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Agrobiological and environmental measures to increase the yield of spring rapeseed on drained organogenic soils under climate change

Abstract. The article examined agrobiological and environmental protection methods for increasing the yield of spring rapeseed on drained organogenic soils under conditions of climate change, taking into account the characteristics of these soils and methodological approaches to determining mineral fertiliser doses in a field stationary experiment on drained organogenic soils of the floodplain of the Supii River. The aim of the research was to determine the effectiveness of the methodology for calculating the most appropriate fertiliser doses and the peculiarities of

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forming the optimal regime for spring rapeseed crops on drained organogenic soils by determining the reasonable rates of mineral fertiliser application depending on the methods that take into account the specifics of these soils. The study used methods such as field research with a complex of biometric, agrochemical and laboratory studies, as well as mathematical and statistical methods. The research focused on the development of optimal mineral fertilisation systems and effective methods of peatland use, taking into account environmental aspects. It was found that the application of mineral fertilisers leads to an intensification of mineralisation processes, which increase with higher fertiliser doses, resulting in the accumulation of nutrients that affect the yield of cultivated crops and their migration into drainage waters. Using field, laboratory and statistical methods, the authors determined that the highest mineralisation of peat and CO₂ emissions occur in crop rotations with annual crops, while perennial grasses reduce peat depletion. It was also found that the highest rapeseed yield was achieved in grass-field crop rotations with the application of mineral fertilisers (3.0-3.3 t/ha), which reduced energy costs and increased economic efficiency. Studies had revealed significant leaching of nitrate nitrogen and potassium into drained waters, especially in spring and autumn, which contributed to water pollution. The proposed methods also increased the stability of the agroecosystem, minimising degradation processes in organogenic soils and reducing the environmental impact on the surrounding environment. The results obtained were of practical value in improving organic fertilisation systems for binary crops and ensuring the sustainability of agroecosystems, and can be used by agricultural producers of various forms of ownership

Keywords: peat soils; decomposition of linen fabric; organic matter; fertilisation; soil cultivation; productivity; biogenic substances

INTRODUCTION

Modern farming systems in the context of climate warming on drained soils require a significant review of key aspects of crop cultivation technology and crop rotation structure. It is important to implement improved technological measures aimed at obtaining high and economically profitable yields, taking into account environmental protection principles. Peat soils, which are low in potassium, often deficient in phosphorus and high in nitrogen, are characterised by intensive mineralisation of organic matter and leaching of nutrients into groundwater. Therefore, sound calculations of mineral fertiliser application rates are extremely important. Such research should ensure the environmental and economic efficiency of the use of the reclamation fund in the context of climate warming, contribute to the restoration of soil fertility and reduce the energy costs of crop cultivation technologies, in particular agromeliorative measures characteristic of reclamation agriculture on drained soils. Addressing these issues will make it possible to maintain crop productivity and economic performance while reducing energy costs and lowering the environmental impact

in areas of drainage reclamation. In general, the development of effective and environmentally friendly technology for growing spring rapeseed on drained organogenic soils will significantly increase the productivity of reclaimed lands in the Polissya region, which will enable agricultural enterprises to allocate additional funds to improve the technical condition of reclamation systems, which is necessary for production.

The development of agrobiological and environmentally friendly measures contributes to the preservation of the fertility of drained organogenic soils and their effective cultivation in conditions of climate warming. These technologies are an important factor in the development of agricultural production in areas of excessive moisture (Tarariko *et al.*, 2025). However, as noted by I. Slyusar *et al.* (2023), farming on drained organogenic soils in Polissya is associated not only with weather conditions, but also with the operation of land reclamation networks, the selection of highly profitable crops, and the technology used to grow them. I. Malinovska & M. Tkachenko (2023), Yu. Tarariko *et al.* (2025) believe that when using drained organogenic soils, it

is essential to take into account environmental protection measures related to the prevention of excessive mineralisation of peatlands and contamination of soil and river waters with biogenic substances. An analysis of the literature by E. Jajor & M. Mrówczyński (2016) and M. Parkhomets *et al.* (2023) showed that by the beginning of the 21st century, rapeseed cultivation had become widespread in Ukraine and Europe. Spring rapeseed began to occupy a leading position in the world among oil crops, with gross oil production reaching 33-35 million tonnes, and in Ukraine it occupies about 1% of arable land (Ryzhuk *et al.*, 2022; Voropai *et al.*, 2024). At the same time, the main factor limiting the cultivation of rapeseed on drained organogenic soils is the lack of sound and environmentally friendly technology in these conditions as the climate warms. This primarily concerns the optimisation of mineral fertilisation, crop rotation, the impact of its cultivation on the intensity of peatland mineralisation and the leaching of biogenic substances into groundwater (Markova *et al.*, 2025).

This theory is also confirmed in the work of I. Slyusar *et al.* (2023), which is based on the theory of ecological and environmental aspects. For humid areas on drained organogenic soils, the introduction of spring rapeseed (annual crops) as a highly profitable crop into the structure of cultivated areas on old-ploughed carbonate peat soils provides a significant economic return from the use of reclaimed land. This contributes to increasing the profitability of agricultural production and provides a stable income from crop sales. The high economic benefits of rapeseed cultivation are due not only to market demand for rapeseed as a source of oil and feed protein, but also to its importance in biofuel production, which is particularly relevant in the context of energy crises and environmental challenges. These results can form the basis for further research aimed at improving agricultural technologies for growing spring rapeseed and other crops on drained organogenic soils.

The aim of the research was to provide a theoretical justification for agrobiological measures for growing spring rapeseed under different mineral fertilisation systems and methods of using drained carbonate organogenic soils in the context of climate change.

MATERIALS AND METHODS

The research was conducted during 2021-2023 in a stationary experiment of an 8-field grain crop rotation on drained old-ploughed organogenic soils of the Panfil Experimental Station of the National Scientific Centre "Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine" (floodplain of the Supii River, Boryspil District, Kyiv Region). The soil of the experimental plot (0-50 cm) is well-decomposed peat (50-55%), carbonate, of cattail-sedge origin, with a thickness of 2.4-2.5 m and a density of 0.215 g/cm³; ash content 40-43%, full moisture capacity (FMC) – 270-280%; gross nitrogen content – 2.33%, phosphorus – 0.76-0.90; potassium – 0.09-0.15, calcium – 20-26%; pH of aqueous solution – 7.3-7.5. The experiment was conducted in three replicates in time and space. Spring rapeseed was grown in a grass-crop rotation with two annual crops (maize and rapeseed) and six fields of perennial grass mixtures, and in a row-crop rotation with only three annual crops (sunflower, spring rapeseed, spring triticale) and, for comparison, a field with unchanging sowing of perennial grass mixtures to determine the most effective way to use organogenic soils for growing spring rapeseed. To determine the effectiveness of mineral fertilisers and compare different types, plots without fertiliser application and without fertiliser application + Opti Growth were added to the experimental design; The recommended fertiliser doses were determined based on the analysis of data from long-term studies in crop rotation on drained soils conducted by the National Scientific Centre "Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine", with the highest yield obtained.

The formation of mineral fertilisation options for spring rapeseed was carried out according to the following principle: based on the data obtained from the results of many years of field studies conducted on old-ploughed soils at the Panfil Research Station ($R_{45}K_{120}$); – balance – calculated for yield increase. The balance method is based on (two) methods of determining fertilisers for the planned yield increase:

$$D = (Y_p - Y_k) \times R \times 100 / C_u, \quad (1)$$

where Y_p – planned yield, t/ha; Y_k – long-term yield without fertilisers, t/ha; R – nutrient removal by plants, kg/t; C_u – coefficient of nutrient utilisation from fertilisers, %.

The coefficient of nutrient utilisation from fertilisers was calculated based on long-term data obtained on these soils (Slyusar, 2019). To study biochemical activity in the soil, experiments were conducted using the application method and assessment of total biological activity. In particular, to assess the activity of microorganisms, linen fabric stretched over glass was used, which was placed at a depth of 0-30 cm. The total area of the sowing plot was 20 m², and the accounting area was 15 m². Opti Growth is a biological product for stimulating plant growth and development and ensuring their balanced nutrition based on a concentrated suspension of live nitrogen-fixing, phosphorus- and potassium-mobilising cultures and microorganisms with fungicidal properties.

Soil moisture in the samples was determined by the thermostatic-weight method, nitrate nitrogen content – by the Granwald-Lazh method with disulphophenolic acid in accordance with (DSTU 4725-2007, 2008), the ammonium nitrogen content was determined using the potassium chloride solution extraction method according to (DSTU ISO/TS 14256-1:2005, 2006), the content of mobile phosphorus and potassium compounds – by flame photometry of carbon ammonium extract according to (DSTU 4114-2002, 2003). Soil respiration was

determined by CO₂ release, and the intensity of root system respiration was determined using the Boisen-Jensen method (Kolesnikov, 2019). To convert the intensity of soil organic matter mineralisation, a coefficient of 0.543 was used, which corresponds to 50.2% carbon in peat organic matter (Yevtushenko & Khyzhnyak, 2019). Weather conditions during the years of research at the Panfil Research Station (according to data from the Yahotyn Meteorological Station located 2 km from the research field) were characterised by increased average monthly values for April-September: the air temperature in 2021 was 16.6°C, in 2022 – 16.2°C, and in 2023 – 17.4°C (the long-term average is 15.2°C), and insufficient precipitation (298 mm in 2021, 27 mm more in 2022, and – 391.5 mm compared to the norm of 327 mm).

RESULTS AND DISCUSSION

Monitoring of soil water conditions showed that groundwater levels mostly fluctuated at levels close to the lower limit of optimality, which was particularly noticeable in 2021 (Fig. 1). During this period, higher air temperatures compared to long-term averages contributed to increased moisture evaporation. As a result, increased evaporation reduced the amount of moisture available to plants in the soil. However, this groundwater level, together with the shallow root system of spring rapeseed, ensured sufficient moisture in the root zone, thereby promoting optimal plant growth and development.

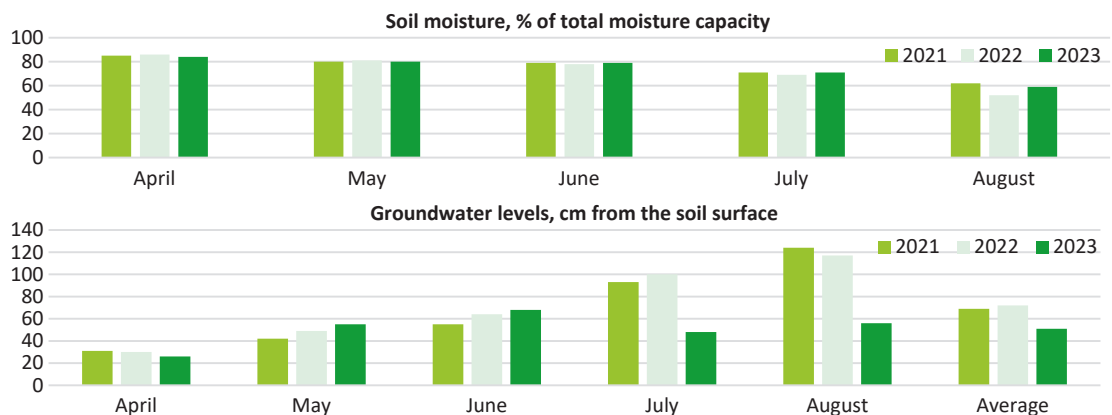


Figure 1. Soil water regime, average for 2021-2023

Source: developed by the authors

This water regime was particularly important because higher temperatures not only increase evaporation but also create additional challenges in maintaining plant access to moisture in the upper soil layers. Thus, the stable presence of groundwater at the specified depth is a key factor for the effective use of available water resources by plants, which had a positive overall effect on the development of rapeseed plants. Further research confirms that in the context of climate change, such as rising temperatures and uneven rainfall, the presence of groundwater at a certain depth is critical to crop productivity. These factors necessitate the adaptation of water management

and irrigation in modern conditions to ensure stable conditions for crop moisture supply. Accordingly, the moisture content of the active soil layer was within the optimal range during the rapeseed growing season (May-July) – 69-81% of full moisture capacity, with the lower optimal soil moisture content being 40% of full moisture capacity and the upper limit being 80% of full moisture capacity. An analysis of the nutrient content in the soil shows in Table 1 that it significantly depends on both the application of mineral fertilisers and the method of using drained soils, the structure of cropland in crop rotation and the place of rapeseed in it.

