaf area and senescence of lower-tier leaves). That is, the stimulating effect of the PGR led to an acceleration of the plants' passage through phenological stages, resulting in the earlier senescence of lower-tier leaves compared to the control variants.

During the flowering to waxy ripeness period, in the control variants at a plant density of 170 thousand plants/ha, the photosynthetic potential of the crop reached its maximum value in the earlymaturity hybrid Albanus (362.1 thousand m^2/ha*days) and the late-maturity hybrid ES Alize (360.0 thousand m^2/ha*days), while the lowest value was for the mid-early hybrid ES Monsoon (320.3 thousand m^2/ha*days). At this stage, an increase in photosynthetic potential of 2.11%-9.08% was recorded in all variants with the application of PGR. During the grain sorghum development phases from stem elongation to panicle emergence, with an increase in plant density to 200 thousand plants/ha, an increase in the PP index of 9.1%-19.4% was noted in all control variants (Fig. 2). Thus, the highest PP was observed in the ES Alize (266.0 thousand m^2/ha*days) and ES Foehn (261.8 thousand m^2/ha*days) hybrids, and the lowest in the ES Monsoon hybrid (189.2 thousand m^2/ha*days). The influence of growth regulator application at this stage also proved to be differentiated: +2.31% in the Albanus hybrid; +3.00% in Kalatur; +10.29% in ES Foehn; −4.94% in ES Alize and −6.45% in ES Monsoon, for the reasons mentioned previously.



	Kalatur K	Kalatur PPP	ES Alize K	ES Alize PPP	ES Foehn K	ES Foehn PPP	Albanus K	Albanus PPP	ES Monsoon K	ES Monsoon PPP
C-SE	276.8	280.0	276.8	282.0	263.3	298.2	259.4	285.6	283.8	278.8
SE-PE	238.6	245.7	266.0	252.9	261.8	288.8	207.6	212.4	189.2	177.0
PE-F	258.5	265.5	273.0	304.2	266.5	243.9	213.8	218.7	212.9	218.7
F-WR	336.7	370.5	407.2	387.0	398.4	404.0	354.4	362.4	352.8	360.8

Plant density, 200 thousand plants/ha

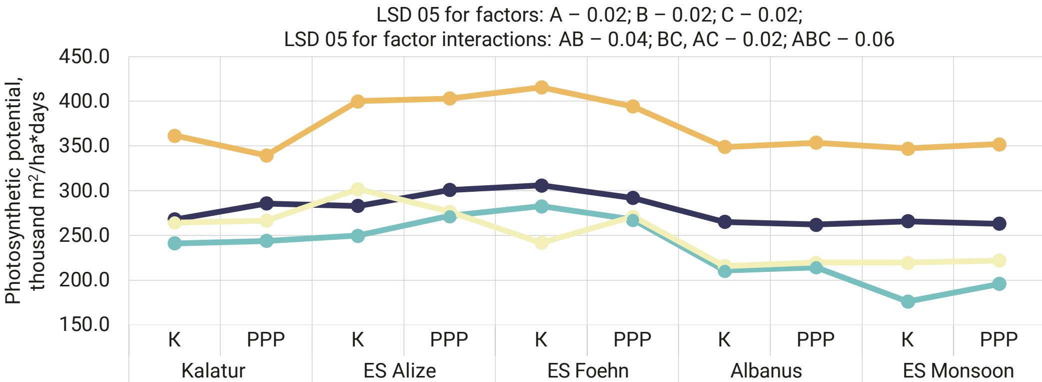
Figure 2. *Photosynthetic potential of crops at a density of 200 thousand plants/ha during the main phenological growth and development stages of the plants*

Note: C – control; PGR – plant growth regulator; SE – seedling; SE – stem elongation; PE – panicle emergence; F – flowering; WR – waxy ripeness

Source: developed by the authors

During the panicle emergence to flowering period, the control variants of ES Alize (273.0 thousand m²/ha*days), ES Foehn (266.5 thousand m²/ha*days), and Kalatur (258.5 thousand m²/ha*days) exhibited the highest photosynthetic potential. A significant positive effect of the growth regulator on PP was observed in the ES Alize hybrid (+11.41%), while others showed increases within the range of +2.35%-2.75% (except for the ES Foehn hybrid, which saw a decrease of 8.48%). During the flowering to waxy ripeness development stages of grain sorghum at a plant density of 200 thousand plants/ha, the variants with the ES Alize (407.2 thousand m²/ha*days) and ES Foehn (398.4 thousand m²/ha*days) hybrids reached maximum values in the control. Furthermore, in the variants with PGR application, the highest value was recorded for the ES Foehn hybrid – 404.0 thousand m²/ha*days. During the grain sorghum stages from stem elongation to panicle emergence, increasing the plant density to 230 thousand plants/ha resulted in a differentiated effect. In the control variants, an increase in the PP index was noted for the Kalatur hybrid by 1.1%, for the ES Foehn hybrid by 8.0%, and for the Albanus hybrid by 1.4% (Fig. 3). The index decreased in other hybrids, indicating excessive density.

During the panicle emergence to flowering period, the control variants showed an increase in the PP index of 2.3% for the Kalatur hybrid, 10.6% for the ES Alize hybrid, and 3.2% for the ES Monsoon hybrid. The increase in density had almost no effect on the Albanus hybrid, while the ES Foehn hybrid showed a decrease in the index of 9.1%. PGR application was effective for all hybrids (+1.08%-11.25%), except for the ES Foehn hybrid (–5.43%). During the flowering to waxy ripeness development stages of grain sorghum at a plant density of 230 thousand plants/ha, the variants with the ES Foehn (415.7 thousand m²/ha*days) and ES Alize (400.0 thousand m²/ha*days) hybrids reached maximum values in the control. Furthermore, in the variants with PGR application, the highest value was observed in the ES Alize hybrid – 403.0 thousand m²/ha*days, which was slightly lower than the ES Foehn variant at a density of 200 thousand plants/ha. Other variants with PGR application demonstrated a PP increase of 0.8%1.38%, except for the Kalatur (–6.09%) and ES Foehn (–5.11%) hybrids.



	K	PPP	K	PPP	K	PPP	K	PPP	K	PPP
	Kalatur		ES Alize		ES Foehn		Albanus		ES Monsoon	
C-SE	268.0	285.6	282.9	301.0	306.0	291.9	265.2	262.2	266.0	263.3
SE-PE	241.2	243.8	249.6	271.6	282.8	267.4	210.6	214.2	176.0	195.8
PE-F	264.5	266.5	302.0	276.5	241.7	271.0	215.6	219.6	219.6	221.9
F-WR	361.5	339.5	400.0	403.2	415.7	394.4	348.8	353.6	347.2	352.0

Plant density, 230 thousand plants/ha

***Figure 3.** Photosynthetic potential of crops at a density of 230 thousand plants/ha during the main phenological growth and development stages of the plants*

Note: C – control; PGR – plant growth regulator; SE – seedling; SE – stem elongation; PE – panicle emergence; F – flowering; WR – waxy ripeness

Source: developed by the authors

L.A. Herasymenko (2014) argued that a crucial condition for ensuring yield is the duration of functioning of the formed leaf area of crops, which is expressed by the photosynthetic potential (PP) index. This index can vary widely depending on the soil and climatic zone and the growing conditions of the given crop. According to their observations, with a row spacing of 45 cm and a plant density of 200 thousand plants/ha, the PP was 4.11 million m²/ha*days for the variety Sylosne 42 and 4.41 million m²/ha*days for the hybrid Medovyi. With an increase in plant density to 300 thousand plants/ha, this index was 4.52 and 4.78 million m²/ha*days, respectively. In the current research, the photosynthetic potential index was calculated at each stage of ontogenesis for a more precise understanding of the dynamics of changes in the grain sorghum hybrid variants depending on the studied factors. However, a comparison of the research results indicates that grain sorghum and sweet sorghum differ significantly in terms of photosynthetic potential even at the same plant density of 200 thousand plants/ha.

In comparison with the indices from the research by L. Pravdyva & V. Doronin (2020), the current study's indices at the same plant density of 200 thousand plants/ha showed lower values, specifically: compared to the varieties Dniprovskyi 39 (1.24 million m²/ha*days) and Vinets (1.18 million m²/ha*days), the photosynthetic potential of the control variants over the vegetation period was: Kalatur hybrid – 1.11 million m²/ha*days; ES Alize – 1.22 million m²/ha*days; ES Foehn – 1.19 million m²/ha*days; Albanus – 1.04 million m²/ha*days; ES Monsoon – 1.04 million m²/ha*days. Furthermore, the variants with the application of the PGR Appetaizer were characterised by significantly higher indices: Kalatur hybrid – 1.16 million m²/ha*days;

ES Alize – 1.23 million m^2/ha*days; ES Foehn – 1.23 million m^2/ha*days; Albanus – 1.08 million m^2/ha*days; ES Monsoon – 1.04 million m^2/ha*-days. In contrast, the net photosynthetic productivity of the investigated hybrids was significantly higher compared to the varieties Dniprovskyi 39 (3.91 g/m^2 per day) and Vinets (3.72 g/m^2 per day): for the Kalatur hybrid – 4.22 g/m^2 per day; ES Alize – 3.77 g/m^2 per day; ES Foehn – 4.09 g/m^2 per day; Albanus – 4.77 g/m^2 per day; ES Monsoon – 5.07 g/m^2 per day. These indices, considering the different agro-meteorological conditions of the areas where the comparative studies were conducted, indicate the adaptability of the investigated hybrids to the arid conditions of the Northern Steppe of Ukraine.

R.M. Vasylenko (2018) investigated the photosynthetic productivity of grain sorghum (Pivdennyi variety with 70 cm row spacing) under different sowing dates, reporting a photosynthetic potential of 1.13 million m^2/ha*days without irrigation and 1.19 million m^2/ha*days under irrigation; and a net photosynthetic productivity of 3.7 g/m^2 per day without irrigation and 3.6 g/m^2 per day under irrigation. These data are significantly lower compared to the Kalatur, ES Alize, ES Foehn, Albanus, and ES Monsoon hybrids, and indicate the effectiveness of the grain sorghum hybrids investigated in non-irrigated conditions, as well as the expediency of using plant growth regulators. Furthermore, R.M. Vasylenko (2018) in their research paid attention to the plant protection system and highlighted its important role in the formation of grain sorghum photosynthetic productivity.

Based on the photosynthetic potential and data on the duration of phenological phase periods, dry biomass yield increments were calculated, after which the net photosynthetic productivity of each variant was determined (Fig. 4).

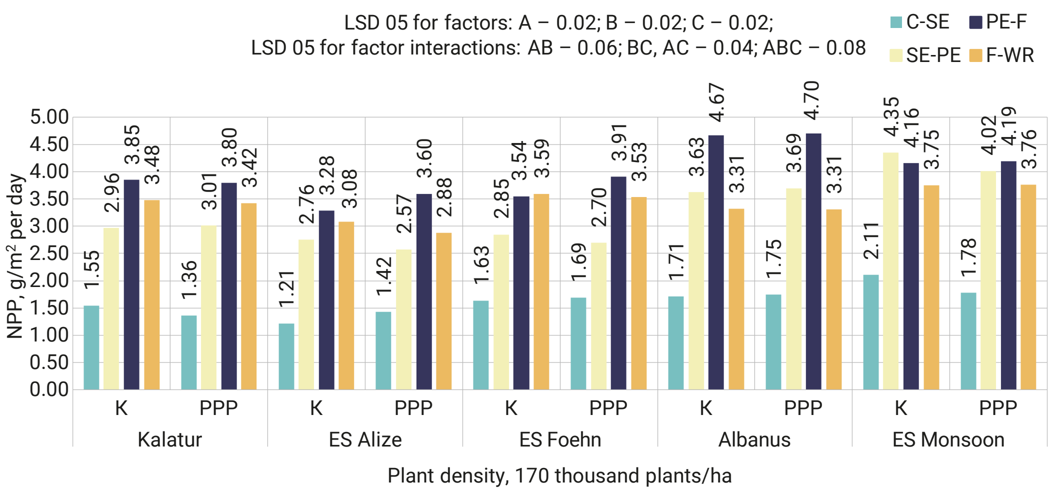


Figure 4. *Net photosynthetic productivity at a density of 170 thousand plants/ha during the main phenological growth and development stages of the plants*

Note: C – control; PGR – plant growth regulator; SE – seedling; SE – stem elongation; PE – panicle emergence; F – flowering; WR – waxy ripeness

Source: developed by the authors

These results indicate that at a plant density of 170 thousand plants/ha, the early-maturity Albanus hybrid exhibited the highest NPP among the hybrids during the stem elongation to panicle emergence (3.63 g/m^2 per day) and flowering to waxy ripeness (4.67 g/m^2 per day) periods. Furthermore, the ES Monsoon hybrid consistently showed high NPP throughout all phases (3.754.35 g/m² per day), despite low photosynthetic potential indices. The Kalatur hybrid was also stable throughout the entire period, with NPP within the range of 2.96-3.85 g/m² per day. At a plant density of 200 thousand plants/ha, the highest net photosynthetic productivity across all variants was recorded (Fig. 5). Among the hybrids, ES Monsoon (3.74-5.07 g/m² per day), Albanus (3.564.77 g/m² per day), and Kalatur (3.95-4.22 g/m² per day) distinguished themselves with high values in the control plots. In the variants with PGR application, the highest NPP values were observed in the ES Monsoon (3.77-5.12 g/m² per day), Albanus (3.61-4.89 g/m² per day), and ES Foehn (2.98-4.63 g/m² per day) hybrids.