Table 1. Mobile nitrogen content in the 0-30 cm soil layer under spring rapeseed depending on the structure of sown areas in crop rotation, mg/kg of dry soil

Fertilisation	N-NO ₃				N-NH ₄			
	2021	2022	2023	average	2021	2022	2023	average
Row crop rotation with two annual crops (perennial grasses, maize, spring rapeseed)								
Without fertilisers (control)	159.0	78.0	23.0	86.7	38.5	42.0	43.5	41.3
Recommended fertiliser dose based on experiments	134.0	91.0	24.0	83.0	38.5	44.5	41.0	41.3
Calculated dose for yield increase	112.0	98.0	27.0	79.0	40.0	44.5	37.5	40.7
Recommended fertiliser dose based on experiments + Opti-Growth	135.0	102.0	68.0	101.7	33.5	44.5	35.8	37.9
Fertiliser: organic-mineral – Opti Growth	152.0	123.0	62.0	112.3	30.0	39.2	39.3	36.2
Crop rotation with three annual crops (sunflower, spring rapeseed, spring triticale)								
Without fertilisers (control)	107.0	69.0	135.0	103.7	36.5	46.5	48.5	43.8
Recommended fertiliser dose based on experiments	123.0	87.0	107.0	105.7	28.5	45.5	42.8	38.9
Calculated dose for yield increase	132.0	87.0	102.0	107.0	31.0	42.0	44.5	39.2
Recommended fertiliser dose based on experiments + Opti-Growth	129.0	100.0	95.0	108.0	28.5	44.5	42.8	38.6
Fertiliser: organic-mineral – Opti Growth	108.0	117.0	93.0	106.0	45.5	43.5	40.0	43.0
Perennial grasses 8 years								
Without fertilisers (control)	91.0	49.0	-	70.0	38.5	41.0	50.5	43.3
Recommended fertiliser dose based on experiments	87.0	79.0	-	83.0	36.5	43.5	49.5	44.8
Calculated dose for yield increase	81.0	91.0	-	96.0	33.5	44.5	54.5	44.2
Recommended fertiliser dose based on experiments + Opti-Growth	91.0	98.0	-	94.5	32.8	43.5	55.5	43.9
Fertiliser: organic-mineral – Opti Growth	94.0	32.2	-	63.1	36.5	42.0	60.5	46.3

Source: developed by the authors

Thanks to the stable groundwater level at the optimal depth, the moisture content of the active soil layer during the rapeseed growing season (May-July) was maintained within the range of 69-81% of full moisture capacity (FMC),

with the lower optimal soil moisture limit at 40% FMC and the upper limit at 80% FMC. Such moisture levels are optimal for the growth and development of rapeseed, as they provide sufficient water for the root system, especially in

conditions of climate change, which increase the risk of drought.

According to the results of soil nutrient analysis, their content is determined not only by the amount of mineral fertilisers applied, but also by a number of other factors, such as the method of drained soil cultivation, crop rotation composition, and the place of rapeseed in the crop structure (Table 2). Applying fertilisers

taking into account the specifics of each field and the needs of agricultural crops allows avoiding excessive or insufficient saturation of the soil with nutrients, in particular nitrogen, potassium and phosphorus. This is especially important for rapeseed, which has specific phosphorus and potassium requirements but, at the same time, avoids excess nitrogen, which can lead to leaching into groundwater.

Table 2. Content of mobile P₂O₅ and K₂O in the 0-30 cm soil layer on spring rapeseed crops, depending on the structure of cultivated areas in crop rotation, mg/kg of dry soil

Fertilisation	P ₂ O ₅				K ₂ O			
	2021	2022	2023	average	2021	2022	2023	average
Grass-based crop rotation with two annual crops (perennial grasses, sunflower, spring rapeseed)								
Without fertilisers (control)	61.1	36.0	22.5	39.9	105.0	102.0	88.0	98.0
Recommended fertiliser dose based on experiments	82.0	41.2	16.0	46.4	260.0	102.0	88.0	150.0
Calculated dose for yield increase	82.6	42.2	17.0	46.9	272.0	110.0	84.0	155.0
Recommended fertiliser dose based on experiments + Opti-Growth	82.0	40.0	22.5	48.2	269.0	123.0	132.0	175.0
Fertiliser: organic-mineral – Opti-Growth	76.0	41.4	27.0	48.5	104.0	88.0	126.0	106.0
Grass-based crop rotation with three annual crops (sunflower, spring rapeseed, spring triticale)								
Without fertilisers (control)	56.0	34.1	20.0	36.7	120.0	84.0	198.0	134.0
Recommended fertiliser dose based on experiments	66.0	32.0	21.2	39.7	162.0	86.0	216.0	155.0
Calculated dose for yield increase	69.0	45.0	19.4	44.5	170.0	88.0	263.0	174.0
Recommended fertiliser dose based on experiments + Opti-Growth	54.0	45.0	21.2	40.1	176.0	84.0	216.0	159.0
Fertiliser: organic-mineral – Opti-Growth	32.0	42.4	23.5	32.6	162.0	86.0	216.0	155.0
Perennial grasses 8 years								
Without fertilisers (control)	52.2	30.0	10.0	30.7	176.0	72.0	102.0	117.0
Recommended fertiliser dose based on experiments	77.2	36.0	12.0	41.7	126.0	84.0	216.0	142.0
Calculated dose for yield increase	79.0	38.0	20.0	45.7	120.0	98.0	298.0	172.0
Recommended fertiliser dose based on experiments + Opti-Growth	71.0	42.4	16.0	43.0	132.0	94.0	232.0	153.0
Fertiliser: organic-mineral – Opti-Growth	69.0	40.2	16.6	40.9	132.0	89.0	192.0	137.0

Source: developed by the authors

A particularly noticeable decrease in the level of nitrate nitrogen in the soil is observed under perennial grass mixtures, where the content ranges from 63.1 to 94.5 mg/ha of dry soil. This is because perennial grasses form a dense turf, which helps to reduce the mineralisation of

organic matter and the accumulation of nitrogen in mineralised form. In comparison, under annual crops such as rapeseed in grass-crop rotation, nitrate nitrogen levels are significantly higher (103.7-108.0 mg/ha). This indicates an intensive process of organic matter decomposition

in peat soil, which is greatly enhanced by annual crops that stimulate microbiological activity and, accordingly, peat decomposition processes.

In certain years, such as 2022, nitrate nitrogen content varied significantly, which may be due to climatic factors, in particular rising temperatures and changes in the water regime, which contribute to more intensive mineralisation of organic matter in peat soils. In general, regardless of how drained soils are used, all cultivated areas showed medium to high levels of mobile nitrogen, which is an important factor in planning mineral fertiliser application rates. This level of supply creates favourable conditions for high yields, but also requires control to avoid excess nitrogen, which can lead to its leaching into groundwater, increasing the risk of environmental pollution.

The content of mobile forms of phosphorus and potassium under rapeseed crops and perennial grass mixtures is usually associated with the application of mineral fertilisers, but on peaty carbonate soils, the dependence on fertilisers may vary. The vivianite layers in such soils create conditions under which phosphorus in a bound form, when interacting with air during ploughing, becomes available in a

mobile state. This provides an additional source of phosphorus for plants, which is important for maintaining an optimal phosphorus regime even with low fertiliser rates, such as P_{60} . Mobile phosphorus and potassium accumulate in the soil and provide rapeseed crops with nutrients, which has a positive effect on their yield. This is important in the context of maintaining soil fertility and the effective use of drained organogenic soils. The mineralisation of organic matter in peat soils not only enriches the soil with nutrients, but also stimulates the biological activity of microflora, which is one of the key factors in ensuring a nutritious regime. Depending on the composition and activity of microflora, mineralisation processes affect the intensity of accumulation of nutrients such as nitrogen, phosphorus and potassium, which determine crop yields on drained soils. During the growing season, the intensity of its decomposition (as a percentage of the initial mass) was an indicator of the biological activity of the soil. The faster the tissue decomposed, the higher the activity of microflora and the intensity of mineralisation processes, indicating the soil's high potential for converting organic matter into forms accessible to plants (Table 3).

Table 3. Effect of methods of use and fertilisation of drained organogenic soils under spring rapeseed crops on the decomposition of linen fabric, %

Fertilisation	Permanent crops of perennial grasses			Grass-based crop rotation			Crop rotation with annual crops		
	2021	2022	average	2021	2022	average	2021	2022	average
Without fertilisers (control)	30	41	35	54	63	58	70	57	63
Recommended fertiliser dose based on experiments	34	73	53	56	72	64	67	71	69
Calculated dose for yield increase	37	59	48	60	82	71	65	69	67

Note: soil layer 0-30 cm (exposure period 18.05-25.09)

Source: developed by the authors

It was found that the application of mineral fertilisers has a positive effect on the mineralisation processes of flax fabric, as does an increase in the proportion of annual crops in crop rotation. This contrasts with the decomposition of fabric observed after sowing perennial grasses. Thus, the decomposition of flax fabric over two years without the application of mineral fertilisers on perennial grass mixtures was 35%, while in grass-cereal crop rotation it was

58%, and in crop rotation containing only annual crops it was 63%. With the application of the recommended fertiliser doses ($P_{45}K_{120}$), these figures increased to 53%, 64% and 69% respectively, while the estimated yield increase under these conditions was 48%, 71% and 67%.

An important indicator for the use of drained organogenic soils is the determination of the actual mineralisation of peat, which allows assessing the efficiency of peatland exploitation

depending on the method of their use (Slyusar *et al.*, 2023). To this end, during 2021-2023, observations were made of the intensity of CO₂ release, which is a consequence of peat mineralisation under spring rapeseed crops under various conditions of organogenic soil use (Table 4).

Table 4. Mineralisation of organic matter in peat soil depending on the method of peat use

Year	Method of use	Level of fertilisation	Intensity of CO ₂ release from the soil, kg/ha per day	Intensity of CO ₂ release by the root system per day, kg/ha	Intensity of peat mineralisation during vegetation, t/ha
2021	Perennial grass crops without rotation	without fertilisers (control)	31.4	3.14	3.17
		recommended fertiliser dose based on experiments	33.0	6.29	3.33
		calculated dose for yield increase	40.9	4.71	4.13
	Spring rapeseed in grass crop rotation	without fertilisers (control)	51.9	9.43	5.24
		recommended fertiliser dose based on experiments	72.3	6.29	7.30
		calculated dose for yield increase	59.3	11.00	6.03
	Spring rapeseed in row crop rotation	without fertilisers (control)	83.3	7.86	8.41
		recommended fertiliser dose based on experiments	91.1	11.00	9.21
		calculated dose for yield increase	91.1	12.57	9.21
2022	Perennial grass crops without rotation	without fertilisers (control)	73.1	7.86	7.38
		recommended fertiliser dose based on experiments	66.8	9.43	6.75
		calculated dose for yield increase	58.9	9.43	5.95
	Spring rapeseed in grass crop rotation	without fertilisers (control)	57.4	12.57	5.79
		recommended fertiliser dose based on experiments	69.1	9.43	6.98
		calculated dose for yield increase	53.4	14.14	5.40
	Spring rapeseed in row crop rotation	without fertilisers (control)	80.1	11.00	2.88
		recommended fertiliser dose based on experiments	75.4	13.36	2.59
		calculated dose for yield increase	72.3	15.71	2.36
Average	Perennial grass crops without rotation	without fertilisers (control)	52.2	5.50	5.27
		recommended fertiliser dose based on experiments	49.9	7.86	5.04
		calculated dose for yield increase	49.9	7.07	5.04
	Spring rapeseed in grass crop rotation	without fertilisers (control)	54.7	11.00	5.49
		recommended fertiliser dose based on experiments	70.7	7.86	7.02
		calculated dose for yield increase	56.4	12.57	5.72
	Spring rapeseed in row crop rotation	without fertilisers (control)	81.7	9.43	6.05
		recommended fertiliser dose based on experiments	83.2	12.18	5.90
		calculated dose for yield increase	81.7	14.14	5.78
HiP ₀₅			4.3	0.39	1.05

Source: developed by the authors

It was found that CO₂ emissions from the soil during the exposure period on unfertilised plots under perennial grass mixtures amounted to 52.2 kg/ha per day. Under spring rapeseed in a grass-crop rotation with two annual crops, CO₂

emissions per day increased by 2.2 kg/ha, and in a row-crop rotation – by 29.5 kg/ha. The application of mineral fertilisers under rapeseed resulted in even greater CO₂ emissions from the soil. On plots with the recommended fertiliser

doses in the grass-based system, CO₂ emissions increased by 35.4%, and in the crop rotation with annual crops – by 59.4%. Thus, the data obtained confirm the importance of proper mineral nutrition management and crop selection in crop rotations to optimise microbiological processes in the soil and increase the efficiency of drained organogenic soils.

It should be noted that the mineralisation of peatlands and their increased depletion under agricultural use, especially with the introduction of crop rotations that include only annual crops, contributes to a greater accumulation of mobile nitrogen and mobile organic matter in the topsoil. Such accumulation is particularly pronounced in areas where groundwater is close to the surface (40–60 cm). Under such

conditions, especially during heavy rainfall, there is a risk of biogenic substances being washed into the groundwater. Groundwater has a hydrological connection with rivers, which causes pollution of water bodies with various biogenic elements, such as nitrates, phosphates and other soluble compounds. In view of this, studies were conducted to investigate the process of leaching soluble substances into groundwater under spring rapeseed crops under various conditions of use of drained organogenic soils. The studies showed that nitrate nitrogen and potassium compounds were leached most intensively from rapeseed crops. The phosphorus content in drained waters, on the contrary, was significantly lower, and this indicator was stable throughout the year, regardless of the season (Table 5).