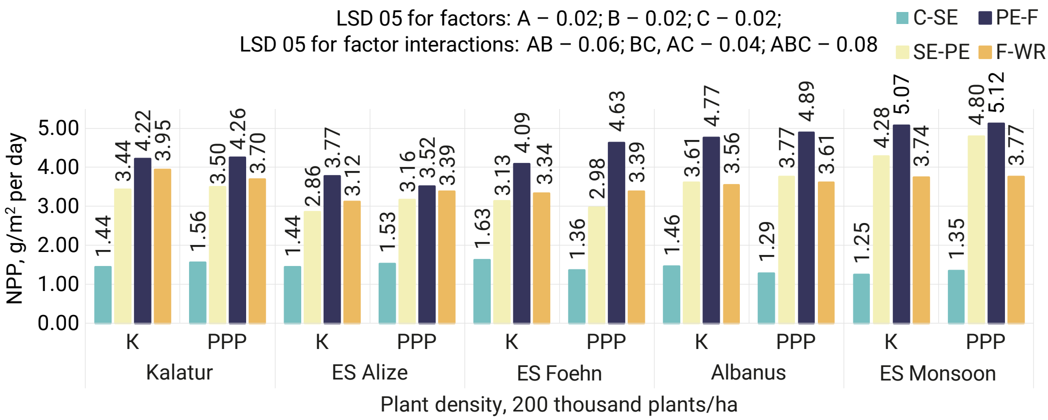


***Figure 5.** Net photosynthetic productivity at a density of 200 thousand plants/ha during the main phenological growth and development stages of the plants*

Note: C – control; PGR – plant growth regulator; SE – seedling; SE – stem elongation; PE – panicle emergence; F – flowering; WR – waxy ripeness
Source: developed by the authors

Increasing plant density to 230 thousand plants/ha led to a decrease in NPP in the control variants during the stem elongation-panicle emergence stages by 12% for the Kalatur hybrid, 2% for the ES Alize hybrid, and 16% for ES Foehn, while remaining unchanged for the Albanus and ES Monsoon hybrids (Fig. 6). During the panicle emergence-flowering period, the NPP index decreased by 15% for the ES Alize hybrid and 8% for ES Monsoon; for other hybrids, the change was insignificant. The flowering-waxy ripeness period was characterised by a decrease in NPP for the Kalatur and ES Foehn hybrids by 13% and 10%, respectively. The indices for other hybrids remained almost at the same level.The application of the growth regulator to the variants had a differentiated effect on the hybrids at various development stages: for the Kalatur hybrid, a reduction in the effect of increased density of 1%-14% was observed; for the ES Alize hybrid – a reduction in the negative impact of increased density of 6%-18%; for the ES Foehn hybrid – 5%-7%; a decrease in NPP occurred for the Albanus hybrid by 1%-3% at all development stages, and for the ES Monsoon hybrid there was a decrease of 16% during the stem elongation-panicle emergence period, and an increase of 1%-2% in other periods.

According to O.S. Tytarenko & L.M. Karpuk (2022), research results for grain sorghum hybrids Brigga and Yutami in the Right-bank Forest-Steppe of Ukraine, a region with unstable moisture, showed that without plant growth regulators, NPP during the stem elongation-panicle emergence period ranged from 3.29 to 3.87 g/m² per day. With the application of the PGRs Regoplant or Stimpo, it ranged from 3.30 to 3.88 g/m² per day. In comparison, the hybrid Kalatur had an NPP of 4.22 g/m² per day; ES Alize – 3.77 g/m² per day; ES Foehn – 4.09 g/m^2 per day; Albanus – 4.77 g/m^2 per day; and ES Monsoon – 5.07 g/m^2 per day on the control variants. With the application of the PGR Appetaizer, the NPP values increased to 4.26 g/m^2 per day for the Kalatur hybrid; 3.52 g/m^2 per day for ES Alize; 4.63 g/m^2 per day for ES Foehn; 4.89 g/m^2 per day for Albanus; and 5.12 g/m^2 per day for ES Monsoon. A similar dynamic is also observed during the panicle emergence-flowering and flowering-waxy ripeness periods. This indicates the greater effectiveness of the PGR Appetaizer compared to the other growth regulators. However, the aforementioned research also included the application of micronutrients, which, in combination with the use of PGRs, resulted in photosynthetic productivity indices that exceeded those of the grain sorghum hybrids investigated in the present study.

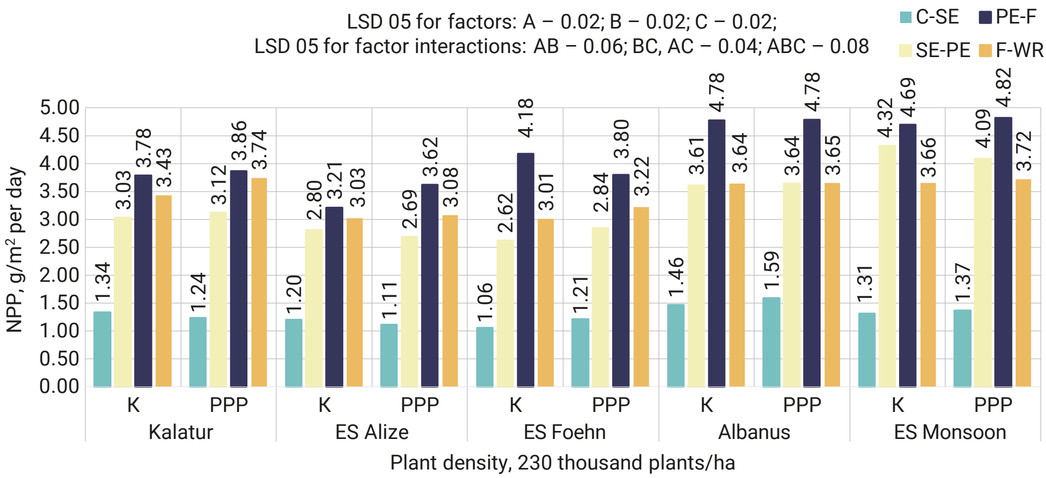


***Figure 6.** Net photosynthetic productivity at a density of 230 thousand plants/ha during the main phenological growth and development stages of the plants*

Note: C – control; PGR – plant growth regulator; SE – seedling; SE – stem elongation; PE – panicle emergence; F – flowering; WR – waxy ripeness

Source: developed by the authors

A. Shrestha *et al.* (2016) investigated the tolerance of grain sorghum to high salt concentrations under laboratory conditions, which allowed the assertion that grain sorghum is a strategic crop for cultivation on saline soils. However, according to research by I.G. Daniells *et al.* (2001) under field conditions, the productivity of grain sorghum on saline soils is rather limited and can be up to 50% of the potential yield. The peculiarities of grain sorghum's physiological responses during drought stress involve an increase in photosynthetic rate through reduced stomatal conductance and transpiration rate (Zhang *et al.*, 2019), increased leaf temperature (Kapanigowda *et al.*, 2014), decreased chlorophyll content, and increased oxygen evolution (Bao *et al.*, 2017). Consequently, an enhanced photosynthetic rate, which provides the nutrients and energy required for plant growth and development, is the main mechanism by which tolerant genotypes maintain grain yield in sorghum during stress (Getnet, 2015). Thus, under conditions of insufficient moisture, the photosynthetic apparatus is fundamental to plant growth and development, as well as yield formation.

According to L.A. Herasymenko (2014), sowing dates and seed burial depth significantly influence sorghum photosynthetic productivity, with optimal conditions being sowing in the second ten-day period of May and a seed burial depth of 4-6 cm. Field research by L.A. Herasymenko (2014) also established that key factors influencing crop photosynthetic productivity are row spacing (30 cm is optimal for sweet sorghum) and plant density (300 thousand plants/ha is optimal for sweet sorghum). M.B. Grabovskiy *et al.* (2017) hold a similar view, focusing specifically on the optimal temperature for grain sorghum sowing (+10°C-12°C), and their research results indicate a close interrelationship between photosynthetic potential, net photosynthetic productivity, and increased yield.

In the research conducted by R.E. Grishchenko *et al.* (2020) on the photosynthetic productivity of the Artemida variety at a plant density of 180 thousand plants/ha with 45 cm row spacing, it was found that the highest indices of sorghum crop photosynthetic potential (2.96 million m^2/ha*days) and net photosynthetic productivity (5.4-5.76 g/m^2 per day) were achieved with the main application of $N_{60}P_{60}K_{60}$ and additional nitrogen feeding (N_{15}) alongside seed treatment with the BTU preparation. Considering the somewhat lower indices in current research, it can be concluded that the agricultural practices investigated, namely the grain sorghum hybrids, plant density of 200 thousand plants/ha, and the application of the studied additive, are expedient under the unfavourable and arid conditions of the Northern Steppe of Ukraine. Thus, the obtained results demonstrate significant variability in photosynthetic potential and net photosynthetic productivity depending on the hybrid composition, plant density, and the application of the growth regulator. The optimal conditions for realising the biological potential of the hybrids were found to be a density of 200 thousand plants/ha and the use of the Appetaizer preparation, which ensured an increase in photosynthetic activity indices and productivity stability during the phases of active growth. The hybrids Kalatur, ES Foehn, and ES Monsoon proved particularly effective under the conditions of the Northern Steppe of Ukraine.

Conclusions

The presented results allow for the conclusion that, in terms of photosynthetic potential, the optimal variants were the combinations of: the ES Alize hybrid at a plant density of 170 thousand plants/ha with PGR application; the ES Alize and ES Foehn hybrids at a plant density of 200 thousand plants/ha in the control; the ES Foehn hybrid at a plant density of 200 thousand plants/ha with PGR application; the ES Alize and ES Foehn hybrids at a plant density of 230 thousand plants/ha in the control, as well as ES Alize with PGR application.

Conversely, regarding net photosynthetic productivity, the best variant at a plant density of 170 thousand plants/ha proved to be the early-maturity Albanus hybrid, both without (4.67 g/m^2 per day) and with the application of the PGR Appetaizer (4.70 g/m^2 per day). At a density of 200 thousand plants/ha, the best control variants were the Albanus (4.77 g/m^2 per day) and ES Monsoon (5.07 g/m^2 per day) hybrids, as well as the variants with PGR application on these hybrids (4.89 and 5.12 g/m^2 per day, respectively). The Albanus and ES Monsoon hybrids also performed well at a density of 230 thousand plants/ha: in the control variants with values of 4.78 and 4.69 g/m^2 per day, respectively; and in the variants with PGR application with maximum values of 4.78 and 4.82 g/m^2 per day. Furthermore, the aforementioned indicates that grain sorghum photosynthetic activity is significantly dependent on plant density and the genetic characteristics of the hybrids (individual sensitivity to high density), and the application of the investigated preparation increases the indices of photosynthetic potential and net photosynthetic productivity of crops or improves plant plasticity in cases of stem stand crowding.