Table 5. Impact of mineral fertiliser application and crop structure on the leaching of biogenic substances into groundwater, mg/l of water, average for 2021–2023

Soil use	Fertilisation	Spring				Autumn			
		NO ₃	NH ₃	P ₂ O ₅	K ₂ O	NO ₃	NH ₃	P ₂ O ₅	K ₂ O
Permanent crops of perennial grasses	without fertilisers (control)	9.2	2.4	0.3	5.6	2.1	2.1	1.5	8.2
	recommended fertiliser dose based on experiments	6.8	2.5	0.3	9.9	1.1	1.3	3.6	25.9
	calculated dose for yield increase	9.8	1.9	0.5	-	3.4	2.9	1.5	20.9
Grass-based crop rotation	without fertilisers (control)	2.8	2.5	0.1	5.7	4.7	2.5	1.1	14.2
	recommended fertiliser dose based on experiments	2.3	1.1	0.3	6.6	4.3	3.2	3.0	19.1
	calculated dose for yield increase	-	1.5	0.3	6.1	7.0	3.5	3.3	18.6
Spring rapeseed in row crop rotation	without fertilisers (control)	11.9	2.0	0.1	4.1	8.6	0.8	1.2	10.1
	recommended fertiliser dose based on experiments	12.7	2.6	0.3	5.1	11.2	1.0	3.8	15.1
	calculated dose for yield increase	12.7	1.2	0.3	6.3	12.6	0.7	2.3	25.4
Hip ₀₅		1.6	0.4	0.02	0.5	1.1	0.3	0.02	1.1

Source: developed by the authors

The results of seasonal observations showed that different elements are leached at different times of the year. Thus, the largest amount of nitrate nitrogen was leached in spring, while potassium migrated most in autumn. In crop rotation with annual crops, the concentration of nitrate nitrogen in drainage water was recorded at 11.9–12.7 mg/l in spring and 8.6–11.6 mg/l in autumn. The concentration of potassium in water in spring was 4.1–6.3 mg/l, while in autumn it was 10.1–25.4 mg/l.

Such seasonal dynamics are associated with the peculiarities of mineral fertiliser application and plant assimilation processes.

In particular, potash fertilisers are often applied in spring, which leads to a decrease in the potassium content in drainage waters in spring and due to the active consumption of this element by plants during the growing season. Nitrogen fertilisers, which are important for the growth and development of rapeseed throughout the season, are also intensively used

by plants, but part of them decomposes and accumulates in the soil during autumn and winter. With the onset of spring, when the groundwater level rises closer to the arable layer, the nitrate nitrogen accumulated during the winter is intensively washed out of the soil into drainage water.

The results obtained indicate the need for a rational approach to fertiliser application on peat soils, especially in conditions of close groundwater occurrence. To minimise the negative impact on the environment, it is necessary to optimise the application of nitrogen and potassium fertilisers, taking into account the seasonal needs of plants and the risk of leaching of

biogenic elements. This will reduce groundwater pollution and ensure stable crop yields on drained organogenic soils.

Studies have shown that the highest yield of spring rapeseed on drained organogenic soils was achieved with grass-crop rotation (5-6 fields of perennial grasses with 2-3 fields of annual crops, including rapeseed) under conditions of applying the recommended doses of mineral fertilisers or doses calculated for a yield increase of 2.1-3.8 cwt/ha (compared to the option without fertilisers). According to the average figures for 2021-2023, the yield in this crop rotation was 3.0-3.3 cwt/ha (Table 6).

Table 6. Spring rapeseed yield depending on mineral fertilisation and method of use on drained organogenic soils, t/ha

Fertilisation	Method of using organogenic soil	Year			average
		2021	2022	2023	
Without fertilisers (control)	grass-based crop rotation	1.8	3.0	1.4	2.1
	crop rotation with annual crops	2.4	2.4	1.6	2.1
Recommended fertiliser dose based on experiments	grass-based crop rotation	2.1	3.4	3.4	3.0
	crop rotation with annual crops	2.8	3.1	3.1	3.0
Calculated dose for yield increase	grass-based crop rotation	2.9	3.3	3.8	3.3
	crop rotation with annual crops	2.7	3.4	3.0	3.0
Hip ₀₅		0.31	0.29	0.31	-

Source: developed by the authors

The use of crop rotation, which includes only annual crops, also provided similar rapeseed yields, although they were on average 0.3 t/ha lower. However, this approach has negative environmental consequences: due to the more active mineralisation of organic peat mass, peatlands are being intensively depleted. This leads to accelerated decomposition of organic matter, a decrease in the organic content of the soil, and increased carbon dioxide (CO₂) emissions into the environment, which negatively affects the environment and increases the risk of soil fertility loss.

Under conditions of grass-field crop rotation with perennial grasses, which ensure reduced peat depletion, there is a more stable preservation of organic matter in the soil. Perennial grasses act as a kind of “protective barrier”, preventing the intensive decomposition of organic matter. In addition, such crop rotation contributes to improving soil structure,

preserving its water-air balance and ensuring the gradual accumulation of organic matter.

The use of mineral fertilisers in grass-based crop rotation increases the efficiency of nutrient use and allows for stable rapeseed yields, reducing the risk of peat soil depletion. This indicates the advisability of introducing crop rotations with perennial crops, which minimise degradation processes in organogenic soils, ensuring their long-term fertility. Thus, the results obtained indicate the advantages of grass-based crop rotations for growing spring rapeseed on peat soils. The use of perennial grasses in the crop rotation structure allows to preserve the organic matter of the soil, reduces the intensity of peat mineralisation, ensuring stable crop productivity and increasing the ecological stability of the agroecosystem.

The effective and environmentally friendly use of drained organogenic soils in the context of climate change is one of the key conditions for

ensuring the sustainable development of agricultural production (Jauhiainen *et al.*, 2019). Climate warming is accompanied by an increase in the rate of peat mineralisation, which poses a threat of soil degradation and water pollution. In this context, the introduction of agricultural technologies aimed at stabilising the carbon balance and limiting the loss of organic matter is particularly relevant (Truskavetskyi, & Tsapko, 2016; Klymenko *et al.*, 2022). According to the results of research by I. Slyusar (2019), one of the promising solutions is the technology of growing annual crops in the structure of grass-field crop rotation with the inclusion of 5-6 fields of perennial grasses and 2-3 annual crops. This approach allows for the comprehensive solution of several problems: increasing the biological activity of the soil, stabilising its agrochemical indicators, and reducing the intensity of peat mineralisation processes. The works of S. Kolomiyets & P. Pyyipchuk (2017), I. Slyusar (2019), Yu. Tarariko *et al.* (2025) highlight that the application of calculated doses of phosphorus and potassium fertilisers in this system is a balanced solution, which, on the one hand, meets the nutritional needs of crops and, on the other hand, prevents the leaching of biogenic substances into subsoil horizons and groundwater, as confirmed in the works of M. Heino *et al.* (2020) on obtaining high yields of agricultural crops in various cultivation systems.

As shown by the studies of V. Polyovy *et al.* (2022) and V. Tymofeyev *et al.* (2022), ecological and economic aspects are also an integral part of the proposed approach. The inclusion of both spring rapeseed and other annual crops in the structure of cultivated areas provides additional commercial production and creates financial reserves to maintain the operability of land reclamation systems. Thus, the technology combines environmental feasibility with economic efficiency, which meets the modern requirements for farming systems in the context of climate change. According to the results of studies by L. Hlisnikovskiy & E. Kunzova (2014) and G. Voropai *et al.* (2024), the proposed system allows for a 5-10% reduction in organic matter losses, as well as a reduction in energy costs per unit of production, which is a strong argument in favour of its implementation in production

practice. In addition, according to S. Balyuk & R. Truskavetskyi (2025), the development of the concept of "soil health" can only be ensured by establishing an optimal nutrient regime that contributes to increased crop yields compared to existing technologies of both domestic and foreign origin.

In general, the results of these scientific developments are important for the formation of adaptive models of sustainable agriculture on drained organogenic soils. They confirm that the integration of agroecological principles into technological solutions allows achieving a balance between soil fertility conservation, crop productivity improvement, and economic feasibility of agricultural production in the context of global climate challenges.

CONCLUSIONS

The developed technology for achieving high yields of spring rapeseed (3.4-3.8 t/ha of grain) is based on the introduction of environmentally friendly grass-cereal crop rotations, which include 5-6 fields of perennial grasses and 2-3 fields of annual crops. The use of such crop rotations in combination with the application of phosphorus and potassium fertilisers in calculated doses or doses justified by long-term agrochemical observations ensures balanced crop nutrition and contributes to the ecological stability of agroecosystems. This approach prevents excessive mineralisation of organic matter in peat and reduces the risk of leaching of biogenic elements – primarily nitrates and potassium – from the active soil layer into groundwater, which is particularly important for preserving the quality of the aquatic environment.

The developed grass-field crop rotation with the inclusion of perennial grasses in the structure of spring rapeseed crops ensures the stabilisation of microbiological processes in the soil, maintains a moderate rate of mineralisation that corresponds to the rate of nutrient consumption by crops, and prevents the imbalance of biogeochemical cycles. This contributes to maintaining the ecological sustainability of agroecosystems, prevents excessive carbon dioxide emissions into the atmosphere, and reduces the environmental impact of agricultural activities. The inclusion of perennial grasses in crop rotation has

a positive effect on the structural and agronomic properties of the soil: its structure improves, the organic matter content increases, and the water-air regime stabilises, which is especially important on drained organogenic soils. In addition, this approach reduces anthropogenic impact on ecosystems, prevents degradation processes in the soil cover, and contributes to the long-term preservation of peat soil fertility. As a result, an optimal environment for growing spring rapeseed is formed, the efficiency of agricultural production is increased, and a harmonious combination of productivity and environmental protection potential of agricultural land use is ensured.

Prospects for further research lie in an in-depth study of the mechanisms of interaction between the components of the agroecosystem under different options for grass-field crop rotations, refinement of the dynamics of the carbon balance in soils of organogenic origin, and modelling of nutrient leaching into drained waters under different climate scenarios. Particular

attention should be paid to assessing the energy and economic efficiency of agricultural technologies, as well as the impact of anthropogenic factors on the long-term fertility of drained soils in the context of climate change.

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CONFLICT OF INTEREST

None.

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Агробіологічні й природоохоронні заходи підвищення врожайності ріпаку ярого на дренажних органогенних ґрунтах за умов кліматичних змін

Анотація. У статті досліджено агробіологічні та природоохоронні методи підвищення врожайності ріпаку ярого на дренажних органогенних ґрунтах в умовах кліматичних змін, що враховують особливості характеристики цих ґрунтів та методологічні підходи визначення доз мінеральних добрив в умовах польового стаціонарного дослідження на дренажних органогенних ґрунтах заплави р. Супій. Мета досліджень полягала у визначенні ефективності методології розрахунків найдоцільніших доз добрив та особливості формування оптимального режиму під посіви ріпаку ярого на дренажних органогенних ґрунтах через визначення обґрунтованих норм внесення мінеральних добрив залежно від методик, що враховують специфіку цих ґрунтів. В дослідженні використано такі методи, як польовий з комплексом біометричних, агрохімічних і лабораторних досліджень та математично-статистичний. Дослідження фокусувались на розробці оптимальних систем мінерального удобрення та ефективних методів використання торфовищ, враховуючи екологічні аспекти. Було встановлено, що внесення мінеральних добрив призводить до посилення мінералізаційних процесів, які зростають зі збільшенням доз добрив, а це зумовлює накопичення поживних речовин, що впливають на урожайності вирощуваних культур та міграцію їх у дренажні води. Використовуючи польові, лабораторні та статистичні методи, автори визначили, що найбільша мінералізація торфу та виділення CO₂ відбувається в сівозміні з однорічними культурами, тоді як багаторічні трави знижують

спрацювання торфу. Також встановлено, що найвища врожайність ріпаку досягається у травопільній сівозміні з внесенням мінеральних добрив (3,0-3,3 т/га), що забезпечує зменшення енерговитрат і підвищення економічної ефективності. Дослідження виявили значне вимивання нітратного азоту і калію в дренажній воді, особливо навесні та восени, що сприяє забрудненню водних ресурсів. Запропоновані методи також підвищили стабільність агроєкосистеми, мінімізуючи деградаційні процеси в органічних ґрунтах та знижуючи екологічне навантаження на навколишнє середовище. Отримані результати мають практичну цінність у вдосконаленні органічних систем удобрення бінарних посівів культур та забезпечення стійкості агроєкосистем і можуть бути використані виробниками сільськогосподарської продукції різних форм власності

Ключові слова: торфові ґрунти; розклад льняної тканини; органічна речовина; удобрення; обробіток ґрунту; продуктивність; біогенні речовини

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Influence of the predecessor on sugar beet yield in short-rotation crop rotations in the western forest-steppe of Ukraine

Abstract. Due to the intensification of sugar beet production in short-rotation crop rotations, the importance of optimal predecessor selection to ensure stable yields increases. Rational crop alternation was a key factor in maintaining soil fertility and reducing the risk of phytosanitary problems. The purpose of the study was to assess the influence of various predecessors on sugar yield and harvest, considering the type of soil in the western forest-steppe of Ukraine. The study used the method of comparative analysis of sugar beet productivity after different predecessors on soils of different genetic origin; statistical processing of the results was carried out by the method of variance analysis and regression modelling. Root crop yields, sugar content levels, and gross sugar yield were studied after such predecessors as winter wheat, winter barley, soybeans, and corn. It was found that the highest yield was provided by grain predecessors (winter wheat, barley), especially on highly productive soils. The relationship between soil type and predecessor efficiency was analysed: on carbonate and sandy soils, the yield after soybeans and corn decreased to 8.7-9.5 t/ha. It has been generalised that soil fertility mitigates the negative impact of less favourable predecessors. It was found that the effect of the predecessor significantly depends on the type of soil: on chernozems and forest soils, the effect of grain was most pronounced. The results obtained can serve as a basis for developing regionally adapted recommendations on the structure of crop rotations in beet farms. The results of the study can be used by agronomists, consultants and agricultural producers to improve crop rotations and optimise the technology of growing sugar beet in the western forest-steppe

Keywords: carbonate soils; soil type; productivity of agrocoenoses; structural and agrochemical properties; soil fertility

INTRODUCTION

In the current conditions of development of the agro-industrial complex of Ukraine, the issue of rational use of agricultural land and

effective planning of crop rotations is becoming particularly relevant. Increased intensification of production, increased economic pressure on

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agricultural enterprises, and high profitability of individual crops – in particular corn, soybeans, and winter wheat – led to the widespread use of short-rotation crop rotations, often with a limited number of crops and irrational alternation. Sugar beet is one of the main industrial crops of the western forest-steppe of Ukraine, and its placement in crop rotation plays a key role in ensuring stable yields, sugar content, and production efficiency. Simultaneously, this particular crop is extremely sensitive to re-seeding, monoculture, and to the presence of unsuitable predecessors.

L. Skivka & S. Hudz (2021) and M. Anar *et al.* (2021) conducted a study and analysed the effect of various crop rotation and tillage systems on sugar beet yield and nitrate dynamics in the soil using the RZWQM2 model (USA). The simulation covered long-term field data from three rotations: beets after wheat, corn, and perennial grasses. The results showed that crop rotation with wheat provided 3-6.5% higher beet yield and also reduced the accumulation of nitrates in the soil compared to other schemes. Research conducted in Iran by M. Orazizadeh *et al.* (2020), found that the introduction of cereals before beets improved growth parameters, reduced field contamination, and increased the sugar content of root vegetables.

Meta-analysis performed by Z. Gazdík *et al.* (2025) on sustainable sugar beet production pointed out the need for precision farming, integration of systems for reducing the intensity of tillage, optimisation of nutrition and plant protection systems within short-term crop rotations. The research by P. Götze *et al.* (2017) presented the results of a 45-year study of various links of crop rotation with sugar beet, and the impact on the yield, quality of raw materials, and stability of sugar production were analysed. It was found that compliance with the period of interstitial saturation (at least 3-4 years) reduces the risk of developing rhizoctoniosis and cercosporoses. Similar findings by H. Koch *et al.* (2018), based on a survey of farmers and stationary field studies, were published in the paper.

In a number of scientific studies, L. Hlushchenko *et al.* (2021), S. Arshad *et al.* (2022) considered the dynamics of yield changes in the cultivation of sugar beet monoculture in

comparison with its cultivation in crop rotation. It was proved that in a monoculture, the yield significantly decreases, the pressure of diseases, and weeds increases, and the technological suitability of root crops for processing decreases.

Adaptive management of growing technologies, including compliance with crop rotations during climate changes, is essential for intensive beet farming. The paper by S. Bastaubayeva *et al.* (2022) presented the results of sugar beet cultivation in Central Asia, and the influence of each individual factor (droughts, temperature conditions, agrotechnical solutions) on the development of a strategy for sustainable sugar beet cultivation was considered in detail. One of the options for adaptive management of sugar beet cultivation technology can be considered the creation of digital crop rotations based on artificial intelligence and BigData analysis, which allows predicting the production of programmable yields based on predecessor matrices and accumulated local data, which forms the basis for managerial decision-making (Kluger *et al.*, 2025). A study on climate change forecasting for typical European crop rotations was conducted and it was found that adaptive planning and changes in crop structure can partially compensate for the negative impact of rising temperatures and moisture deficiency (Pohanková *et al.*, 2025).

The purpose of the study was to establish the dependence of sugar beet yield and quality indicators on its predecessor in short-rotation crop rotations in the western forest-steppe of Ukraine, and to determine the agrobiological and economic consequences of beet placement after various crops.

LITERATURE REVIEW

The problem of the influence of the predecessor on the yield of sugar beet in the conditions of short-rotation crop rotations was considered by a number of studies covering agrophysical, phytosanitary, and biological aspects of this phenomenon. The study by L. Zimny *et al.* (2005) and C. Guo *et al.* (2024) presented the results of a long-term experiment in Central Europe, predecessors from the group of cereals, in particular, wheat and barley, provided an increase in beet yield by 3-6% compared to soybeans or

corn. Similar conclusions were also obtained by Ya. Tsymbal *et al.* (2022), O. Prysiashniuk *et al.* (2022) in the conditions of Ukraine, where the effective use of moisture and mineral nutrition after grain crops was established, and the use of various agrotechnical measures, such as mulching, deep loosening, and compliance with crop rotation, facilitated stable cultivation of sugar beet. Conclusions in scientific research by D. Kluger *et al.* (2025), obtained using simulations in the United States, confirmed the feasibility of growing beets after wheat, where yields were higher by 3-6.5% due to better moisture supply. Instead, soybeans, which are often positioned as a favourable predecessor due to their symbiotic nitrogen fixation potential, were less effective in crop rotations with beets. The main limitations of its use were the allelopathic effect, residual herbicidal background and weak structure-forming effect, especially on soils with low moisture capacity. Positive impact of cereals in research by G. Bodner & M. Alsalem (2023), Y. Makukh *et al.* (2024) was explained by both an improvement in the water regime and a decrease in the phytosanitary load.

It is worth noting that not only the structure of crop rotation, but also its duration is of key importance. According to research by P. Götze *et al.* (2017) and H. Yan *et al.* (2024), it was found that extending rotation to three years or more stabilises beet yields, improves soil microbiological activity, and increases the adaptive potential of crops to climate stresses. The study by D. Kluger *et al.* (2025), based on satellite monitoring, found that the predecessor effect is significantly enhanced in years with high humidity, and the effectiveness of soybeans as a predecessor decreases in a warming climate.

In general, the results of the latest research indicate the advantage of cereals as predecessors for sugar beet in conditions of short-rotation crop rotations, especially on fertile and well-moistened soils. The studies by T. Hurisso *et al.* (2015) and Y. Makukh *et al.* (2025) established that a regional-adaptive approach to crop rotation planning is necessary, considering soil type, weather conditions, fertiliser history, and phytosanitary conditions.

Reviews by G. Bodner & M. Alsalem (2023) and Z. Gazdík *et al.* (2025) indicated that the

integration of optimal sowing dates with the latest technologies of sustainable production (strip cultivation, cover crops, biostimulants) allows minimising the risks of climate stress and increasing the environmental sustainability of beet agrosystems.

Ukrainian researchers are actively investigating the features of sugar beet cultivation in the forest-steppe and Steppe of Ukraine, focusing on sowing dates, fertiliser systems, and crop rotations. L. Hlushchenko *et al.* (2021) in experiments on the right-bank forest-steppe found that the use of short-rotation crop rotations with sugar beet leads to a decrease in yield by 10-12%, but optimisation of sowing dates partially compensates for this negative impact, ensuring the stability of sugar collection from one hectare. The researchers emphasised that early sowing in combination with optimal predecessors can reduce the phytosanitary load. Ya. Tsymbal *et al.* (2022) proved that beet productivity varies significantly depending on the fertiliser system and sowing time. The highest yield indicators (more than 50 t/ha) were obtained with the organo-mineral fertiliser system at early sowing dates, while late sowing, even with optimal fertiliser, reduced productivity by 7-9%. Y. Makukh *et al.* (2025) in experiments on chernozems of the western forest-steppe, found that the timing of sowing significantly affects the efficiency of soil moisture use. Early sowing allowed beets to make better use of spring moisture, reducing the risk of summer droughts. This contributed to an increase in the water consumption rate by 12-15% compared to later dates.

The main problems of short-rotation crop rotations in beet farming, which are worth highlighting: soil fatigue – due to the frequent return of beets to the same field, there is a deterioration in the physico-chemical properties of the soil, a decrease in humus content, deterioration of the structure and water-air regime; accumulation of pathogens and pests – short rotations contribute to the reproduction of specialised pests (nematodes, wireworms) and pathogens (cercosporosis, root rot), especially when re-growing beets or sowing them after corn; reduced biological diversity – loss of crop diversity in crop rotation worsens the phytosanitary condition of the field, reduces the soil activity of the

microbiota; violation of the nitrogen balance – the absence of legumes or green manure in the crop rotation leads to nitrogen deficiency and an increase in the need for mineral fertilisers; compaction of the soil – often in short crop rotations, beets are sown after corn, which is a poor predecessor due to the deep root system, which leaves coarse post – harvest plant debris, poorly decomposes, and causes compaction of the upper layers of the soil, depletion of the microelement composition – frequent beet cultivation reduces the content of boron, manganese, magnesium, and calcium, which affects the quality of the crop; crop instability – short crop rotation causes strong yield fluctuations depending on the year, which complicates planning and economic forecasting.

All this indicates the need for a reasonable choice of predecessor when growing sugar beet, especially in conditions of short crop rotation. The most important crops are those that can improve the agrochemical parameters of the soil, reduce pathogenic load, and help to preserve the soil structure. Thus, the study of the influence of predecessors on beet yield in short-rotation crop rotations is an important step towards

improving the stability and efficiency of beet farming in the western forest-steppe of Ukraine.

MATERIALS AND METHODS

The research was conducted during 2018-2024 in the production conditions of the private enterprise “Zakhidnyi Buh”, which is one of the leading agricultural farms in the Western Ukraine. The total area of the company’s land bank is approximately 65,000 hectares, of which about 45,000 hectares are included in the beet crop rotation. The analysis used data on actual recorded yields within the divisions of the private enterprise (PE) “Zakhidnyi Buh”. The farm operates on the territory of Lviv, Ternopil, Chernivtsi, and Volyn oblasts, which are part of the agroclimatic zone of the western forest-steppe of Ukraine. Growing areas are characterised by a temperate continental climate with sufficient moisture and a predominance of dark grey podzolic and grey soils, meadow-chernozem soils, and sod-podzolic soils in the northern part (Table 1). The analysis used 82,000 hectares of sugar beet crops, of which 68,900 hectares were on productive soils and 13,100 hectares on carbonate and sandy soils.

Table 1. Weather and climate conditions for cultivation in 2018-2024 studies

Division	2018		2019		2020		2021		2022		2023		2024	
	Precipitation, mm	Sum of active temperatures, °C	Precipitation, mm	Sum of active temperatures, °C	Precipitation, mm	Sum of active temperatures, °C	Precipitation, mm	Sum of active temperatures, °C	Precipitation, mm	Sum of active temperatures, °C	Precipitation, mm	Sum of active temperatures, °C	Precipitation, mm	Sum of active temperatures, °C
Zastavna	689	3,876	658	4,105	701	4,045	652	3,599	501	4,051	703	4,293	582	3,957
Chorny Ostriv	741	3,581	701	3,765	803	3,716	782	3,257	675	3,580	844	3,863	749	3,552
Shymkivtsi	615	3,435	493	3,621	661	3,647	637	3,118	511	3,375	605	3,696	612	3,359
Rozvoriany	639	3,716	581	3,911	676	3,840	671	3,361	598	3,646	697	3,991	605	3,676
Byshiv	733	3,737	597	3,949	787	3,869	810	3,372	801	3,639	688	3,963	767	3,679
Zhvyrka	662	3,722	591	3,963	731	3,836	742	3,361	767	3,650	845	3,934	750	3,653

Source: developed by the author

The annual area of sugar beet crops within the enterprise ranges from 14,500-15,500 hectares, which ensures a stable presence of the crop in short-rotation crop rotations. The duration of the growing season ranged from 100 to 160 days, proportional within each location to ensure continuous harvesting

and crop rotation. The seeding rate of sugar beet was 120,000 seeds/ha, row spacing was 45 cm, sowing depth was 2 cm. The research involved fields after various predecessors – winter wheat, corn for grain, soybeans. Of the analysed acreage, the predecessors were winter wheat on an area of 41,000 hectares,

29,000 hectares, and grain corn of 13,000 hectares. Agrophones were aligned according to the main agrotechnical measures, the fertiliser system (nitrogen – 125 kg/ha in dry matter;

phosphorus – 50 kg/ha in dry matter; potassium – 150 kg/ha in dry matter). The sugar beet protection scheme is generally accepted in the region (Table 2).

Table 2. Sugar beet cultivation technology

BBCH	Herbicides	Fungicides	Insecticides	Trace elements	Basic fertilisers
Autumn, under the main tillage					Potassium chloride 250 kg/ha; Ammophos 150 kg/ha
00					Urea 150 kg/ha
9-10	Betanal expert 1.0 l/ha; Goltix Gold 1.0 l/ha		Bradby 0.3 l/ha		
12	Betanal Max Pro 1.5 l/ha; Goldix Titanium 1.5 l/ha			Magnesium sulphate 1.0 kg/ha	
16	Betanal expert 1.5 l/ha; Goltix Gold 1.5 l/ha		Bombardier Duo 0.2 l/ha	Monocalium phosphate 1.5 kg/ha	Ammonium nitrate 130 kg/ha
18	Steptrel 0.3 l/ha; Goltix Gold – 1.5 l/ha; Betanal Max Pro – 1.5 l/ha		Bombardier Duo 0.2 l/ha	Boron 1.0 l/ha Monocalium phosphate 1.5 kg/ha	
31-39	Agil 0.8 l/ha	Stark 0.4 l/ha		Manganese 2.0 l/ha Boron 1.0 l/ha	
49		Medyan Extra 1.8 l/ha Rex Plus 1.3 l/ha		Boron 1.5 l/ha	
49 (18 days from the previous one)		Rex Duo 0.7 l/ha, Manzat 1.5 kg/ha		Boron 1 l/ha	
49 (18 days from the previous one)		Split 0.5 l/ha; Dot 1 l/ha; Medyan Extra 2 l/ha			

Source: developed by the author

The study used a method of comparative analysis of sugar beet productivity after different predecessors on soils of different genetic origin. Statistical processing of the results was performed using variance analysis (ANOVA) and the construction of second-order regression models. Microsoft Excel 365 spreadsheets (*Analysis ToolPak* package) were used to process empirical data, and the Statistica 10 software environment to refine variation parameters and verify the significance of factors. Graphs, trend lines, and results were plotted in Excel. This approach provided a comprehensive analysis of the relationships between the predecessor, soil

type, and yield level. The study was conducted in accordance with the ethical standards of Convention on Biological Diversity (1992) and Convention on the Trade in Endangered Species of Wild Fauna and Flora (1976).