Prospects for further research include expanding experiments to other agro-climatic zones of Ukraine to establish the regional stability of photosynthetic indicators for different grain sorghum hybrids. It is also advisable to investigate the dynamics of photosynthetic activity in conjunction with the biochemical characteristics of leaves and the level of water resource utilisation for a comprehensive assessment of the crop's adaptive potential under varying moisture conditions and soil tillage technologies.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Вплив агротехнічних заходів на особливості фотосинтетичної активності гібридів сорго зернового в умовах Північного Степу України

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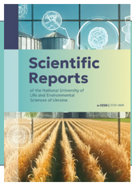
Анотація. Вивчення фотосинтетичної активності сорго зернового є важливим для підвищення його продуктивності в умовах Північного Степу України, що характеризується нестабільним зволоженням і високими температурними коливаннями. Метою досліджень було визначити вплив гібридів, густоти стояння рослин і застосування регулятора росту рослин «Аппетайзер» на показники фотосинтетичної активності сорго зернового. Дослідження проводили протягом періоду 2022-2024 рр. на дослідних ділянках Дніпропетровської області. Попередником була пшениця озима, агротехніка вирощування – загальноприйнята для зони вирощування (окрім досліджуваних елементів та ширини міжряддя, яке становило 45 см). Серед методів, що використовувалися, були: польовий – спостереження за фенологічними фазами росту та розвитку культури, вплив досліджуваних елементів на фотосинтетичну активність сорго зернового; табличний – для систематизації, впорядкування та відображення отриманих даних; графічний – для відображення отриманих даних. У ході дослідження встановлено, що за фотосинтетичним потенціалом оптимальними були комбінації: гібриду ЕС Алізе за густоти 170 тис. рослин/га із застосуванням регулятору (далі – РРР) росту рослин (392,7 тис.м^2/га*діб); гібридів ЕС Алізе та ЕС Фоен за густоти 200 тис. рослин/га на контролі (407,2 та 398,4 тис.м^2/га*діб); гібриду ЕС Фоен за тієї ж густоти з РРР (404,0 тис.м^2/га*діб); гібридів ЕС Алізе та ЕС Фоен за густоти 230 тис. рослин/га на контролі (400,0 та 415,7 тис.м^2/га*діб), а також ЕС Алізе із застосуванням РРР (403,2 тис.м^2/га*діб). За чистою продуктивністю фотосинтезу найкращими були: гібрид Албанус при густоті 170 тис. рослин/га — без РРР (4,67 г/м^2/добу) та з РРР (4,70 г/м^2/добу); гібриди Албанус (4,77) та ЕС Муссон (5,07) при 200 тис. рослин/га на контролі, а також з РРР (4,89 та 5,12 г/м^2/добу відповідно); при 230 тис. рослин/га — гібриди Албанус (4,78) та ЕС Муссон (4,69) на контролі та з РРР (4,78 та 4,82 г/м^2/добу). Отже, фотосинтетична активність сорго залежала від густоти, гібриду та дії регулятора росту досліджуваної добавки. Отримані результати дозволять агровиробникам обґрунтовано добирати оптимальні комбінації густоти стояння, гібридів сорго та доцільність застосування регулятора росту для підвищення фотосинтетичної активності та урожайності посівів

Ключові слова: фотосинтетичний потенціал; чиста продуктивність фотосинтезу; фенологічні фази; живлення рослин; біостимулятор; сорго зернове

Received 02.01.2025 Revised 01.04.2025 Accepted 25.04.2025

Vol. 21, No. 2
2025



Scientific Reports of the National University of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 712.3:631.53:582.708

DOI: 10.31548/dopovidi/2.2025.134

Features of generative reproduction in plants of the genus *Cercis* L.

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Abstract. The challenge of germinating *Cercis* L. seeds, caused by their physiological and physical dormancy, necessitates the improvement of generative propagation methods using growth stimulants. This study examined the influence of organo-mineral growth stimulants on the germination efficiency of experimental species seeds, as well as their subsequent impact on the morphometric parameters of seedlings. Field germination was determined by direct counting of germinated seeds, while laboratory germination was assessed according to the International Seed Testing Association (ISTA) methodology for evaluating seed quality. Statistical data processing was performed using MS Excel (one-way ANOVA and Standard Deviation). The study revealed a statistically significant effect of the tested preparations on seed germination efficiency. It was found that *Cercis siliquastrum* "Alba" seeds exhibited the highest germination rate when treated with Succinic acid at a concentration of 1 g/L. For *Cercis canadensis* L., the preparations "Megafol" (5.0 mL/L, germination rate 70-77%) and "Alga 600" (1.25 g/L, germination rate 50-70%) demonstrated a positive effect. Additionally, experimental data showed that seedlings derived from stimulant-treated seeds exhibited greater growth increments compared to the control group. Treatment with "Succinic acid" resulted in a 2.5-2.9-fold increase in *Cercis siliquastrum* "Alba" seedlings. Similarly, *Cercis canadensis* L. seedlings from seeds treated with

Suggested Citation:

Babyn, O., & Pinchuk, A. (2025). Features of generative reproduction in plants of the genus *Cercis* L.. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 21(2), 134-147. doi: 10.31548/dopovidi/2.2025.134.

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"Succinic acid" showed nearly double the growth increment. Application of "Radifarm" (5.0 mL/L) increased the height of *Cercis canadensis* L. seedlings by approximately 1.6-fold

Keywords: seed propagation; Judas tree; seedlings; growth stimulants; germination

Introduction

The genus *Cercis* L. comprises ornamental woody plants distinguished by their vibrant flowering and distinctive leaf morphology, making them widely used in landscaping, garden design, and botanical cultivation. Despite their horticultural value, large-scale propagation of *Cercis* remains challenging due to the biological characteristics of its seeds. Specifically, the seeds exhibit deep physiological and physical dormancy, significantly complicating germination and limiting the widespread application of generative propagation in nursery conditions. Consequently, there is a need to refine stratification techniques and employ growth stimulants to enhance *Cercis* seed germination and reduce pre-sowing preparation time.

The simplest propagation method is generative. As noted by N. Nimavat & P. Parikh (2024), generative reproduction carries a risk of parental trait segregation. However, for plants that are difficult to propagate via cuttings, grafting serves as an alternative for preserving the ornamental traits of parent plants. This technological process requires rootstock planting material, which is typically obtained through generative propagation. Thus, improving generative propagation techniques and studying the influence of growth stimulants on seed germination efficiency and subsequent seedling quality remain pressing issues.

According to F.A. Chattha *et al*. (2025), seed germination is a complex process influenced by both endogenous and exogenous factors. Key determinants of successful germination include temperature, moisture, and oxygen. The endosperm acts as a nutrient reservoir, containing hormones that regulate germination. Phytohormones play a critical role in germination and early seedling development. For instance, auxins regulate embryo growth and development, with their concentration controlling differentiation into various plant organs. Gibberellins, another vital group of phytohormones, are used in seed treatment to induce amylase production, which promotes germination. Post-germination, increased sugar content elevates respiration rates, facilitating growth. Cytokinins regulate seedling development, particularly stem elongation and enzyme induction. These phytohormones are synthesised in the apical tissues of young roots. In contrast, abscisic acid acts as an inhibitor and interacts antagonistically with gibberellins. Additionally, exogenous chemicals are employed to modulate seed and plant growth, influencing not only development but also providing insights into seed physiology through compositional analysis.

R. Zhou *et al*. (2025) investigated the effects of gibberellic acid and cold stratification on the germination of the perennial medicinal plant Ferula gigantea via controlled experiments. They found that a 90-day cold stratification period yielded the highest germination rate (86.7%), recommending this pre-sowing treatment for the species. Garg (2024) studied the positive influence of beneficial microbes, including arbuscular mycorrhizal fungi, *Trichoderma* spp., rhizobia, and other bacteria, noting significant germination improvements in cereals, oilseeds, and vegetables.

During the generative propagation of *Zostera marina* L., researchers R. Pieraccini *et al*. (2025) investigated the effects of light and gibberellic acid on seed germination in the studied species. They examined the combined influence of light spectra (white, red, and absence of light), photoperiod, and gibberellic acid at concentrations of 0, 50, 500, and 1000 mg/L on germination rates. Their findings revealed that the absence of light or exposure to red light spectra, in combination with gibberellic acid, significantly increased the likelihood of seed germination. Additionally, it was noted that moderate (50 mg/L) and high (500 mg/L) concentrations of gibberellic acid also had a positive effect on reducing germination time. Based on their research, the authors concluded that seed treatment could mitigate dormancy periods induced by stress or handling and may represent a viable strategy for generative propagation in nursery settings.

The study by X. Wang *et al.* (2025) focused on the effects of freezing and stratification on the germination of pecan (*Carya illinoinensis*) seeds, which are widely used for rootstock cultivation. The authors emphasised that, despite the traditional emphasis on scions, rootstocks largely determine plant growth, phenology, and resilience. The primary challenges arise from the seeds deep dormancy and hard seed coat. It was found that stratification significantly improved germination rates (up to 48.5%) and reduced germination time (to 18 days), whereas freezing without stratification demonstrated markedly lower efficacy (germination rate of 15.7%, with germination occurring after 37 days). Conversely, the combination of freezing and stratification negatively affected the results. Seed provenance had no significant influence.

M. Szymajda & R. Maciorowski (2025) investigated the impact of different treatment methods on the germination and growth of cherry seedlings under greenhouse conditions. The tested treatments included varying durations of cold stratification (+5°C) and several approaches to removing germination inhibitors present in the endocarp, seed coat, endosperm, and cotyledons of the embryos. Their results indicated that the highest germination rates were achieved by removing the seed coat attached to the endosperm and exposing the embryos to +20°C after 90 days of stratification. Germination rates reached 80-90%, with germination time ranging between 10-15 days. The authors also noted that under conventional stratification methods (seeds in endocarps at +5°C), a significant proportion of seeds failed to germinate even after 150 days. Using this method, seedlings 20-25 cm tall were obtained within five months, while the final germination rate for the control group varied between 16.4% and 54.4%. Seedlings derived from seeds stratified for 90 days exhibited better growth than those subjected to shorter stratification periods.

The objective of this study was to determine the effects of organo-mineral growth stimulants on the germination of experimental *Cercis* L. species and to analyse subsequent changes in the morphometric characteristics of the resulting seedlings.

Materials and Methods

Germination tests were conducted by sowing seeds of *Cercis canadensis* L. and *Cercis siliquastrum* "Alba" in multi-cell trays (60×40 cm, cell size 4.5×4.5×7.0 cm). Seeds of *Cercis canadensis* L. "F" and *Cercis siliquastrum* "Alba" were collected from trees growing in the O.O. Fomin Botanical Garden and from a plant located on V. Petriv Str. (*Cercis canadensis* L. "K"). The seeds subsequently underwent cold stratification at +4°C for four months. Pre-sowing treatment included scarification of the seed coat using hot water: seeds were soaked in boiling water (t = 100°C) and left to cool for 24 hours. Afterward, the seeds were soaked in solutions of the tested preparations at varying concentrations (according to the experimental design) for 24 hours. The tested substances included "Megafol", "Radifarm", "Alga 600", and succinic acid. The seeds were then sown in individual cells of the trays at a depth of 1-1.5 cm, with one seed per cell. Lowland peat was used as the substrate. The trays were placed in a greenhouse. The study was conducted between 2022 and 2024. Irrigation was performed as needed based on substrate dryness, supplemented by automated watering three times daily (5-minute intervals at 8:00, 12:00, and 16:00) via fine mist nozzles (flow rate: 2 L/h). Germination rates were assessed 30 days after sowing. Seedling height was measured on day 40 and after growth completion (five months post-sowing).