RESULTS AND DISCUSSION

During 2018-2024, the sugar beet yield was generalised within the production crops of PE “Zakhidnyi Buh”, depending on the main groups of its predecessors. Accounting was carried out without differentiating fields by soil type, which helped to obtain an integral assessment of the average influence of the predecessor in the

conditions of a farm with a large spatial variability of soil indicators. Figure 1 shows the relative yield of sugar beet (% to the average level),

grouped by three main types of predecessors: corn per grain – 104%; cereals (wheat, barley) – 104%; soybeans – 96%.

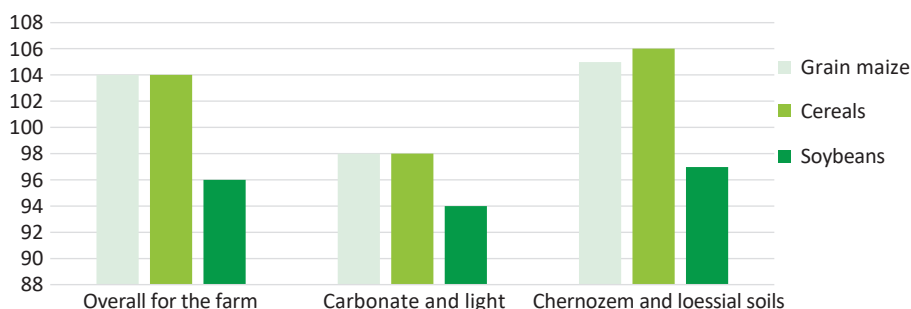


Figure 1. Relative yield of sugar beet in 2018-2024 in the conditions of the PE “Zakhidnyi Buh” after different predecessors on different types of soils

Source: developed by the author

The data obtained indicate that there is no statistically significant difference in beet yield after corn for grain crops. In both cases, there was a 4% increase in yield compared to the baseline average. This may be due to the best phytosanitary condition of the field, the structure of the soil after grain crops, and the technological compatibility of the terms of the main cultivation and sowing. But after soybeans, the yield was 4-8% lower compared to other predecessors. The decrease may be conditioned by the following factors: increased phytopathogenic load after soy; rapid depletion of available nitrogen; suboptimal structure of post-harvest residues; potential influence of the previous herbicide background. In the case of differentiation by soil type, in particular, on carbonate and light loamy sandy soils with low moisture capacity and low organic matter content, a different pattern of influence of the predecessor on sugar beet yield was observed. According to the analysis of data for 2018-2024, the relative yield of the crop in these conditions was: grain corn – 98%; cereals (wheat, barley) – 98%; soybeans – 94% (Table 2).

Compared to the integral average (100%), there was a slight decrease in yield in all variants. However, the most significant decline was observed after soybeans (-6%), which was probably conditioned by the following factors: weak structure-forming effect of soybeans in sandy and carbonate soils does not provide sufficient

soil density and water retention, which is critical in conditions of low moisture capacity; crop residues of soybeans have a high C:N ratio that slows down their mineralisation and temporarily blocks nitrogen in the soil; a low supply of moisture in the arable layer after soybeans can be a consequence of less deep root penetration and a weak mulching effect in the summer; the phytosanitary situation on these soils after soybeans is potentially worse – rapid drying contributes to root rot damage. After cereals and corn, the relative yield of sugar beet on grain was the same (98%), which indicates a neutral or slightly positive effect of these predecessors in light soil conditions. Conditionally unfavourable water supply on these types of soils probably negates the potential benefits of the leguminous predecessor.

The results obtained indicate an increased sensitivity of beets to the structure and moisture storage capacity of the soil, which should be taken into consideration when planning crop rotation for carbonate and sandy areas. As a result of the differentiation of results by agricultural production groups of soils, it was found that on the most fertile soils of the PE “Zakhidnyi Buh” – chernozems and loessial loams – the reaction of the crop to the predecessor was clearly positive, with a tendency to increase the yield after grain.

Based on data for 2018-2024, it was found that the relative yield of sugar beet for the main

groups of predecessors was: cereals (wheat, barley) – 106%; grain corn – 105%; soybeans – 97%. Thus, after grain crops, there was the greatest increase in yield – 6% above the average level, which was conditioned by the favourable soil structure after these crops, good residual humidity, a developed root system, and less damage by soil pests. Grain corn, despite its shortcomings as a predecessor (high level of post-harvest residues, potential compaction of the soil), also showed an increase in yield (+5%), which can be explained by the high structure-forming ability, and the ability of corn to effectively use and accumulate nutrients from deeper horizons in crop residues. Soybeans, which are usually considered a good predecessor, provided the lowest results under these conditions – 97% relative yield, that is, 8-9% lower than after cereals. This decrease may be conditioned by the following factors: potential moisture deficiency at the initial stages of beet development due to insufficient mulching effect of soybean plant residues; high sensitivity of beet to herbicide residues used in soybean cultivation technology; lower soil loosening depth due to a weaker soybean root system. The results obtained indicate a mixed influence of the predecessor on the yield of sugar beet, which depends on the type of soil and the adaptive ability of the crop to the conditions of a particular agroecosystem. In the conditions of the PE “Zakhidnyi Buh”, the general trend indicates an increase in the relative yield after grain crops (wheat, barley) and grain corn – 104% on average for 2018-2024, which confirms the results of previous studies by P. Demelandt *et al.* (2010) and P. Götze *et al.* (2017), who also found a positive effect of these predecessors on the yield and quality of root crops.

The decrease in yield after soybeans (-4-8%) was not consistent with established ideas about legumes as valuable predecessors, which can be explained by phytosanitary risks, low residual moisture content, and possible exposure to herbicides with a long soil half-life (Prysiashniuk *et al.*, 2022; Kluger *et al.*, 2025). A particularly significant decrease in yield after soybeans was observed on light soils with low buffering capacity, which confirms the high dependence of beets on the structural and agronomic state of the soil (Bodner & Alsalem, 2023). Analysis

of agricultural soil groups showed that chernozems and loessial loams provide a steady increase in yield after grain – up to 106%, while on sandy and carbonate soils the positive effect of the predecessor was weaker or was levelled by water scarcity. Similar patterns were found in the studies by T. Hurisso *et al.* (2015), where it was proved that in conditions of limited water supply, the physical and chemical properties of the soil significantly affect the level of yield even with the same agrotechnical measures. After corn, and after grain, there was an increase in yield even despite possible competition with beets for moisture and a high amount of crop residues. This is consistent with data by H. Koch *et al.* (2018), who indicated the positive effect of corn, provided that soil compaction is controlled and the seed layer is properly prepared. Despite the general recognition of soybeans as a good predecessor, in the conditions of short-rotation crop rotation with high saturation with industrial crops, its efficiency was lower. This result was consistent with conclusions of C. Guo *et al.* (2024), who indicated the limited structural capacity of soybeans and the risks for subsequent crops in arid zones.

Thus, the results obtained did not confirm the expected advantage of leguminous predecessors, in particular soybeans, in short-rotation crop rotations, which indicates the need for further research considering individual soil and climatic zones, technological operations, and fertiliser systems. In general, on highly productive soils, the positive effect of grain predecessors was most fully manifested, which serves as an argument in favour of their priority use in short-rotation crop rotations in appropriate soil and climatic conditions.

CONCLUSIONS

In the course of long-term production studies conducted in 2018-2024 on the farm of PE “Zakhidnyi Buh”, it was established that the predecessor is one of the key agrotechnical factors that determines the level of productivity of sugar beet in the conditions of short-rotation crop rotations in the western forest-steppe of Ukraine. A comparative analysis of the effectiveness of the three main groups of predecessors: cereals, grain corn, and soybeans showed a clear

preference for cereals, in particular, winter wheat and barley. On average, over the years of the study, these crops provided the highest relative yields (104-106%) compared to the baseline level, which confirms their agronomic feasibility as predecessors in beet crop rotations. Soy, which is traditionally considered a valuable predecessor due to its ability to fix nitrogen, did not confirm its effectiveness under the analysed conditions. The yield of beets after soybeans remained 6-9% lower than after cereals, and in some years reached only 94% of relative productivity. The decrease in yield was explained by a number of negative factors: a weak mulching effect of post-harvest residues, potential exposure to residual herbicides, a high level of damage by soil pathogens, and a reduced supply of moisture in the arable layer after growing soybeans. The effect of the predecessor on yield was significantly modified by the type of soil. On highly productive soils – chernozems and loessial loams, the positive effect of cereals and corn was most pronounced – an increase in beet yield by 5-6%. On the other hand, on carbonate and sandy soils with low moisture capacity, the differences between the variants were less pronounced, and the overall beet yield decreased. In such conditions, soy was particularly ineffective, which indicates a restriction of its use in low-buffer areas with an increased risk of moisture deficiency.

Thus, the results obtained did not confirm the generally accepted preference of soybeans as a predecessor in short-rotation crop rotations in the conditions of the western forest-steppe of Ukraine. This requires a review of approaches to planning crop rotations in intensive agricultural systems and considering the complex influence of the predecessor, soil type, and microclimatic conditions. To increase the adaptability of crop rotations, it is recommended to apply a differentiated approach, in which cereals are priority predecessors on fertile soils, and soybeans should be excluded from beet predecessors on light, low-moisture soils. The prospects for further research consist in a detailed study of the interaction between the predecessor, fertiliser systems, and structural and agronomic properties of the soil, to create adaptive agricultural technologies for growing sugar beet in the context of climate change and the intensification of agriculture.

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CONFLICT OF INTEREST

None.

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Вплив попередника на врожайність цукрового буряка в короткоротаційних сівоzmінах в умовах Західного Лісостепу України

Анотація. У зв'язку з інтенсифікацією виробництва цукрового буряка в умовах короткоротаційних сівоzmінів зростає значення оптимального вибору попередника для забезпечення стабільної врожайності. Раціональне чергування культур є ключовим фактором підтримання родючості ґрунтів та зниження ризику фітосанітарних проблем. Метою роботи було оцінити вплив різних попередників на урожайність і збір цукру з урахуванням типу ґрунтів у Західному Лісостепу України. У дослідженні використано метод порівняльного аналізу продуктивності цукрового буряка після різних попередників на ґрунтах різного генетичного походження; статистичну обробку результатів проведено методом дисперсійного аналізу та регресійного моделювання. Було досліджено урожайність коренеплодів, рівень цукристості та валовий збір цукру після таких попередників, як озима пшениця, озимий ячмінь, соя та кукурудза. Було встановлено, що найвищу врожайність забезпечували зернові попередники (озимі пшениця, ячмінь), особливо на високопродуктивних ґрунтах. Було проаналізовано взаємозв'язок між типом ґрунту і ефективністю попередника: на карбонатних і піщаних ґрунтах урожайність після сої та кукурудзи знижувалась до 8,7-9,5 т/га. Було узагальнено, що родючість ґрунту пом'якшує негативний вплив менш сприятливих попередників. Було встановлено, що дія попередника істотно залежить від типу ґрунту: на чорноземах і лісових ґрунтах ефект зернових був найбільш вираженим. Отримані результати можуть слугувати основою для розробки регіонально адаптованих рекомендацій щодо структури сівоzmінів у бурякосіючих господарствах. Результати роботи можуть бути використані агрономами, консультантами та аграрними виробниками для удосконалення сівоzmінів та оптимізації технології вирощування цукрового буряка в умовах Західного Лісостепу

Ключові слова: карбонатні ґрунти; тип ґрунту; продуктивність агроценозів; структурно-агрохімічні властивості; родючість ґрунтів

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Biochemical composition and nutritional value of rowan-chokeberry hybrids (*×Sorbaronia fallax* (C.K. Schneid.) C.K. Schneid.) developed in Ukraine

Abstract. This study provided a comprehensive analysis of the biochemical composition and nutritional value of nine promising rowan-chokeberry hybrids (*×Sorbaronia fallax*) developed at the National University of Life and Environmental Sciences of Ukraine (NULES). These hybrids were compared to two established cultivars: 'Vseslava' and 'Nero'. The research aimed to evaluate the content of dry matter, soluble solids, total sugars, titratable acidity, pectin, ascorbic acid, polyphenolics, anthocyanins, and chalcones. Fruit samples were collected in 2023-2024 from NULES experimental orchards. The results showed significant differences between the genotypes. Specifically, genotype 5-84 exhibited the highest levels of dry matter, soluble solids, ascorbic acid, anthocyanins, and chalcones, while genotype 3-15 generally had the lowest levels. The effect of the cultivation year was only statistically significant for pectin content. Strong positive correlations were observed between dry matter and soluble solids ($r=0.90$) and between anthocyanins and chalcones ($r=0.99$). Overall, the hybrids surpassed the parent cultivar in several nutritional aspects, including sugar content, pectin, ascorbic acid, anthocyanins, and chalcones, highlighting their significant genetic potential. The findings of this study offered valuable information for breeding programmes focused on improving the nutritional traits of these fruits. Breeders and agronomists can use these results to select the best genotypes for further cultivation. Furthermore, producers of food and dietary supplements can leverage this data to develop new functional products

Keywords: *×Sorbaronia fallax* subsp. *fallax*; genotypes; ascorbic acid; polyphenols; anthocyanidines

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INTRODUCTION

The development of contemporary horticulture is increasingly driven by the introduction of new fruit crops that offer enhanced resistance to abiotic and biotic environmental factors and possess a unique biochemical composition rich in biologically active substances. Many formerly wild fruit plants, such as blueberry, cranberry, kiwifruit, sea buckthorn, and black chokeberry, are cultivated on hundreds of thousands of hectares in many countries, providing people with valuable fruit for fresh and processed consumption. In the 20th century, a new fruit crop called black chokeberry, also known as black rowan, gained widespread popularity as a novel fruit crop. Its fruits are highly valued for their exceptional content of bioflavonoids. According to research by Z. Kobus *et al.* (2019), the therapeutic properties of bioflavonoids for cardiovascular health are highlighted. A. Sidor & A. Gramza-Michałowska (2019) pointed to the high antioxidant potential of the fruits, making them beneficial for a healthy diet. Furthermore, H. Yang *et al.* (2019) noted that due to their high anthocyanin content, the fruits are also used as a food colouring. Recent reviews, such as those by J. Xu *et al.* (2024), highlighted the diversification of chokeberry products into juices, fermented beverages, and functional foods, driven by growing market demand. This research underscores the numerous applications of chokeberry as a functional food, primarily due to the health benefits of its polyphenolic compounds and exceptional antioxidant properties, positioning chokeberries as an important source of natural functional ingredients. According to B. Strik *et al.* (2003) and B. Green *et al.* (2023), garden chokeberry cultivation has expanded beyond Europe to other continents.

Horticulturalists initially regarded the cultivated plant as a cultivated variety of *Aronia melanocarpa* (Michx.) Elliott. However, subsequent molecular studies definitively established it as a hybrid, resulting from the intergeneric cross between *Aronia melanocarpa* (black chokeberry) and *Sorbus aucuparia* L. (common rowan). Various names have been proposed for this hybrid by systematists: *Aronia mitschurinii* A. Skvortsov & Maitulina and *×Sorbaronia mitschurinii* A. Skvortsov & Maitulina. However,

the botanically correct name for hybrids between these parent species is *×Sorbaronia fallax* (C.K. Schneid.) C.K. Schneid. (International code of..., n.d.). Morphologically, the new fruit plants are more similar to *Aronia* species, while *Sorbaronia fallax*, the preferred name for such hybrids, has leaves with an intermediate morphology between the simple leaves of *Aronia* species and the compound leaves of *Sorbus*. To address this, A. Stalažs & A. Bādere (2023) recognised two subspecies within *Sorbaronia fallax*: subsp. *fallax* with intermediate-structure leaves and subsp. *mitschurinii* A. Skvortsov & Maitulina with simple leaves. All cultivars of the garden chokeberry, also known as the black chokeberry *sensu* horticulturists, belong to *×Sorbaronia fallax* subsp. *mitschurinii*. These plants are notable for their apomictic seed development, a trait that ensures seedlings largely retain the characteristics of the mother plant, thereby facilitating the establishment of industrial plantations using seed-derived planting material. Despite this, horticultural practice often favours varietal culture through the vegetative propagation of superior genotypes, which are then recognised as named varieties or cultivars. The first cultivar, *Sorbaronia fallax* subsp. *mitschurinii* 'Nero', was registered in Czechoslovakia in 1989. In subsequent years, other named cultivars of *Sorbaronia fallax* subsp. *mitschurinii* appeared in various European countries. Due to the apomictic development of their seeds, these cultivars were practically identical to each other.

The first variety of garden chokeberry of Ukrainian breeding, 'Vseslava', was included in the State Register of Plant Varieties of Ukraine in 2019 (Ministry of Agrarian Policy..., 2025). Uniquely among the widely cultivated varieties of this crop, 'Vseslava' belongs to *Sorbaria fallax* subsp. *fallax*. According to V. Mezhenkyj *et al.* (2024), while 'Vseslava' surpasses *×Sorbaronia fallax* subsp. *mitschurinii* cultivars in fruit size and number of fruits per cluster, it exhibits lower levels of polyphenol compounds. Unlike *Sorbaronia fallax* subsp. *mitschurinii*, which produces genetically and morphologically homogeneous seedlings, 'Vseslava' seedlings exhibit significant variability. This variability provides a solid foundation for future breeding efforts aimed at

enhancing the cultivation of garden chokeberry and garden rowan, which are both RCH's.

Therefore, this study specifically aimed to investigate the biochemical variability of selected *×Sorbaronia fallax* subsp. *fallax* 'Vseslava' seedlings, providing insights into their potential for further horticultural development.

MATERIALS AND METHODS

Plant Materials. The breeding fund, consisting of 'Vseslava' seedlings, was cultivated using a 3×1 m planting scheme in the Fruit & Vegetable Garden at the National University of Life and Environmental Sciences of Ukraine (NULES) in Kyiv. The study used nine RCH's genotypes from this collection: 2-49, 2-50, 2-63, 3-6, 3-15, 3-42, 3-88, 5-58, and 5-84. Cultivars 'Nero' and 'Vseslava' from the collection orchard of the Educational, Research and Productive Laboratory of Genetic Resources, Introduction and Breeding of Rare Fruits and Ornamental Plants at the Department of Horticulture of NULES, near Kyiv, were also used. The plants were cultivated according to the standard agricultural practices employed for fruit crops in the region, with due consideration given to the local soil and climatic conditions. Fruit samples of these hybrids and cultivars were harvested in mid-August of consecutive years (2023 and 2024) when the pomes were visually assessed as ripe based on their black colour at maturation. The study was conducted in compliance with the ethical standards of the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1976).

Dry matter. To determine dry matter, fruit samples (3-4 g) were dried to a constant weight in an SNOL 58/350 (Ukraine) drying cabinet at 98-100°C. The results are expressed as a percentage.

Soluble solids. Soluble solids were measured using a PAL-1 ATAGO (China) portable refractometer. For the analysis, 15-20 fruits were homogenised, and a drop of the resulting juice was placed on the refractometer glass. The data are also expressed as a percentage.

Organic titrated acids. To extract the acids, 25 g crushed sample was extracted with hot distilled water. After cooling and filtering, 20 ml of the extract was titrated with 0.1 N sodium hydroxide using phenolphthalein as an indicator

until a stable pink colour appeared. The acid content was then calculated using an equation that includes a conversion factor to citric acid and expressed as a percentage of the raw mass.

Sugars. Sugars were extracted from the fruit with hot distilled water. The extract was then purified to remove proteins and pigments. Sucrose was hydrolysed into glucose and fructose by heating with 10% hydrochloric acid. The resulting sugars were oxidised using Fehling's solution, and the optical density of the solution was measured at 640 nm with a ULAB 102UV (China) spectrophotometer. A standard curve, created from glucose solutions of known concentrations, was used to calculate the final sugar content, which was expressed as a percentage of the original mass.

Pectin Substances. To determine the content of pectin substances, the sample was first purified with ethyl alcohol to remove sugars and pigments. Soluble pectin was then extracted with water, and protopectin was extracted with 1N sulphuric acid. The protopectin was hydrolysed to galacturonic acid by heating. A coloured complex was formed by adding a 0.2% carbazole solution and concentrated sulphuric acid to both the soluble pectin and protopectin extracts. The optical density of these solutions was measured at 535 nm using a ULAB 102UV spectrophotometer. The final pectin content was calculated using a calibration graph based on galacturonic acid standards, with results expressed as a percentage.

Ascorbic Acid. To determine ascorbic acid, a sample was mashed and extracted with a solution of 2% oxalic acid and 1% hydrochloric acid. The filtered extract was then titrated with a 2,6-dichlorophenolindophenol solution (Tilmans' paint). The ascorbic acid content was calculated using an equation based on the titration results and expressed as mg per 100 g of raw mass.

Total polyphenolic. The total polyphenolic content was extracted from a mashed sample using ethyl alcohol. The resulting extract was then combined with distilled water, Folin-Denis reagent, and a saturated sodium carbonate solution. After a one-hour reaction period, the optical density was measured at 640 nm using a ULAB 102UV spectrophotometer. The final content was calculated using a standard curve prepared with chlorogenic acid solutions and

expressed as mg/100 g of raw mass.

Anthocyanin and Chalcone. Anthocyanin and chalcone content were determined spectrophotometrically. An alcohol extract from an acidified plant homogenate (containing 3.5% hydrochloric acid) was prepared, and its absorption was measured at 530 nm and 364 nm, respectively, using a ULAB 102UV spectrophotometer. The results are expressed in mg/100 g of raw mass.

Statistical analyses. Descriptive statistics were used to analyse the data obtained and calculate the average values, standard deviation (SD), and coefficient of variation (CV%) for each trait over two years. The percentage change between 2023 and 2024 for each biochemical composition trait was determined, as was the range of fluctuations. An independent two-sample Welch's t-test was performed to detect significant differences between cultivars for each parameter, assuming unequal variances and a significance level of $\alpha = 0.05$. The effect of year and genotype on each selection parameter was assessed separately using a two-factor analysis of variance (ANOVA) in Microsoft Excel. Fisher's least significant difference (LSD) test was used to determine significant differences between means at a 95%

confidence level ($p \leq 0.05$). Results are presented as the mean \pm standard deviation. To assess the linear relationships between the measured parameters, Pearson correlation coefficients were calculated using Microsoft Excel. The dendrogram of genotypes was constructed using the Python programming environment. Data normalisation was performed using Z-score (StandardScaler), and hierarchical clustering was carried out by Ward's method (Ward's linkage) with the aid of the scikit-learn and SciPy libraries. Visualisation was performed using Matplotlib.

RESULTS AND DISCUSSION

Two cultivars were included in the study: *Sorbaronia fallax* subsp. *mitschurinii* 'Nero', a typical example of garden chokeberry; and *Sorbaronia fallax* subsp. *fallax* 'Vseslava', the mother cultivar of the nine RCH's genotypes studied. Due to the different growing conditions, these varieties cannot be used as controls for these RCH's genotypes. However, a comparative analysis of biochemical parameters enables to identification of common features and differences. The biochemical composition of these cultivars is presented in Table 1 and Table 2.

Table 1. Biochemical composition of two cultivar fruits, %

Genotype	Dry matter	Soluble solids	Total sugar	Titrateable acidity	Sugar/Acid ratio	Pectin substances
'Nero'	22.56 \pm 5.93	17.91 \pm 3.83	6.91 \pm 0.42	1.58 \pm 0.21	4.41 \pm 0.83	0.99 \pm 0.01a
'Vseslava'	17.90 \pm 1.83	17.76 \pm 0.93	5.70 \pm 1.41	1.49 \pm 0.07	3.81 \pm 0.77	0.72 \pm 0.01b

Note: the data represent average values for 2023-2024 ($\bar{x} \pm SD$, $n=2$), where SD – standard deviation, n – number of replicates. Different letters within a column indicate a statistically significant difference ($p < 0.05$, Welch's t-test). Letters are assigned from the highest to the lowest mean value

Source: compiled by the authors

Table 2. Biologically active compounds of two cultivar fruits, mg/100 g

Genotype	Ascorbic acid	Total polyphenols	Anthocyanins	Chalcons
'Nero'	12.44 \pm 2.63	3,318.45 \pm 193.11a	148.92 \pm 11.77	74.35 \pm 22.27
'Vseslava'	13.72 \pm 2.22	2,111.45 \pm 147.86b	113.47 \pm 22.44	42.00 \pm 7.35

Note: the data represent average values for 2023-2024 ($\bar{x} \pm SD$, $n=2$), where SD – standard deviation, n – number of replicates. Different letters within a column indicate a statistically significant difference ($p < 0.05$, Welch's t-test). Letters are assigned from the highest to the lowest mean value

Source: compiled by the authors

Welch's t-test successfully demonstrated that most traits were not statistically significant ($p > 0.05$). However, statistically significant

differences were observed between 'Vseslava' and 'Nero' for pectin substances and total polyphenol content only. The anthocyanins and

chalcones traits approached statistical significance. Specifically, 'Vseslava' accumulates lower amounts of both pectin substances and total polyphenols in its fruits compared to 'Nero'. Research by S. Kulling & H. Rawel (2008) showed that the pectin content in fresh chokeberry fruits ranges from 0.30 to 0.75%. This range is supported by the study by M. Trenka *et al.* (2020), who reported a pectin content of 0.35-0.50%. Notably, the pectin content in 'Vseslava' under experimental conditions was significantly higher than the reported ranges.

Cultivars of garden chokeberry belonging to *×Sorbaronia fallax* subsp. *mitschurinii* are valued precisely for their extremely high total polyphenol content. The lower quantity of these compounds in the fruits of *Sorbaronia fallax* subsp. *fallax* 'Vseslava' may indicate a reduced value of this cultivar in terms of this biochemical trait. These data align with earlier comparative studies of *Aronia* and garden chokeberry cultivars. For example, V. Mezhenkyj *et al.* (2024) propose that the total polyphenol content decreases

in the following order: *Aronia melanocarpa* > *×Sorbaronia fallax* subsp. *mitschurinii* > *×Sorbaronia fallax* subsp. *fallax*. M. Brand *et al.* (2017) also reported a higher content of total polyphenols in chokeberry species compared to garden chokeberry cultivars.