Laboratory germination capacity of the seeds was determined in accordance with the International Rules for Seed Testing 2025 by the International Seed Testing Association (ISTA) at the State Enterprise "State Centre of Agricultural Products Certification and Examination". Seeds from different harvest years (2021 and 2023) and subjected to different stratification methods were used for the experiment. The 2021 seeds were stored under controlled cold conditions, whereas the 2023 seeds were collected directly from trees immediately before sowing, thus undergoing natural stratification. Due to the absence of the studied genus and species in the aforementioned Rules, it was decided to conduct the research using the methodology for determining the sowing qualities of *Robinia pseudoacacia* L. seeds, as this species requires similar pre-sowing preparation procedures and has a hard seed coat. According to the methodology, the seeds were germinated on filter paper under alternating temperatures: 20°C for 16 hours and 30°C for 8 hours. Seed evaluation was recommended to be conducted first on day 7 (germination energy) and finally on day 14 (germination capacity). To determine the influence of the germination method on laboratory germination capacity, seeds were placed for germination between layers of filter paper. Seeds used for germination included those from the 2021 harvest, which had undergone cold stratification (for 4 months at +4°C) in 2021-2022 and were subsequently stored at room temperature, as well as seeds from the 2023 harvest, collected directly from trees immediately before the experiment (March 2024) and not subjected to artificial stratification. Germination was carried out in a laboratory incubator with cooling (ST700 BASIC, manufactured by PolEko Aparatura, Poland) under a variable temperature regime in accordance with the methodology, as well as under a variable photoperiod – 8 hours with light and 16 hours without light. Seed evaluation was conducted following the methodology; however, the final evaluation period was extended to day 30 due to low germination energy. The study was conducted in compliance with the Convention on Biological Diversity (1992).

Results and Discussion

Seed germination capacity was evaluated on day 30, and morphometric measurements were taken on day 40 after sowing. The summarised data on germination capacity are presented in Table 1.

Table 1. *Efficacy of the influence of tested preparation concentrations on the germination rate of the studied plant species*

Preparation	Concentration, ml/l	Germination rate, %		
		C. canadensis **L. (O.O. Fomin Botanical Garden)**	***C. canadensis*** **L. (V. Petriv Str.)**	***C. siliquastrum*** **"Alba"**
Radifarm	2.5	60.0 ± 3.4	66.7 ± 2.8	80.0 ± 4.7
	5.0	56.7 ± 2.8	46.7 ± 3.6	66.7 ± 2.9
	10.0	36.7 ± 5.1	50 ± 4.3	63.3 ± 3.2
Megafol	2.5	63.3 ± 3.2	60 ± 3.7	56.7 ± 4.1
	5.0	70 ± 4.1	76.7 ± 4.6	70.0 ± 5.3
	10.0	56.7 ± 5.3	50 ± 5.2	56.7 ± 5.1
Alga 600 (g/l)	1.25	70 ± 3.6	50.0 ± 4.2	60.0 ± 2.9
	2.5	56.7 ± 3.1	56.7 ± 3.5	56.7 ± 3.8
	5.0	36.7 ± 3.8	46.7 ± 2.9	46.7 ± 3.4

Table 1. *Continued*

Preparation	Concentration, ml/l	Germination rate, %		
		C. canadensis **L. (O.O. Fomin Botanical Garden)**	***C. canadensis*** **L. (V. Petriv Str.)**	***C. siliquastrum*** **"Alba"**
Succinic acid	0.5	66.7 ± 3.2	73.3 ± 3.6	80.0 ± 4.0
	1	73.3 ± 3.3	73.3 ± 4.3	83.3 ± 3.3
	2	66.7 ± 3.1	63.3 ± 3.6	63.3 ± 4.1
Control		70.0 ± 7.6	80.0 ± 6.8	93.3 ± 2.3

Source: developed by the authors

The data presented in Table 1 demonstrate that the seed germination rate of the studied plant species varies depending on both the concentrations of the tested substances and the species. Specifically, the seeds of *Cercis siliquastrum* "Alba" exhibited a higher germination rate compared to those of *Cercis canadensis* L., which were collected from two different locations in Kyiv. It was hypothesised that this difference in germination rate may reflect a species-specific trait of *C. siliquastrum* "Alba". Statistical analysis confirmed that the preparation concentrations had a statistically significant effect on the seed germination rate of the studied species. The results of the data analysis are presented in Table 2.

Table 2. *One-way ANOVA*

Source of variation	SS	df	MS	F	P-value	F crit
Between groups	4400.824	12	366.7353	6.16992	0.0000534	2.147926

Note: *df* – number of degrees of freedom; *MS* – variances; *F* – calculated value of the Fischer criterion; *P-value* – calculated value of the minimum substantiality; *Fcrit* – critical value of the Fischer criterion
Source: developed by the authors

"Radifarm" showed the greatest efficacy at a concentration of 2.5 ml/l, whereas "Megafol" was most effective at 5.0 ml/l. Succinic acid demonstrated optimal influence at the manufacturer-recommended concentration of 1 g/l (Figs. 1, 2).

The data obtained during the study revealed that the germination rate of *C. canadensis* L. seeds ranged from 36.7% (treated with "Radifarm" and "Alga 600" at a concentration of 5.0 g/L) to 73.3% (succinic acid at 1 g/L). The least variability in germination results (66.7-73.3%) was observed with the "Succinic Acid" preparation. The germination variability of *Cercis canadensis* L. seeds collected from plants growing on V. Petriv Street ranged from 46.7% ("Radifarm" and "Alga 600" at concentrations of 2.5 g/L and 5.0 g/L, respectively) to 80% (Control). The smallest fluctuation in seed germination between preparation concentrations was noted for "Succinic Acid" (63.3-73.3%) and "Alga 600" (46.7-56.7%).

It was established that succinic acid at a concentration of 1 g/L is optimal for enhancing the germination of *Cercis* L. seeds. However, it should be noted that a high germination rate (80%) was observed in *C. siliquastrum* "Alba" seeds treated with "Radifarm" at 2.5 ml/l. At the same time, high germination rates in *C. canadensis* L. were achieved with "Megafol" at 5.0 ml/l and "Alga 600" at 1.25 g/L. The control sample of *Cercis siliquastrum* "Alba" seeds exhibited a germination rate of 93.3%, the highest recorded.

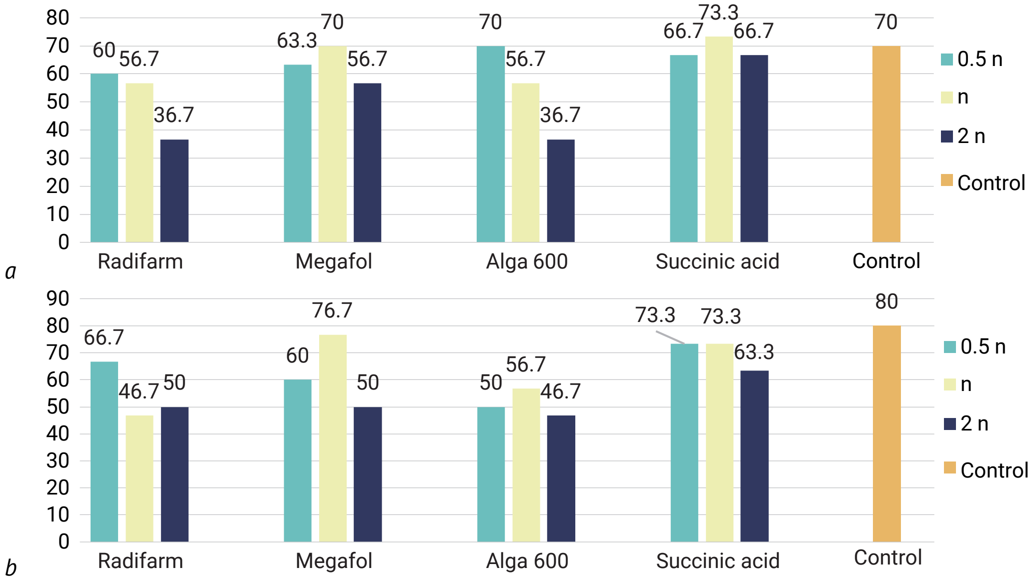

Figure 1. *Efficacy of organo-mineral biostimulant concentrations on the generative propagation of Cercis canadensis L.*

Note: a – seeds from a tree growing in the O.O. Fomin Botanical Garden ("F"); b – seeds from a tree growing in Kyiv, V. Petriv Str. ("K"); n = manufacturer-recommended concentration

Source: developed by the authors

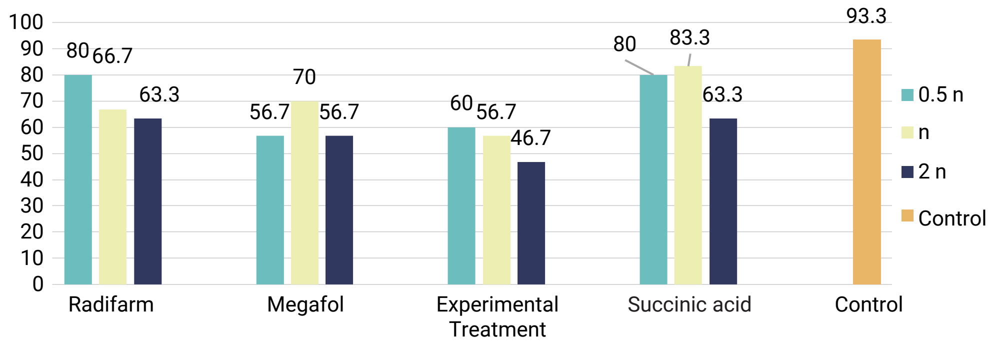

Figure 2. *Effect of tested preparation concentrations on the field germination of C. siliquastrum "Alba"*

Note: n = manufacturer-recommended concentration

Source: developed by the authors

The most common practice for using growth regulators involves vegetative propagation using plant cuttings. However, as asserted by J.D. Bewley & M. Black (1985), these substances can also be employed to break seed dormancy. The researchers provide a list of compounds capable of mitigating or eliminating such issues, including respiratory inhibitors, oxidisers, nitrates, nitrites, and phytohormones themselves. Gibberellins promote the induction of cell wall hydrolases, thereby weakening and damaging the endosperm. Abscisic acid (ABA), acting as an antagonist to gibberellic acid, inhibits the induction of cell wall hydrolases, reducing endosperm weakening and damage. As stated by K. Müller *et al.* (2006), gibberellic acid enhances, while abscisic acid suppresses, embryonic growth potential. The work of H. Fernandez *et al*. (1997) demonstrates significant variations in gibberellins during dormancy release in beech (*Fagus sylvatica* L.) seeds and the capacity of non-dormant seeds to undergo metabolic transformations.

Although the germination percentage of control samples was equal to or slightly higher than that of seeds subjected to pre-sowing treatment, qualitative indicators such as seedling height were significantly lower in the control group (Table 3).

Table 3. *Morphometric parameters of Cercis L. (x ± SDev, n = 30)*

Preparation	Concentration, ml/l (g/l)	Seedling height, cm					
		16.05.2022			16.10.2022		
		C. canadensis L. "F"	*C. canadensis* L. "K"	*C. siliquastrum* "Alba"	*C. canadensis* L. "F"	*C. canadensis* L. "K"	*C. siliquastrum* "Alba"
Radifarm	2.5	4.6 ± 1.8	6.2 ± 1.2	2.6 ± 0.3	11.5 ± 3.9	9.2 ± 3.5	7.5 ± 2.9
	5.0	4.7 ± 1.8	5.9 ± 1.0	2.5 ± 0.5	12.5 ± 4.3	10.0 ± 3.2	5.9 ± 2.7
	10.0	5.8 ± 1.4	5.7 ± 1.5	2.3 ± 0.3	10.8 ± 4.7	9.6 ± 3.7	4.8±1.2
Megafol	2.5	4.6 ± 1.9	6.2 ± 1.2	2.3 ± 0.3	8.1 ± 1.5	13.6 ± 3.1	8.0 ± 1.6
	5.0	4.7 ± 1.8	5.9 ± 1.0	2.5 ± 0.5	7.8 ± 2.3	9.5 ± 2.9	7.3 ± 1.7
	10.0	5.8 ± 1.4	5.7 ± 1.5	2.3 ± 0.3	8.3 ± 1.7	10.2 ± 3.4	6.0 ± 1.9
Alga 600	1.25	4.3 ± 1.4	4.8 ± 1.7	2.8 ± 0.6	9.9 ± 3.2	11.4 ± 2.2	9.3 ± 3.3
	2.5	4.3 ± 1.4	5.7 ± 1.4	2.6 ± 0.6	10.0 ± 2.6	12.5 ± 3.1	8.1±2.7
	5.0	4.6 ± 1.7	5.8 ± 1.1	3.0 ± 0.7	10.6 ± 2.9	11.1 ± 3.9	8.8 ± 2.5
Succinic acid	0.5	4.1 ± 1.8	5.1 ± 1.7	2.5±0.4	12.6±3.7	12.0±3.3	9.8±2.9
	1.0	4.2±1.8	5.0±1.8	2.5±0.4	12.5±4.0	10.8±3.1	9.4±2.7
	2.0	4.1±1.5	5.6±2.3	2.7±0.5	10.5±3.8	13.4±2.8	9.3±3.3
Control		4.2±1.3	4.9±1.4	2.1±0.5	8.1±2.4	8.3±1.7	4.5±2.0

Source: developed by the authors

Seedling height of the studied species on the 40th day after sowing ranged from 2.1 cm (control sample of *Cercis siliquastrum* "Alba") to 6.2 cm (*Cercis canadensis* L. "K" treated with "Radifarm" at 2.5 ml/l). Seedling height measurements were conducted after growth cessation, five months after the initial assessment. At the end of the growth period, seedling height varied between 4.5 cm (control, *Cercis siliquastrum* "Alba") and 13.4 cm (*Cercis canadensis* L. "K" treated with succinic acid at 2 g/L). The growth increment data are presented in Table 4.

Table 4. *Dynamics of changes in the mean shoot increment of seedlings from the genus Cercis L.*

Preparation	Concentration, ml/l (g/l)	Seedling increments					
		Absolute (Δh), cm			Relative, %		
		C. canadensis L. "F"	*C. canadensis* L. "K"	*C. siliquastrum* "Alba"	*C. canadensis* L. "F"	*C. canadensis* L. "K"	*C. siliquastrum* "Alba"
Radifarm	2.5	6.9	3	4.9	150	48	188
	5.0	7.8	4.1	3.4	166	69	136

***Table 4.** Continued*

Preparation	Concentration, ml/l (g/l)	Seedling increments					
		Absolute (Δh), cm			Relative, %		
		C. canadensis L. "F"	*C. canadensis* L. "K"	*C. siliquastrum* "Alba"	*C. canadensis* L. "F"	*C. canadensis* L. "K"	*C. siliquastrum* "Alba"
Radifarm	10.0	5.0	3.9	2.5	86	68	109
Megafol	2.5	3.5	7.4	5.7	76	119	248
	5.0	3.1	3.6	4.8	66	61	192
	10.0	2.5	4.5	3.7	43	79	161
Alga 600	1.25	5.6	6.6	6.5	130	138	232
	2.5	5.7	6.8	5.5	133	119	212
	5.0	6.0	5.3	5.8	130	91	193
Succinic acid	0.5	8.5	6.2	7.3	207	122	292
	1.0	8.3	5.8	6.9	198	116	276
	2.0	6.4	7.8	6.6	156	139	244
Control		3.9	3.4	2.4	93	69	114

Source: developed by the authors

The data presented in Table 4 allow for a comparison of changes in seedling height between the initial measurement and the end of the growth period. Over five months, seedling increments ranged from 2.4 cm (control sample, *Cercis siliquastrum* "Alba") to 8.5 cm (succinic acid, 0.5 g/L, *Cercis canadensis* L. "F"). However, given that seedlings had varying initial heights, those with identical absolute increments may exhibit differing relative values. Calculating the relative increment provides insight into the change in seedling height relative to their initial value. Figure 6 illustrates the dynamics of seedling height. The best-performing seedlings were those of *Cercis siliquastrum* "Alba", with the smallest height increase observed in samples treated with "Radifarm" at 10 ml/l (109%), and the largest in those treated with succinic acid at 0.5 g/L (292%). The relative height change in the control sample was 114%, representing the second-lowest increment for this cultivar (Fig. 3).

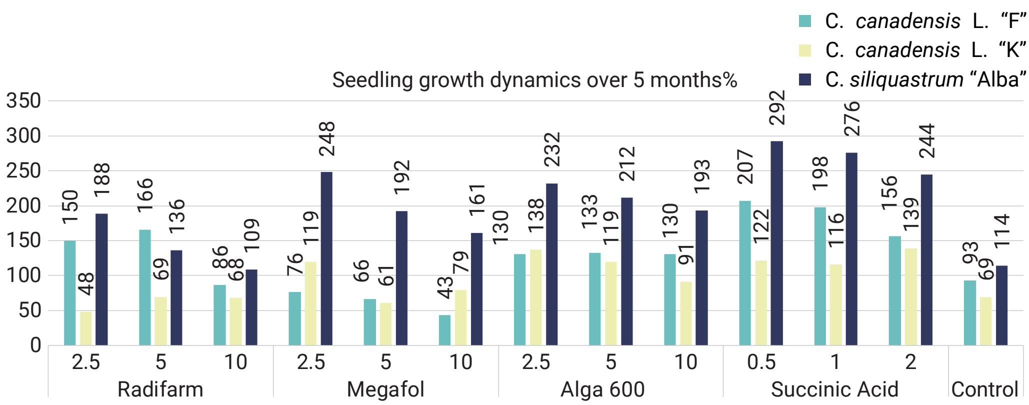

***Figure 3.** The effect of tested preparation concentrations on the dynamics of height changes in seedlings of the studied plant taxa*

Source: developed by the authors

Among *Cercis canadensis* L. "F" seedlings, the variability in height change ranged from 43% (for the preparation "Megafol" at a concentration of 10 ml/l) to 207% (for succinic acid at a concentration of 0.5 g/L). The dynamics of height increment in *Cercis canadensis* L. "K" seedlings varied from 48% (for "Radifarm", 2.5 ml/l) to 139% (for succinic acid, 2 g/L). In summary, it can be concluded that both the preparations and their concentrations significantly influence growth and development.

During the experiments, it was established that regular irrigation adversely affects the growth and development of seedlings of the studied genus. In particular, triple irrigation with fine-dispersed nozzles, with each irrigation lasting 5 minutes and a water flow rate of 2 l/h, leads to waterlogging of the root system and suppression of seedling development, eventually resulting in their complete mortality (Fig. 4).

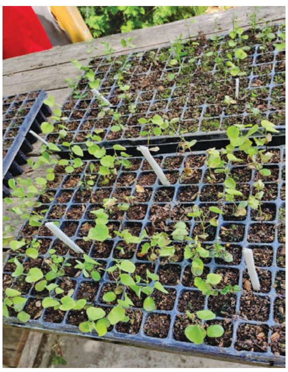

Figure 4. *The process of root system waterlogging and seedling mortality*
Source: authors' photo

During the experiment, a decision was made to extend the seed evaluation period from 14 to 30 days. This was justified, firstly, by the absence of the studied genus in the ISTA methodology; therefore, it was decided to conduct the research in accordance with the germination testing method for *Robinia pseudoacacia* L. Secondly, the germination rate on the 14th day exhibited high variability: from 4% for *Cercis siliquastrum* "Alba" (2023 harvest) to 94% for *Cercis canadensis* L. (2021 harvest). Seed germination was also influenced by the sprouting method, as seeds germinated according to the filter paper method (fP) demonstrated higher germination rates compared to those germinated between filter paper layers (bF). Germination rates ranged from 68% (bF) to 94% (fP) for *Cercis canadensis* L. and from 26% (bF) to 76% (fP) for *Cercis siliquastrum* "Alba". Additionally, during seed germination, the release of secondary metabolites on the filter paper was observed (Fig. 5). The results of laboratory germination are presented in Table 5.

Figure 5. *Isolation of secondary metabolites from C. canadensis L. (2023)*
Source: authors' photo

Table 5. *The effect of pre-sowing treatment and germination methods on the germination capacity of Cercis L.*

Harvest year (germination method)	Species, cultivar	Germination energy (7 days), %	Germination capacity (14 days), %	Germination capacity (30 days), %
2021 (on paper)	*C. canadensis* L. "F"	66 ± 6.2	94 ± 3.1	94 ± 3.1
	C. *canadensis* L. "K"	42 ± 5.5	68 ± 4.2	74 ± 4.5
	C. *siliquastrum* "Alba"	0	12 ± 2.5	76 ± 3.6
2023 (on paper)	C. *canadensis* L. "K"	0	8 ± 2.9	20 ± 3.4
	C. *siliquastrum* "Alba"	0	4 ± 1.8	24 ± 4.1

Table 5. *Continued*

Harvest year (germination method)	Species, cultivar	Germination energy (7 days), %	Germination capacity (14 days), %	Germination capacity (30 days), %
2021 (between paper layers)	*C. canadensis* L. "F"	20 ± 2.4	58 ± 3.8	72 ± 3.3
	C. *canadensis* L. "K"	8 ± 2.1	42 ± 3.3	68 ± 3.8
	C. *siliquastrum* "Alba"	0	6 ± 2.2	26 ± 2.5

Source: developed by the authors

The conducted experiment established that seed germination efficiency is significantly influenced by pre-sowing treatment, specifically cold stratification. The effect of cold stratification duration was investigated by Greek researchers E. Pipinis *et al.* (2011). Their study aimed to determine how the germination rate of *Cercis siliquastrum* L. seeds varied under different exposure times to sulfuric acid scarification and cold stratification periods. The experimental design was as follows: seeds were treated with concentrated sulfuric acid (95-97%) for 20, 40, and 60 minutes. After scarification, the seeds underwent cold stratification at 2-4°C in moist river sand for 1, 2, 3, and 4 months. The results demonstrated that seeds subjected to neither scarification nor stratification failed to germinate. The highest germination rates (88-98%) were observed in seeds scarified for 20-60 minutes and cold-stratified for 3 months. As noted by E. Pipinis *et al.* (2011), seed germination increased to 95-97% under cold stratification conditions. Their experiments showed that germination rates rose from 31% (1-month stratification) to 94% (3-month stratification). However, extending the stratification period beyond 3 months led to a decline in germination efficiency, dropping to 81% after 4 months (Table 6).

Table 6. *Basic physical and chemical parameters of raw materials (n = 4)*

H_2SO_4 scarification (min)	Stratification (2-4°C) (months)	Germination, %
20	2	31.0 ± 5.03
	3	94.0 ± 5.16
	4	81.0 ± 6.0
40	2	38.0 ± 4.0
	3	88.0 ± 5.66
	4	68.0 ± 5.66
60	2	65.0 ± 6.0
	3	98.0 ± 2.31
	4	59.0 ± 5.03

Source: developed by the authors based on E. Pipinis *et al*. (2011)

Research on the generative propagation of plants from the genus *Cercis* L. has been conducted by a number of foreign scientists. The influence of various groups of phytohormones on the germination of *Cercis siliquastrum* L. seeds was studied by M. Grbić *et al.* (2014), a group of researchers from Serbia. The essence of their research lay in examining the effect of gibberellic acid in combination with cold stratification of seeds, as well as the ability of gibberellic acid to break seed dormancy and enhance overall germination rates.

As a result of their studies, P. Profumo *et al.* (1979) and O. Babyn *et al.* (2024) asserted that gibberellic acid has a significant impact on the germination of *Cercis siliquastrum* L. seeds.

However, they did not recommend simultaneously combining gibberellic acid treatment with cold stratification, explaining that gibberellic acid at 4°C does not exhibit its physiologically active properties. The findings of E. Pipinis *et al.* (2011) align with the data of J.L. Frett & M.A. Dirr (1979). According to the latter, unscarified seeds did not absorb moisture or germinate due to the presence of a hard seed coat (Orozco-Almanza *et al.*, 2003). The restrictive effect of a hard seed coat on germination has also been studied in several species of the Leguminosae family (Demel, 1996).