Nevertheless, 'Vseslava' demonstrated the capacity to accumulate total polyphenols as some cultivars of *×Sorbaronia fallax* nothosubsp. *mitschurinii*, and the fruits of its seedlings can have a higher content of total polyphenols (Gürer *et al.*, 2023; Mezhenkyj *et al.*, 2024). Considering that 'Vseslava' possesses significantly better productivity characteristics (such as the number of fruits per cluster and their mass) compared to *×Sorbaronia fallax* subsp. *mitschurinii* cultivars, it represents a valuable source for garden chokeberry breeding. Therefore, a breeding fund of several hundred 'Vseslava' seedlings was established. Nine genotypes, selected based on the aforementioned morphological fruit characteristics, were analysed for their fruit biochemical composition (Tables 3, 4).

Table 3. Biochemical composition of RCH fruits, %

Genotype	Dry matter	Soluble solids	Total sugar	Titrateable acidity	Sugar/Acid ratio	Pectin substances
2-49	20.74 ± 0.90cd	18.31 ± 0.98bc	7.44 ± 1.10	1.36 ± 0.42	5.88 ± 2.65	0.97 ± 0.02b
2-50	19.04 ± 0.63d	16.36 ± 3.20cd	6.77 ± 0.41	1.64 ± 0.02	4.12 ± 0.30	1.09 ± 0.01a
2-63	23.91 ± 0.16abc	21.02 ± 1.16ab	7.76 ± 0.04	1.17 ± 0.07	6.65 ± 0.43	0.86 ± 0.06d
3-6	23.38 ± 0.74bc	20.36 ± 2.35bc	7.16 ± 0.14	1.44 ± 0.04	4.97 ± 0.25	0.74 ± 0.02f
3-15	18.67 ± 4.67d	15.11 ± 0.72d	6.71 ± 1.06	1.23 ± 0.16	5.55 ± 1.56	0.59 ± 0.01g
3-42	24.47 ± 0.04ab	21.66 ± 1.36a	7.27 ± 0.72	1.07 ± 0.07	6.84 ± 1.13	0.96 ± 0.01b
3-88	22.16 ± 1.70bcd	18.26 ± 2.49bc	6.11 ± 0.03	1.07 ± 0.34	6.01 ± 1.88	0.83 ± 0.02e
5-58	20.75 ± 0.85ab	20.76 ± 1.22ab	6.52 ± 1.40	1.14 ± 0.02	5.76 ± 1.34	0.58 ± 0.01g
5-84	27.24 ± 2.00a	23.01 ± 1.71a	6.27 ± 0.85	1.02 ± 0.09	6.10 ± 0.28	0.92 ± 0.01c

Note: the data represent average values for 2023-2024 ($\bar{x} \pm SD, n=2$), where SD – standard deviation, n – number of replicates. Different letters indicate values that are significantly different within one column according to results of the LSD test ($p \leq 0.05$). Letters are assigned from the highest to the lowest mean value

Source: compiled by the authors

Table 4. Biologically active compounds of RCH fruits, mg/100 g

Genotype	Ascorbic acid	Total polyphenols	Anthocyanins	Chalcones
2-49	19.90 ± 0.42b	1,617.70 ± 280.40	93.30 ± 8.35ab	40.05 ± 4.88ab
2-50	21.56 ± 1.39a	1,564.55 ± 129.32	42.31 ± 6.81c	25.15 ± 1.48c
2-63	20.78 ± 0.55ab	1,699.60 ± 184.78	41.70 ± 0.28c	26.90 ± 0.57c
3-6	18.82 ± 1.66bc	1,357.55 ± 561.94	78.78 ± 22.79b	36.80 ± 0.00b
3-15	6.17 ± 2.08d	1,644.00 ± 768.17	20.10 ± 0.71c	20.85 ± 0.78c
3-42	21.07 ± 0.70ab	2,021.90 ± 357.96	101.27 ± 5.43ab	44.00 ± 6.79b
3-88	16.95 ± 0.97c	1,919.70 ± 99.42b	91.66 ± 5.47ab	38.20 ± 4.10ab

Table 4, Continued

Genotype	Ascorbic acid	Total polyphenols	Anthocyanins,	Chalcones
5-58	20.00 ± 0.28ab	2,215.95 ± 383.18	119.32 ± 6.10a	47.20 ± 5.52a
5-84	21.08 ± 0.42ab	2671.40 ± 261.06	114.53 ± 24.08a	46.70 ± 8.49a

Note: the data represent average values for 2023-2024 ($\bar{x} \pm SD$, $n=2$), where SD – standard deviation, n – number of replicates. Different letters indicate values that are significantly different within one row according to results of the LSD test ($p \leq 0.05$). Letters are assigned from the highest to the lowest mean value

Source: compiled by the authors

A two-factor ANOVA revealed statistically significant differences ($p \leq 0.05$) between genotypes for most biochemical parameters under study, except total sugars, titratable acidity, the sugar-acid index, and total polyphenols. This finding underscores the substantial genetic control over these traits and highlights the crucial role of genotype in determining desirable fruit quality characteristics. For instance, genotype 5-84 consistently exhibited the highest levels of dry matter, soluble solids, ascorbic acid, anthocyanins, and chalcones, whereas genotype 3-15 generally showed the lowest levels of these substances. Furthermore, genotypes 2-50, 2-63, 3-42, and 5-58 demonstrated ascorbic acid content comparable to genotype 5-84, while genotypes 2-49, 3-88, and 5-58 were similar in their anthocyanin and chalcone accumulation. Although there were no significant differences in total polyphenol content among genotypes, potentially due to the limited number of observations, genotypes 5-58 and 5-84 numerically exhibited the highest levels of anthocyanins, chalcones, and overall total polyphenols. Significant differences in pectin content were also identified across almost all genotypes, with genotype 2-50 notably accumulating the highest level, which was also associated with the highest ascorbic acid content.

The fruits of the studied genotypes exhibited high sugar content and a favourable sugar-to-acid ratio, contributing positively to their

nutritional value and taste. These characteristics generally positioned them as superior to the two reference cultivars, including the 'Vseslava' parent cultivar. However, it is important to acknowledge that differences in soil conditions across cultivation sites might have influenced these characteristics (Yavorovskiy & Brovko, 2014). Furthermore, the accumulation of high amounts of pectin supports the nutritional value of these genotypes and enhances their suitability for fruit processing. According to A. Sidor & A. Gramza-Michałowska (2019) and J. Xu *et al.* (2024), biologically active substances with high antioxidant potential, such as ascorbic acid and bioflavonoids, are crucial components of a healthy modern diet. Fruits of the RCH seedlings, in particular, demonstrated higher ascorbic acid content than the cultivars under study, with some genotypes also exhibiting comparable levels of bioflavonoids. According to the two-factor ANOVA, the effect of the year of cultivation was statistically significant ($p \leq 0.05$) exclusively for pectin content. This indicates that while certain parameters may exhibit inter-annual variation influenced by weather conditions, the primary determinant for most characteristics resides at the genetic level. Table 5 provides a summary of the statistics for each chemical trait across the two growing years (2023 and 2024), offering valuable insights into the mean values, variability, and dynamic changes in the fruit's chemical composition among the studied genotypes.

Table 5. Statistics describing the chemical composition of the fruits of the genotypes that were studied for each trait ($n = 9$)

Trait	Year	$\bar{x} \pm SD$	CV, %	Min – max	Change, % (2024 compared to 2023)
Dry matter	2023	23.04 ± 2.77	12.01	19.49–28.72	-6.76
	2024	21.48 ± 3.21	14.94	15.36–25.75	
Soluble solids	2023	20.47 ± 2.73	13.33	15.62–24.22	-10.00
	2024	18.39 ± 2.72	14.81	14.10–21.80	

Table 5, Continued

Trait	Year	$x \pm SD$	CV, %	Min – max	Change, % (2024 compared to 2023)
Total sugar	2023	6.89 ± 0.69	9.96	5.66–7.78	-3.22
	2024	6.60 ± 0.94	13.43	5.53–8.21	
Titratable acidity	2023	1.23 ± 0.29	23.85	0.83–1.66	2.09
	2024	1.25 ± 0.20	16.26	1.02–1.66	
Sugar-Acid Ratio	2023	5.86 ± 1.21	20.59	4.01–7.34	-3.26
	2024	5.67 ± 1.40	24.66	3.90–7.75	
Pectin substances	2023	0.82 ± 0.17	20.98	0.57–1.08	3.21
	2024	0.85 ± 0.18	20.72	0.58–1.10	
Ascorbic acid	2023	18.27 ± 5.28	28.91	4.70–21.56	2.27
	2024	18.69 ± 4.47	23.95	7.64–22.54	
Total phenolics	2023	1885.89 ± 486.78	25.81	1101.00–2856.00	-2.95
	2024	1830.23 ± 503.76	27.52	970.10–2486.90	
Anthocyanins	2023	78.54 ± 38.12	48.53	19.60–131.56	-1.09
	2024	77.68 ± 34.61	14.55	20.60–115.00	
Chalcones	2023	37.79 ± 11.74	31.05	20.30–52.70	-8.38
	2024	34.62 ± 8.34	24.09	21.40–43.50	

Source: compiled by the authors

The inherent variability of plants can be described by the coefficient of variation, where 5-24% is the “lower” norm, 25-44% is the “upper” norm, and 45-63% is “large variation” (Mezhenskij, 2021). Most biochemical composition traits of the genotypes under study generally fluctuated within normal ranges, with the notable exception of anthocyanidin content in 2023. This anomaly was primarily influenced by the low anthocyanidin content observed in genotype 3-15, which, unlike the other genotypes and both cultivars, produces purple rather than characteristic black fruits. Nevertheless, the coefficient of variation for this trait decreased to the ‘lower’ norm the following year due to a smaller range of fluctuations. The decrease in the coefficient of variation for anthocyanins in 2024 could be because genotypes responded more uniformly to this year’s conditions. In general, secondary metabolites, such as ascorbic acid and compounds of flavonoid complex, have a higher coefficient of variation within the “upper” range. A higher coefficient of variation indicates significant genotypic variability in this trait, which is desirable for breeding purposes, as it enables the selection of genotypes with a high

concentration of these compounds. Such pronounced genotypic diversity, evidenced by a wide range of values, is crucial for breeding programmes aimed at improving fruit quality. Importantly, some genotypes were found to possess higher total content of polyphenols, anthocyanins, and chalcones compared to the original ‘Vseslava’ cultivar.

Comparison of annual averages revealed distinct trends in biochemical composition. Specifically, from 2023 to 2024, the content of dry matter, soluble solids, total sugars, total polyphenols, anthocyanins, chalcones, and the sugar-acid ratio, decreased by 1.09-10.00%. Conversely, titratable acidity, pectin substances, and ascorbic acid content increased by 2.09-3.21%. These fluctuations suggest that the stability of chemical component expression across different genotypes is influenced by yearly environmental conditions. Genotypes, therefore, can adapt to varying environmental conditions by altering both the average level and the degree of variability of biochemical indicators within the population. The linear relationships between the measured biochemical parameters of the fruit are shown in Table 6.

Table 6. Pearson correlation coefficients between indicators (r)

Indicator	Dry matter	Soluble solids	Total sugar	Titrate-ble acidity	Sugar/Acid Ratio	Pectin substances	Ascorbic acid	Total poly-phenols	Antho-cya-nins	Chalcones
Dry matter	1									
Soluble solids	0.90	1								
Total sugar	0.03	0.11	1							
Titrate-ble acidity	-0.58	-0.55	0.28	1						
Sugar/Acid ratio	0.56	0.57	0.24	-0.85	1					
Pectin substances	0.23	0.09	0.23	0.30	-0.08	1				
Ascorbic acid	0.49	0.65	0.22	0.07	0.09	0.62	1			
Total polyphenols	0.58	0.61	-0.54	-0.74	0.46	-0.02	0.25	1		
Anthocyanins	0.52	0.69	-0.31	-0.48	0.34	0.03	0.54	0.65	1	
Chalcones	0.57	0.74	-0.25	-0.51	0.40	0.02	0.53	0.66	0.99	1

Source: compiled by the authors

Following the classification by V. Mezhen-skiy (2021), the relationship between the traits is considered weak with a correlation coefficient of 0.1-0.29, moderate with a coefficient of 0.3-0.49, noticeable with a coefficient of 0.5-0.69, high with a coefficient of 0.7-0.89, and very high with a coefficient of 0.9-0.99. As anticipated, a very strong positive correlation ($r=0.90$) was observed between dry matter and soluble solids, given that soluble solids constitute the primary component of dry matter. Interestingly, despite the common association between dry matter and sugars, this study revealed only a weak correlation between soluble solids and sugar content. This suggests that other components of fruit composition, possibly the flavonoid complex, have a stronger influence on soluble solids. Soluble solids exhibit a noticeable or high positive correlation with the sugar/acid ratio ($r=0.57$), total polyphenols ($r=0.61$), ascorbic acid ($r=0.65$), anthocyanins ($r=0.57$), and chalcones ($r=0.74$). Conversely, high negative correlations were observed between titratable acidity and the sugar-acid index ($r=-0.85$) and total polyphenols ($r=-0.74$). A noticeable negative relationship also existed between titratable acidity and dry matter, soluble solids, and chalcones ($r=-0.58$ to -0.51). This suggests that, as the product ripens and acidity decreases, the concentration of these phenolic compounds, which often contribute to colour and antioxidant properties, increases.