Additionally, scarified but non-stratified seeds also failed to germinate, indicating the presence of endogenous dormancy in the seeds. As noted by R. Martinuzzi *et al.* (1985), endogenous seed dormancy may be linked to the presence of ferulic acid in the endosperm, which limits oxygen availability to the embryo. G.H. Gebre & N.S. Karam (2004) recommended an optimal cold stratification period of 16 weeks for mechanically scarified seeds. According to the study by E. Pipinis *et al.* (2011), the duration of cold stratification could be reduced to three months if preceded by acid scarification. The authors suggested that this reduction might be due to differences in seed scarification methods, as also mentioned by L.S. Rosner *et al.* (2003), or to variations in the degree of endogenous dormancy in seeds of the same species under different habitat conditions (Anderson & Milberg, 1998). It is also worth noting that J.L. Tipton (1992) observed in their research that seeds of *Cercis canadensis* var. mexicana also failed to germinate without scarification and cold stratification.

M. Zencirkıran *et al.* (2010) reported a positive effect of three different seed scarification methods: mechanical, acid immersion, or hot water treatment. In their study, the authors used seed soaking in concentrated H_2SO_4 for 30 minutes, followed by cold stratification for 8 weeks at 1-5°C. Under these conditions, they achieved approximately 85% seed germination. As noted by N.Y. Liu *et al.* (1981), acid treatment of seeds yields slightly better and more stable results.

Among domestic researchers, L.A. Koldar (2003) also studied seed propagation of plants from the genus *Cercis* L. In her work, she described the influence of seedling pricking-out timing on morphometric parameters and the survival rate of *Cercis* L. seedlings. The author noted that seeds of the studied genus exhibit "hard-seededness", which negatively affects germination vigour. For this reason, she conducted pricking-out in three stages: 05.06, 15.06, and 25.06.2003. Her research data indicate a direct correlation between pricking-out timing and seedling morphometric parameters, such as seedling height, stem thickness at the root collar, and crown diameter.

Thus, the research results demonstrate that the germination efficiency of *Cercis* L. seeds depends not only on the degree of physical and physiological embryo dormancy but also on germination conditions and pre-sowing seed treatment. By ensuring optimal germination conditions and pre-sowing preparation, high-quality planting material of Cercis L. plants obtained through generative propagation can be achieved.

Conclusions

Based on the research results, a positive effect of cold stratification for 4 months at +4°C, followed by seed scarification with boiling water ($t = 100$°C), has been established. Seeds subjected to artificial stratification under the above scheme maintained high laboratory germination rates (70-90%) compared to seeds undergoing natural stratification (20-30%).

Experimental studies confirmed that the tested growth stimulants influence seed germination and subsequent seedling development compared to the control sample. The optimal concentrations of growth stimulants were as follows: "Radifarm" – 2.5 ml/l; "Megafol" – 5.0 ml/l; "Succinic acid" – 1 g/L; Alga 600 – 1.25 g/L. Notably, the control sample exhibited higher germination rates, but the subsequent morphometric parameters of seedlings treated with growth stimulants were superior to those of the control. It was observed that "Succinic Acid" at all tested concentrations and Megafol at 2.5 ml/l had the best effect on the morphometric parameters of *Cercis siliquastrum* "Alba" seedlings. Seedlings increased in height by 2.44 to 2.92 times compared to initial measurements. "Radifarm" at 5.0 ml/l and "Succinic Acid" at 0.5 g/L positively influenced the development of *Cercis canadensis* L. "F" seedlings.

It was established that substrate waterlogging negatively affects the development of *Cercis* L. plants. With triple watering (2 L/h for 5 min), seedling root systems became waterlogged, leading to complete loss of planting material. During laboratory germination tests, it was found that germination efficiency depends on the seed germination method. Higher germination rates were achieved when germinating *Cercis* L. seeds on filter paper, following the methodology for determining *Robinia pseudoacacia* L. germination. Further research will focus on studying the influence of biochemical processes and growth stimulants on morphometric parameters and the growth intensity of planting material.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

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Особливості генеративного розмноження рослин роду *Cercis* L.

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Анотація. Проблема складного пророщування насіння *Cercis* L., зумовлена його фізіологічним і фізичним станом спокою, потребує удосконалення методів генеративного розмноження з використанням стимуляторів росту. В даній статті розглядався вплив органо-мінеральних стимуляторів росту на ефективність проростання насіння дослідних видів, а також подальший вплив на морфометричні показники сіянців. Ґрунтова схожість визначалась шляхом прямого підрахунку схожого насіння, а лабораторна схожість визначалась згідно методики визначення посівних якостей насіння International Seed Testing Association (ISTA). Статистична обробка даних проводилась за допомогою MS Excel (однофакторний дисперсійний аналіз ANOVA та Standard Deviation) У результаті проведених досліджень виявлено статистично значущий вплив апробованих препаратів на ефективність проростання насіння. Встановлено, що найкращий вплив на схожість насіння *Cercis siliquastrum* 'Alba' має «Бурштинова кислота» в концентрації 1 г/л. Позитивний вплив на проростання насіння *Cercis canadensis* L. мали препарати «Megafol» в концентрації 5,0 мл/л (схожість варіювалась в межах 70-77 %), а також «Альга 600» в концентрації 1,25 г/л (схожість варіювалась в межах 50-70 %). Окрім цього дослідним шляхом встановлено, що сіянці, насіння яких було оброблено стимуляторами росту мали вищі показники приростів, ніж контрольний зразок. При обробці насіння препаратом «Бурштинова кислота» сіянці *Cercis siliquastrum* 'Alba' збільшились в 2,5-2,9 рази. Динаміка приростів сіянців *Cercis canadensis* L., насіння яких оброблене препаратом «Бурштинова кислота» збільшились майже вдвічі. Вплив препарату «Radifarm» в концентрації 5,0 мл/л на динаміку сіянців *Cercis canadensis* L. проявився у збільшенні висоти в майже в 1,6 рази

Ключові слова: насіннєве розмноження; іудине дерево; сіянці; стимулятори росту; схожість

Received 03.12.2024 Revised 11.03.2025 Accepted 25.04.2025

Vol. 21, No. 2
2025

Scientific Reports of the National University
of Life and Environmental Sciences of Ukraine

Journal homepage: https://scireports.com.ua/en

UDC 633.174:631.5

DOI: 10.31548/dopovidi/2.2025.148

Photosynthetic productivity of grain sorghum hybrids depending on different forms and doses of fertilisers

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Abstract. The research relevance of the photosynthetic productivity of sorghum hybrids is determined by the need to optimise fertilisation to increase yields in the forest steppe of Ukraine. The study aimed to investigate the effect of complex granular mineral fertilisers on grain yield formation, specifically the photosynthetic productivity of grain sorghum plants. The research was conducted in 2021, 2023-2024 in the experimental field of the State Biotechnological University. The experiment was conducted using the method of systematic repetitions with three times repeatability to ensure the reliability and validity of the results. Sowing was conducted at a ten-centimetre soil layer temperature of 10-12°C with a sowing rate of 200 thousand seeds/ha using a wide-row method with a row spacing of 45 cm. Leaf surface area and net photosynthetic productivity were determined by the method of A.A. Nichiporovich. The study determined that the maximum possible leaf area per plant and hectare of sowing is formed by plants of the Aggil hybrid under the variant of fertiliser application Dura SOP at a dose of 80 kg/ha and Renovation Fuerza at doses of 80 and 100 kg, and plants of the Brigga hybrid under the variant of fertiliser application Renovation Fuerza at both doses. The photosynthetic productivity of both hybrids increased under the variant of application of all forms and doses of fertilisers compared to the absolute control. The net photosynthetic productivity was the highest in both studied hybrids under the variant of application of Renovation Fuerza mineral fertiliser in doses of 80 and 100 kg/ha. A linear correlation was established, and the regression equation between leaf area and net photosynthetic productivity for both studied hybrids is as follows: $y = 0.0479x - 0.098$ ($R^2 = 0.88$). The results can be used to optimise the mineral fertilisation of sorghum hybrids to increase yields and reduce costs in the forest-steppe of Ukraine

Keywords: grain sorghum; mineral fertilisers; leaf surface area; photosynthetic potential; net photosynthetic productivity

Suggested Citation:
Mohylevska, V. (2025). Photosynthetic productivity of grain sorghum hybrids depending on different forms and doses of fertilisers. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine*, 21(2), 148-158. doi: 10.31548/dopovidi/2.2025.148.

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Introduction

In the context of climate change and water shortages, the cultivation of drought-resistant crops, including grain sorghum, is becoming increasingly important. Due to its high adaptability to arid conditions, heat tolerance and stable yield, this crop is promising for expanding its cultivation in the central and southern regions of Ukraine. At the same time, the level of its productivity largely depends on photosynthetic activity, which is determined by both the hereditary characteristics of hybrids and mineral nutrition. Optimisation of the use of mineral fertilisers can activate photosynthesis, improve morphophysiological processes and increase dry matter accumulation. However, there is a lack of data in the scientific literature on the effect of different forms and doses of fertilisers on the photosynthetic productivity of grain sorghum hybrids under specific agroecological conditions. This necessitates in-depth research to improve the technology of crop cultivation.

Ya.V. Alekseev (2020) believe that hydrothermal changes in plant growing conditions in Ukraine require different approaches to the technology of growing major cereals, including sorghum. According to S.Yu. Davydenko & A.O. Rozhkov (2022), the main global areas of this crop are in India, Africa and the United States of America, which account for more than 70% of the world's sorghum acreage. The study argued that sorghum is one of the oldest crops in world agriculture, which is the undisputed leader among cereals grown in conditions of prolonged droughts and high temperatures. The wide range of its use for food, feed and technical purposes and its unpretentiousness to growing conditions make it important to research and improve the elements of its cultivation technology, namely the application of complex mineral fertilisers, which is one of the most urgent tasks that will contribute to the formation of high photosynthetic productivity of grain sorghum.

According to K.B. Abreha *et al.* (2022), in dry conditions, sorghum plants, due to morphological characteristics, consume moisture economically and form a significant leaf surface area with a specific type of photosynthesis. R.E. Grishchenko *et al.* (2020) studied photosynthetic productivity under variants of mineral fertiliser application and concluded that even under stressful conditions of vegetation periods, photosynthetic productivity increases with fertiliser application.

M. Stefanov *et al.* (2023) studied photosynthesis as a vital process under different drought conditions and concluded that the photosynthetic apparatus of sorghum plants should increase the area of the assimilative leaf surface as quickly as possible to provide plants with photosynthetic products. The study noted that the rapid deployment of the leaf apparatus can compensate for the effects of short-term stress and maintain yields. O.S. Titarenko & L.M. Karpuk (2022) believed that one of the factors of grain sorghum cultivation technology is the creation of optimal mineral nutrition for plants to form the leaf surface area. According to the observations, the use of fertilisers in balanced doses stimulates the development of a photosynthetically active surface, which increases the absorption of solar energy by plants.

W. Sun *et al.* (2024) studied the effect of irrigation water in arid conditions in China and proved that the leaf surface area varies greatly under different conditions of moisture supply, temperature, mineral nutrition and agronomic cultivation methods. R. Zhang *et al.* (2023) proved that the photosynthetic activity of plants is a rather mobile indicator. The rapid development and achievement of optimal leaf surface area increases photosynthetic productivity and keeps the leaves in the active layer for a longer period, which contributes to better use of photosynthetic productivity to accumulate as much organic matter as possible, which is the main component of the plant yield. T. Jayanti *et al.* (2021) proved that in different countries of the world, mineral fertilisers affect plant nutrition and fertiliser application increases plant growth and development and leads to an increase in photosynthesis of sorghum crops. The study noted that the use of balanced mineral complexes significantly improves photosynthetic activity and contributes to an increase in sorghum biomass and yield under different soil and climatic conditions.

Despite the availability of thorough research, the issue of the complex effect of forms and doses of mineral fertilisers on the photosynthetic productivity of grain sorghum hybrids under specific agricultural and ecological conditions of the Eastern Forest-Steppe of Ukraine remains insufficiently studied. This necessitates targeted research, the results of which can improve the elements of the technology for growing the crop.

The study aimed to determine the effect of forms and doses of mineral fertilisers on the yield and photosynthetic productivity of grain sorghum hybrids in the Eastern Forest-Steppe of Ukraine.

Materials and Methods

Field trials were conducted in 2021, 2023-2024 at the experimental field of the State Biotechnological University. The two-factor field experiment had the following scheme: *factor A* grain sorghum hybrids Aggil and Brigga F_1; *factor B* forms and doses of fertilisers Absolute control, zonal control (Nitroammophoska 100 kg/ha, NPK ratio 16:16:16), Dura SOP 80 kg/ha, Dura SOP 100 kg/ha (NPK ratio 10:10:17), Renovation Fuerza 80 kg/ha, Renovation Fuerza 100 kg/ha (NPK ratio 8:14:6). The experiment was set up using the method of systematic replication, with a constant seeding rate of 200 thousand seeds/ha, using a wide-row sowing method with a row spacing of 45 cm. Sowing was carried out when the ten-centimetre soil layer was warmed up to a temperature of 10-12 °C.

Leaf surface area and net photosynthetic productivity were determined by the method of A.A. Nichiporovich. The object of the research was an early ripe grain sorghum hybrid Brigga and a medium early hybrid Aggil of French selection and complex granular mineral fertilisers Dura SOP and Renovation Fuerza (Spain). Soils of the experimental field are typical chornozem, characterised by a deep humus profile reaching 120 cm, containing 5.0-6.0% humus, good physical properties, high content of mobile forms of NPK and generally high biological activity. The total depth of the humus profile of the regraded chornozem reaches 90-110 cm, with a humus content of 4.7-5.0%. The type of typical chornozem is a poorly washed, low-humus, heavy loamy soil on carbonate loess and is characterised by the following agrochemical parameters: pH of the salt extract 6.5-7.0; total humus content in the topsoil 5.0%; P_2O_5 102 mg per 1 kg of soil; K_2O 179 mg per 1 kg of soil (according to Chirikov).

The weather conditions during the study years were favourable in 2021 and 2023, and in 2024 there was an excess of air temperature and a prolonged period of drought compared to long-term averages. The research was conducted following the Convention on Biological Diversity (1992).

Results and Discussion

The studies conducted in the Eastern Forest-Steppe of Ukraine demonstrated that the leaf surface area was significantly influenced by the form and dose of fertiliser (Table 1). The introduction of all forms and doses of fertilisers ensured the formation of a larger photosynthetically active leaf area for a much longer period. The highest leaf surface area starting from the phenological phase of tillering was formed by both hybrids under the variants of Dura SOP and Renovation Fuerza application in doses of 80 and 100 kg/ha. In this phase, the highest leaf area was formed by the Brigga hybrid under the Renovation Fuerza application variant at a dose of 100 kg/ha, which provided the highest leaf area per hectare of 91 cm^2 and 16.56 thousand m^2/ha, respectively. In this variant, the leaf area of the Aggil hybrid was formed both on one plant and one hectare of crops, respectively, 88 cm^2 and 16.37 thousand m^2/ha.

Table 1. *Effect of different forms and doses of fertilisers on the leaf area of grain sorghum hybrids (average for 2021, 2023-2024)*

Hybrid	Variant	The area of the sheet metal floor in the phase:							
		bushing		tubing		flowering panicle shedding		maturation	
		per plant, cm^2	per 1 ha of sowing area, thousand m^2/ha	per plant, cm^2	per 1 ha of sown area, thousand m^2/ha	per plant, cm^2	per 1 ha of sowing area, thousand m^2/ha	per plant, cm^2	per 1 ha of sowing area, thousand m^2/ha
Aggil	1*	66	10.36	792	14.67	844	17.38	796	16.40
	2	72	12.89	838	17.85	996	22.11	858	19.05
	3	77	13.78	933	19.71	1024	24.88	964	23.42
	4	82	15.17	990	22.16	1079	26.86	1023	25.47
	5	87	16.01	1066	24.91	1106	28.53	828	21.36
	6	88	16.37	1144	27.87	1289	34.03	1218	32.15
Brigga	1*	72	11.09	780	13.21	809	15.37	732	13.91
	2	77	12.86	828	16.18	886	19.23	804	17.45
	3	80	14.00	897	18.52	934	22.79	863	21.06
	4	84	15.20	963	21.09	1028	25.70	941	23.52
	5	88	16.02	1031	23.45	1099	28.24	998	25.65
	6	91	16.56	1066	24.64	1134	28.69	1049	26.54
LSD 0.5			0.71		1.92		2.84		0.96

Note: 1* – absolute control, 2 – zonal control (Nitroammophoska 100 kg/ha), 3 – DuraSOP 80 kg/ha, 4 – Dura SOP 100 kg/ha, 5 – Renovation Fuerza 80 kg/ha, 6 – Renovation Fuerza 100 kg/ha
Source: compiled by the author

The highest values were recorded during the interphase period of panicle emergence and flowering for all fertiliser application options and doses. The area of one plant of the Aggil hybrid with Renovation Fuerza applied at a dose of 100 kg/ha was 1289 cm^2, and the area per hectare of crops was 34.03 thousand m^2/ha, which was slightly lower than that of the Brigga hybrid by 155 cm^2 and 5.34 thousand m^2/ha, respectively. The largest number of preserved leaves with the application of Renovation Fuerza at a dose of 100 kg/ha on average over three years was preserved in the Aggil hybrid, which provided a total leaf area at this point of 1218 cm^2 per plant and 32.15 thousand m^2/ha per hectare of crops. Lower values for this option were found in the Brigga hybrid, 169 cm^2 and 5.61 thousand m^2/ha, respectively.

The application of all forms and doses of fertilisers contributed to the formation of a larger leaf area per plant and per hectare of crops in both hybrids compared to the absolute control. In the Aggil hybrid, starting from the tillering phase, with the application of Dura SOP and Renovation Fuerza at doses of 80 and 100 kg/ha, the leaf area of one plant increased by 11, 16, 21 and 22 cm^2, respectively; in the stem elongation phase, the excesses were 141, 198, 274 and 352 cm^2, and in the interphase of panicle emergence, 180; 235; 262 and 445 cm^2; the increases were slightly lower in the ripening phase, 168; 227; 32 and 422 cm^2. Accordingly, the leaf area per hectare of crops increased in the variants. Compared to the zonal control variant (Nitroammophoska 100 kg/ha), the increase in leaf area per plant and per hectare of crops was lower compared to the absolute control variant. The Brigga hybrid retained the patterns of growth in leaf area per plant and per hectare of crops. The excesses were significantly lower compared to the absolute and zonal controls than in the grain sorghum hybrid Aggil. The application of Dura SOP and Renovation Fuerza at doses of 80 and 100 kg/ha resulted in an increase in the tillering phase compared to the absolute control by 8, 12, 16 and 19 cm^2; in the tube stage by 117, 183, 251 and 286 cm^2; in the interphase of panicle ejection by 125, 219, 290 and 325 cm^2; and in the maturity stage by 131, 209, 266 and 317 cm^2. The best development of leaf surface area in both hybrids was observed in the variant of Renovation Fuerza 100 kg/ha and amounted to 32.15 thousand m^2/ha in the phenological phase of ripening in the Aggil hybrid and 26.54 thousand m^2/ha in the Brigga hybrid, respectively.

Indicators of net photosynthetic productivity reflect the photosynthetic potential of crops, the average data are provided in Table 2. The highest net productivity of photosynthesis of the assimilation apparatus of the grain sorghum hybrid was in the Renovation Fuerza variant application at a dose of 100 kg/ha 4.67 g/m^2. In the variant of this fertiliser application, but in a lower dose, a tendency to decrease the net productivity of photosynthesis was noted, but mathematically the advantages of their application in a higher dose of 100 kg/ha compared to the dose of this fertiliser 80 kg/ha were not proved.

Table 2. *Indicators of photosynthetic productivity of grain sorghum hybrids depending on the forms and doses of mineral fertilisers (average for 2021, 2023-2024)*

Hybrid	Variant	Photosynthetic potential, (thousand m^2/ha)×day	Pure performance of photosynthesis, g/m^2
Aggil	AC (absolute control)	0.80	2.19
	ZC (zone control Nitroammophoska 100 kg/ha)	1.03	2.46
	Dura SOP 80 kg/ha	1.32	3.35
	Dura SOP 100 kg/ha	1.49	3.65
	Renovation Fuerza 80 kg/ha	1.28	4.65
	Renovation Fuerza 100 kg/ha	2.02	4.67
Brigga	AC (absolute control)	0.66	2.64
	ZC (zone control Nitroammophoska 100 kg/ha)	0.92	2.87
	Dura SOP 80 kg/ha	1.18	3.17
	Dura SOP 100 kg/ha	1.36	3.38
	Renovation Fuerza 80 kg/ha	1.54	3.66
	Renovation Fuerza 100 kg/ha	1.62	3.74
LSD 0.5		0.26	0.98

Source: compiled by the author

The correlation and regression analysis between leaf surface area and net photosynthetic productivity of both studied grain sorghum hybrids was performed (Fig. 1).

The results of correlation and regression analysis indicate a close correlation between leaf area and net photosynthetic productivity in grain sorghum hybrid Aggil, where the coefficient of determination is $R^2 = 0.88$, and the correlation coefficient is $R = 0.80$. The results of the correlation-regression analysis also indicate a close correlation between leaf area and net photosynthetic productivity in the grain sorghum hybrid Brigga, where the coefficient of determination is $R^2 = 0.88$, and the correlation coefficient is $R = 0.80$. The increase in leaf area of grain sorghum hybrid Aggil plants was due to a change in the form and dose of complex granular mineral fertiliser Renovation Fuerza up to 100 kg/ha for pre-sowing soil cultivation. The net productivity of photosynthesis in both hybrids under this variant was also the highest. Analysing the results of the research, it is worth noting that there is a direct correlation between the data on leaf area and photosynthetic potential, as well as between the data on leaf area and net photosynthetic productivity.

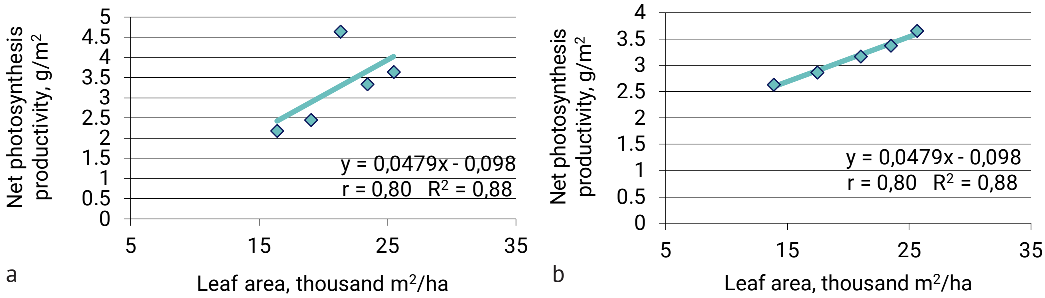

Figure 3. *Correlation and regression relationship between leaf surface area and net photosynthetic productivity of grain sorghum hybrids Aggil and Brigga, average for 2021, 2023-2024*
Note: a) Aggil hybrid; b) Brigga hybrid
Source: compiled by the author

The presence of the same values of correlation and determination coefficients in the two hybrids indicates the constant influence of leaf surface area as a key factor that determines the level of sorghum assimilation capacity under different variants of mineral nutrition. The regression curves have a positive slope, which confirms the linear nature of the relationship, and thus the possibility of predicting photosynthetic productivity based on leaf morphometric characteristics. Notably, under conditions of increased supply of plants with minerals, not only a quantitative increase in the area of the assimilation surface was observed, but also a qualitative increase in its efficiency in the context of net photosynthetic productivity. Such results are a strong justification for further optimisation of fertiliser doses and forms in the technological maps of sorghum cultivation in the Eastern forest-steppe of Ukraine.

The obtained research results, but for the Eastern part of the Forest-Steppe of Ukraine, correlate with the studies of L.A. Pravdyva & V.A. Doronin (2022), which were conducted in 2016-2020 at the Bila Tserkva Experimental Breeding Station of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine in the Right-Bank Forest-Steppe of Ukraine to determine the effect of different doses of complex mineral fertilisers. The studies proved that an increase in the leaf area of grain sorghum plants occurred due to an increase in the dose of mineral fertilisers. The application of the calculated rate ($N_{50}P_{40}K_{70}$) and higher doses of fertilisers ($N_{90}P_{90}K_{90}$ and $N_{120}P_{120}K_{120}$) during the period of ejection of the flowering panicle contributes to the formation of a larger leaf surface area. Under the variants, the highest net productivity of photosynthesis and grain yield of the studied grain sorghum varieties were obtained.

Similar results to the current research were obtained by R.E. Grishchenko *et al.* (2020) in a study on the productivity of grain sorghum in the northern forest-steppe zone of Ukraine under the influence of basic fertilisation and top dressing on the background of seed treatment with BTU. The use of $N_{45}P_{60}K_{60}$ as the main fertiliser and N_{15} as a top dressing contributed to the formation of the maximum leaf area of crops. An increase in the dose of fertilisers to $N_{60}P_{60}K_{60}$ contributed to the accumulation of significant dry mass, at this dose photosynthetic productivity and net photosynthetic productivity increased, and it is proposed to use fertiliser doses of $N_{60}P_{60}K_{60}$ to obtain the maximum possible yield in this growing zone.

The effect of soil irrigation with three different concentrations of $CdCl_2$ on pigment content, photosynthetic activity, carbohydrate content and productivity of *Sorghum bicolour* L. cultivar Dorado at different stages of plant growth and development was studied by H.S. Aldesuquy & A.A. El-Saied (2004). The study also addressed the effect of pre-soaking the grain with kinetin to reduce the toxic effects caused by different levels of $CdCl_2$. The results of the studies demonstrated that in most cases, pretreatment of grain with kinetin increased the amount of photosynthetic pigments, photosynthetic activity, Hill's reaction, and carbohydrate content in leaves of sorghum plants treated with cadmium. In general, there was a decrease in yield and yield parameters of sorghum plants in response to Cd^{2+} treatment, especially when the grain was pre-soaked in kinetin. The improving effect of kinetin was more pronounced at 1 mM $CdCl_2$. Grain priming with kinetin increased grain biomass, carbohydrate, protein and ion content in yielding grains of sorghum plants treated with cadmium. The cadmium treatment changed the balance of growth bioregulators in the developed grains of sorghum plants. From the results obtained, the scientists concluded that $CdCl_2$ in all concentrations used led to a significant decrease in the level of growth stimulants with an increase in the level of growth-inhibiting substances equivalent to abscisic acid. On the other hand, grain priming with kinetin increased the level of growth-promoting substances and decreased the level of abscisic acid.

V.V. Ivanina *et al.* (2021) conducted the study in the zone of insufficient moisture in the forest-steppe of Ukraine. A high grain yield was obtained with the fertilisation system for the main tillage of $P_{90}K_{90}$ and N_{150} in the pre-sowing cultivation. The study determined that a balanced balance of nutrients can be achieved by applying $P_{30}K_{40}$ for ploughing and N_{140} for pre-sowing cultivation. Another way of sowing and applying mineral fertilisers was found by V.G. Lypovy *et al.* (2020) in a study on the effect of mineral fertilisers on the leaf surface area in the zone of stable moisture. The largest leaf surface area and the duration of its active work were obtained in grain sorghum at a dose of mineral fertiliser $N_{120}P_{90}K_{120}$. Under this variant, the maximum value of photosynthetic potential was obtained. The study was conducted with intercropping of sorghum and soybeans. This variant of research formed the highest yield of green mass.

Other components of the cultivation technology were studied by O.S. Titarenko & L.M. Karpuk (2022) in the Right-Bank Forest-Steppe of Ukraine, analysing the effect of microfertilisers and growth regulators under different options of foliar feeding and found an effective effect of microfertilisers and plant growth regulators on photosynthesis and the formation of higher yields. R.M. Vasylenko (2018) and L.I. Storozhik (2017) proved that high photosynthetic activity of agrocenosis is determined by leaf surface area, photosynthetic potential and net photosynthetic productivity, which are the key to high yields of grain sorghum.

A certain parallel with the results of this study was traced in the study by O. Prysiazhniuk *et al.* (2022), where the influence of the timing of growth regulators application on the productivity of sorghum hybrids depending on the phenological phase according to the BBCH and Kuperman scales was established. The authors proved that early application of growth regulators at BBCH 21 provided a significant increase in grain yield in grain hybrids, as well as biomass and dry matter in sugar sorghum hybrids. Particularly noteworthy is the emphasis on the need to consider the exact phenological phases when applying the products, which echoes our findings on the dependence of photosynthetic activity and leaf area on the timeliness and form of fertilisation. This once again confirms the expediency of an individual approach to fertilising sorghum hybrids, which incorporates not only the dose and form of fertiliser but also the dynamics of plant development.

In the arid zone of China, F. Zhang *et al.* (2019) investigated the effect of different irrigation doses on photosynthesis and chlorophyll accumulation in grain sorghum leaves. Under drought and waterlogging conditions, chlorophyll content in leaves and photosynthesis intensity varied. The results confirm the high adaptability of sorghum to drought and waterlogging stress by reducing the rate of photosynthetic product transport and chlorophyll content. Under Indian conditions, S. Li *et al.* (2021) studied different sorghum genotypes that showed significant variability in photosynthetic capacity, leaf nitrogen content and specific leaf area depending on the ozone dose. Bioenergy sorghum is ozone-resistant and can be used to increase biomass productivity in ozone-polluted regions.

Increased tropospheric ozone concentration significantly reduces sorghum photosynthesis and productivity, which requires consideration of environmental factors in the development of fertiliser technologies. A valuable addition to the general scientific context is the results of the research by M.G. Salas Fernandez *et al.* (2015), who studied the photosynthetic capacity of leaves in a large panel of sorghum genotypes. The study determined significant variability in photosynthetic parameters, which is due to both genetic characteristics and nutritional conditions. S. Tang *et al.* (2018) substantiated the prospects of growing sorghum as a crop for high biomass production, emphasising the importance of photosynthetic parameters for realising this potential. A study by H.A. Ajeigbe *et al.* (2018), conducted in Nigeria, demonstrated that the application of different nitrogen rates had a positive effect on the efficiency of moisture use and sorghum productivity, which echoes the conclusions about the feasibility of balanced mineral nutrition in the forest-steppe of Ukraine. A study by M. Bagayoko (2012), conducted in Mali, demonstrated that the optimal combination of plant density, organic matter and nitrogen provided a significant increase in yield, which indicates the importance of adapting technological approaches to specific climatic conditions and resource capabilities of farms.

Thus, the results of the study confirmed the significant influence of forms and doses of mineral fertilisers on the level of photosynthetic activity and yield of grain sorghum hybrids. The highest values of leaf surface area, photosynthetic potential and net photosynthetic productivity were observed with the use of *Renovation Fuerza* complex fertiliser at a dose of 100 kg/ha, which provided effective nutrition during all phases of plant development. A reliable correlation between the morphometric parameters of the leaf apparatus and the level of assimilation productivity was established, which gives grounds for predicting the yield. The data obtained are consistent with the results of domestic and foreign studies while specifying the effective elements of sorghum cultivation technology in the Eastern forest-steppe of Ukraine.

Conclusions

The study determined that the highest development of leaf surface area in both hybrids was observed in the variant of Renovation Fuerza 100 kg/ha and amounted to 32.15 thousand m^2/ha in the phenological phase of ripening in the Aggil hybrid and 26.54 thousand m^2/ha in the Brigga hybrid, respectively. The study noted for the variants of application of all forms and doses of fertilisers in the interphase period of panicle ejection and flowering that the highest area of one plant in the Aggil hybrid was formed in the variant of application of the mineral fertiliser Renovation Fuerza at a dose of 100 kg/ha 1289 cm^2, and the area per hectare of sowing was 34.03 thousand m^2/ha, the figures were slightly lower than the area of the leaf floor in the Brigga hybrid by 155 cm^2 and 5.34 thousand m^2/ha, respectively.

The study determined that the highest photosynthetic potential of grain sorghum crops in the Aggil hybrid was 2.02 thousand m^2/ha×day when Renovation Fuerza fertiliser was applied at a dose of 100 kg/ha and in the Brigga F_1 hybrid 1.62 thousand m^2/ha. The study determined that the net productivity of photosynthesis depends on the use of different forms and doses of fertilisers. It was the highest in the variant of application of mineral fertiliser Renovation Fuerza at a dose of 100 kg/ha in both grain sorghum hybrids. Correlation and regression analysis of the data between photosynthetic potential of crops and leaf area showed a close correlation, with the coefficient of determination being $R^2 = 0.88$ and the correlation coefficient $R = 0.80$ for both grain sorghum hybrids Aggil and Brigga F1. The regression equation of the linear correlation between leaf area and net photosynthetic productivity for both hybrids under study is y = 0.0479x - 0.098 (R^2 = 0.88). Net photosynthetic productivity was the highest in the medium-early hybrid Aggil at 4.67 g/m^2 with the variant of Renovation Fuerza fertiliser at a dose of 100 kg/ha and was lower in the early-ripening hybrid Brigga at 3.74 g/m^2, respectively. The use of Dura SOP fertiliser at doses of 80 and 100 kg/ha contributed to the growth of leaf surface area compared to the absolute and zonal controls in both hybrids. The doses of fertiliser contributed to the formation of higher photosynthetic potential and net photosynthetic productivity.

In the future, it is necessary to study the effect of complex mineral fertilisers Dura SOP and Renovation Fuerza in different organo-mineral systems and doses and identify the most effective options for their use in grain sorghum cultivation technology, which in turn fulfil the potential yield of grain sorghum.

Acknowledgements

The author are grateful to Doctor of Agricultural Sciences, Professor Artur Rozhkov for the idea of researching the impact of fertilisers on the productivity of grain sorghum hybrids.

Funding

None.

Conflict of Interest

None.

Introduction

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Фотосинтетична продуктивність рослин гібридів сорго зернового залежно від різних форм і доз добрив

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Анотація. Необхідність вивчення фотосинтетичної продуктивності гібридів сорго зумовлена потребою оптимізації удобрення для підвищення урожайності в умовах Лісостепу України. Метою роботи було дослідити вплив комплексних гранульованих мінеральних добрив на формування врожайності зерна, зокрема фотосинтетичну продуктивність рослин сорго зернового. Дослідження проводили у 2021, 2023-2024 рр. в умовах дослідного поля Державного біотехнологічного університету. Дослід проводили за методом систематичних повторень із триразовою повторюваністю для забезпечення надійності та достовірності отриманих результатів. Сівбу здійснювали за прогрівання десяти сантиметрового шару ґрунту до температури 10-12°C з нормою висіву 200 тис. шт./га широкорядним способом з шириною міжрядь 45 см. Площу листкової поверхні та чисту продуктивність фотосинтезу визначали за методикою А.А. Ничипоровича. З'ясовано, що максимально можливу площу листкової поверхні однієї рослини та з одного гектару посіву формують рослини гібриду Aggil за варіанта застосування добрив Dura SOP в дозі 80 кг/га та Renovation Fuerza в дозах 80 і 100 кг/, а рослини гібрида Brigga за варіанта застосування добрив Renovation Fuerza в обох дозах. Фотосинтетична продуктивність обох гібридів зростала за варіанта внесення усіх форм і доз добрив порівняно з абсолютним контролем. Чиста продуктивність фотосинтезу найвищою була у обох досліджуваних гібридів за варіанта застосування мінерального добрива Renovation Fuerza в дозах 80 і 100 кг/га. Встановлено лінійну кореляційну залежність, рівняння регресії між площою листкової поверхні та чистої продуктивності фотосинтезу для обох досліджуваних гібридів має вигляд: $y = 0,0479x - 0,098$ ($R^2 = 0,88$). Результати можна використати для оптимізації мінерального удобрення гібридів сорго для підвищення урожайності та зниження витрат у Лісостепу України

Ключові слова: сорго зернове; мінеральні добрива; площа листкової поверхні; фотосинтетичний потенціал; чиста продуктивність фотосинтезу

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Науковий журнал

Том 21, № 2. 2025

Заснований у 2005 р. Виходить 6 разів на рік

Адреса видавництва:
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SCIENTIFIC REPORTS OF THE NATIONAL UNIVERSITY OF LIFE AND ENVIRONMENTAL SCIENCES OF UKRAINE

Scientific Journal

Volume 21, No. 2. 2025

Founded in 2005. Published 6 times a year

Managing Editor:
N. Shevchenko

Publisher's address:
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
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E-mail: info@scireports.com.ua
https://scireports.com.ua/en