Generally, sugar content shows a weak or moderate correlation with almost all indicators

($r=0.23-0.31$), and this relationship can be either positive or negative. However, the correlation between sugars and total polyphenols is notably negative ($r=-0.54$). Pectin substances exhibit weak to moderate positive and negative correlations ($r=0.02-0.30$) with all other biochemical composition parameters, except ascorbic acid, with which they exhibit a high correlation coefficient ($r=0.62$). This suggests that pectin content may be less directly influenced by, or correlated with, changes in sugars, acids, and phenolic compounds that occur during maturation. The weak relationship between ascorbic acid and both titratable acidity and sugar content may suggest independent metabolic pathways. Ascorbic acid's highest correlations were observed with soluble solids ($r=0.65$), pectin substances ($r=0.62$), and anthocyanins ($r=0.54$).

An extremely strong positive correlation almost suggests that anthocyanins and chalcones are chemically very closely related, perhaps in their accumulation patterns within the product. It could also indicate that chalcones are precursors to anthocyanins (Samota *et al.*, 2024). They are common subclasses of flavonoids in fruits and vegetables (Zheng *et al.*, 2025). J. Mahoney *et al.* (2022) provide a detailed description of the biosynthetic pathway of anthocyanins in chokeberry, confirming that the synthesis of flavonoids, including anthocyanins, begins with the formation of chalcones. However, the relationship between these two flavonoids and total polyphenols is only noticeable ($r=0.65-0.66$).

Although anthocyanins and chalcones are part of the total polyphenols, they only constitute a certain fraction. The accumulation patterns of other polyphenolic compounds may differ, which blurs the direct correlation. Different groups of biologically active compounds accumulate in different ways, reflecting the complexity of the chemical composition of garden chokeberry fruit. The main polyphenols in chokeberry fruits are catechol and chlorogenic acid (Yang *et al.*, 2019).

A noticeable positive correlation ($r = 0.53-0.54$) was also observed between anthocyanins/chalcones and ascorbic acid. This indicates a tendency for increased ascorbic acid content, another important bioactive compound in fruits, alongside higher levels of anthocyanins and chalcones, and vice versa. These findings align with previous research by N. Dobros *et al.* (2024), who reported correlations between anthocyanins, ascorbic acid, and other antioxidants varying with the ripening stage of chokeberry fruit. Indeed, the co-accumulation of ascorbic acid and anthocyanins contributes to the high antioxidant capacity of fruits, a finding supported by E. Guerrero-Álvarez *et al.* (2023). Furthermore, H. Yang *et al.* (2019) reported that unripe chokeberry fruits exhibit higher antioxidant activity due to their comparatively greater abundance of flavonoids, phenolic compounds, and total polyphenols compared to fruits at full ripeness. Overall, the correlation analysis not only confirmed established biochemical relationships but also elucidated specific associations within the studied genotypes. These insights are valuable for optimising breeding strategies, facilitating the simultaneous improvement of multiple interrelated fruit quality traits. Hierarchical clustering analysis, visualised through the dendrogram, provides valuable insights into the biochemical diversity and relationships among the genotypes under study (Fig. 1).

Within the first major cluster, genotypes 2-49 and 3-6 formed the tightest subgroup, merging at the lowest level of dissimilarity and exhibiting similar profiles across most parameters. Another distinct subgroup within this cluster comprises genotypes 2-63 and 3-42. These genotypes showed high levels of dry matter and soluble solids, a relatively high sugar-acid

ratio, and low titratable acidity, alongside generally high concentrations of polyphenols and anthocyanins, though they displayed some variations in the specific levels of total polyphenols, anthocyanins, and chalcones. These two subgroups (genotypes 2-49/3-6 and 2-63/3-42) subsequently joined at a Euclidean distance of 4, forming a central cluster characterised by more average or balanced biochemical profiles across all measured traits.

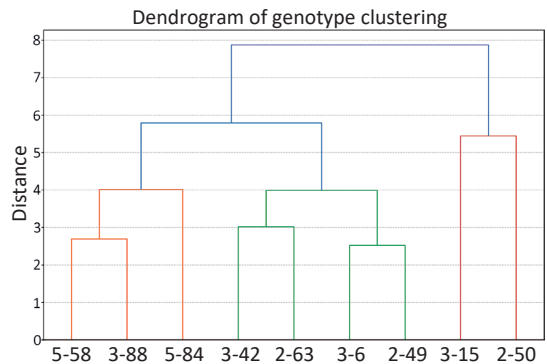


Figure 1. Dendrogram of genotype clustering based on biochemical characteristics

Source: compiled by the authors

The second major cluster was initiated by the close association of genotypes 3-88 and 5-58, merging at a Euclidean distance of approximately 2.7. This pair was then joined at a Euclidean distance of about 4.0 by genotype 5-84, which notably exhibited the highest levels of dry matter and soluble solids in both ripening years. This entire group (genotypes 3-88, 5-58, and 5-84) distinguished itself with exceptionally high levels of total polyphenols, anthocyanins, and chalcones, in addition to generally high levels of dry matter and soluble solids. Despite their initial association being at a slightly higher dissimilarity than that of the tightest cluster (genotypes 2-49 and 3-6), these three genotypes formed a distinct and relatively homogeneous cluster. These genotypes represent valuable sources of bioactive compounds, making them ideal candidates for the development of natural dyes and functional food additives.

Forming a distinct outlier group, genotypes 2-50 and 3-15 exhibited profiles notably different from each other and the main clusters.

They were generally characterised by a low content of anthocyanins and chalcones, as well as lower dry matter and soluble solids content. Genotype 3-15, in particular, displayed significantly lower ascorbic acid values. Conversely, genotype 2-50 is notable for its consistently highest pectin content over both study years. These two genotypes subsequently joined the previously described clusters at a remarkably high Euclidean distance of approximately 7.8, underscoring their significant biochemical dissimilarity from all other genotypes studied. This distinct group, while generally possessing lower levels of the main biochemical composition parameters, is characterised by other unique attributes. Specifically, genotype 3-15 is distinguished by its large, juicy, burgundy fruits. V. Mezhenskyj *et al.* (2024) pointed out that this makes it morphologically more similar to the rowan-like cultivar 'Titan' than to typical chokeberry-like cultivars. This variability highlights their potential for diverse applications, from fresh consumption to specific industrial processing, showcasing the wide genetic diversity within the hybrids under study.

CONCLUSIONS

A comprehensive two-year study (2023-2024) of the biochemical composition of fruits from nine RCH genotypes identified the key factors shaping their quality. Analysis of variance showed a highly statistically significant effect of genotype ($p < 0.05$) on most of the fruit quality parameters examined. This highlights the substantial genetic control over these traits and the critical role of genotype in forming desirable characteristics. Conversely, the effect of the cultivation year was statistically significant only for pectin content. Specifically, genotype 5-84 consistently demonstrated the highest levels of dry matter, soluble solids, ascorbic acid, anthocyanidins, and chalcones. In contrast, genotype 3-15 generally exhibited the lowest values for these compounds. This differentiation is exceptionally valuable for breeding purposes. Genotype 5-84 represents a promising donor for programmes aimed at creating varieties with enhanced nutritional and

antioxidant properties. Furthermore, genotype 2-50 stood out with the highest pectin content, making it a valuable candidate for the processing industry. Other genotypes, such as 3-42, 5-58, 2-49, and 3-88, also showed high or comparable levels of ascorbic acid, anthocyanidins, and chalcones, thus broadening the breeding pool.

Correlation analysis revealed strong interrelationships between key fruit quality parameters. Notably, the strong positive correlation between dry matter and soluble solids ($r = 0.90$) has significant practical value for selection. It allows breeders to use a quick and simple refractometry method to measure soluble solids as a reliable indicator for assessing the total dry matter content in large sample sets, which substantially accelerates the selection process. An extremely strong correlation was also found between anthocyanidins and chalcones ($r = 0.99$). This enables the analysis of only one of these parameters during selection for an indirect assessment of the total bioflavonoid content, which is crucial for selecting genotypes with high antioxidant activity. The visualisation of samples in Euclidean distance space confirmed genotypic differentiation, indicating their unique biochemical profiles. The obtained data underscore the significant genetic potential of the studied genotypes for use in breeding programmes aimed at improving nutritional traits. These results provide a robust foundation for further research and the development of new varieties with enhanced biochemical characteristics. Further research could focus on analysing other bioactive compounds in these genotypes to more comprehensively assess their value, and investigating how specific annual conditions impact the biochemical composition of the fruit.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Біохімічний склад і харчова цінність гібридів горобиноаронії (Sorbaronia fallax* (C.K. Schneid.) C.K. Schneid.) дібраних в Україні**

Анотація. У цьому дослідженні комплексно проаналізовано біохімічний склад та харчову цінність дев'яти перспективних гібридів горобиноаронії (**Sorbaronia fallax*), створених у Національному університеті біоресурсів і природокористування України (НУБіП). Їх порівнювали з двома сортами: 'Всеслава' та 'Nero'. Метою було оцінити вміст сухої речовини, розчинних сухих речовин, цукрів, титрованої кислотності, пектинових речовин, аскорбінової кислоти, поліфенолів, антоціанідинів та халконів. Зразки плодів збирали у 2023-2024 роках в дослідних садах НУБіП України. Результати показали значні відмінності між генотипами. Зокрема, генотип 5-84 мав найвищий вміст сухої речовини, розчинних сухих речовин, аскорбінової кислоти, антоціанідинів та халконів, тоді як генотип 3-15 – найнижчий. Вплив року вирощування був значущим лише для вмісту пектину. Виявлено сильні позитивні кореляції: між сухою речовиною та розчинними сухими речовинами ($r = 0,90$), а також між антоціанами та халконами ($r = 0,99$). Гібриди загалом перевершили батьківський сорт за вмістом цукрів, пектину, аскорбінової кислоти, антоціанідинів та халконів, що свідчить про значний генетичний потенціал. Результати дослідження надали цінну інформацію для селекційних програм, спрямованих на покращення харчових властивостей плодів. Вони можуть бути використані селекціонерами та агрономами для добору найкращих генотипів для подальшого культивування. Крім того, виробники продуктів харчування та дієтичних добавок можуть використовувати ці дані для розробки нових функціональних продуктів

Ключові слова: **Sorbaronia fallax* subsp. *fallax*; генотипи; аскорбінова кислота; поліфеноли; антоціани

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Assessment of the physiological state of the P-HL-A rootstock under conditions of phytoplasma infection

Abstract. The relevance of the study was conditioned by the significant influence of phytoplasma infections on the productivity and physiological state of rootstocks of garden crops, which created risks for the survival and development of buds during grafting and their further growth. The purpose of the study was to evaluate the physiological suitability of the P-HL-A rootstock in conditions of potential or existing phytoplasma infection during grafting. To achieve this goal, methods of molecular diagnostics were used, namely polymerase chain reaction (PCR) in real time to determine the presence of a pathogen, analysis of leaf tissue turgescence to assess water deficiency, and spectrophotometric determination of photosynthetic pigments (chlorophylls and carotenoids). Changes in the water regime and functional state of the photosynthetic apparatus of P-HL-A rootstocks depending on the degree of infection were studied. It was found that phytoplasma damage causes water deficiency in the range of 31.6-37.5% and a decrease in relative turgescence to 62.4-68.4%, which indicated the development of moderate water stress. The content of photosynthetic pigments was analysed, which decreased by 11.9-33.3% depending on the type of pigment and the level of infectious load. It was generalised that the initial exposure to the pathogen was manifested by a decrease in cell turgor and photosynthetic activity, which can negatively affect kidney survival during inoculation. The practical significance of the study lies in the fact that the results obtained can be used by gardeners, agronomists, and researchers in nurseries and research stations to optimise agrotechnical measures, control phytoplasma infections, and increase the efficiency of reproduction of fruit crops

Keywords: water deficiency; photosynthesis; cell turgescence; chlorophyll; carotenoids

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INTRODUCTION

The relevance of the study is conditioned by the growing spread of phytoplasma infections in European fruit crops and the high risk of their transmission during vegetative reproduction. This creates the need to investigate the functional stability of rootstocks used in intensive gardening technologies. Studying the effect of phytoplasma damage on rootstocks is important because these infections are quite common, easily transmitted during vegetative reproduction, and can reduce the compatibility and productivity of fruit crops. The study allows assessing the risks of using infected material and ensuring the effectiveness of vaccination.

Nowadays, gardening is constantly influenced by numerous abiotic and biotic factors that significantly determine the productivity and quality of fruits. A number of researchers such as T. El-Mageed *et al.* (2021), A. Mekdad *et al.* (2021), A. Shaaban *et al.* (2022), showed that abiotic stresses, in particular drought, lower temperatures, and spring frosts, can lead to a significant decrease in garden yields. Simultaneously, biotic factors, including viral, bacterial, and phytoplasma infections, pose a serious threat to plant growth and development. One of these threats is infection of plants with phytoplasmas – phytopathogenic bacteria. According to the literature analysis by R. Wang *et al.* (2024), phytoplasmas used to be called MLOs, and now they belong to the genus '*Candidatus Phytoplasma*' in the class Mollicutes. The main classification method is analysis of the 16S rRNA gene, with two strains considered different species if their similarity is less than 98.65%, and ANI (threshold 95-96%) is used for full-genome comparison. If this data is insufficient, MLSA is used. Phytoplasmas are further divided into 16sr groups and subgroups using RFLP analysis or the virtual iPhyClassifier tool. There are 48 known *Ca* species. Phytoplasma, grouped into 37 groups, for example, in the 16srxi group there are five species that belong to different subgroups.

In particular, G. Asudi *et al.* (2021) found that phytoplasmas cause morphological and physiological disorders such as leaf yellowing, dwarfism, and leaf blade reduction, accompanied by reduced photosynthetic activity and limited transpiration. In addition, these researchers

proved that systemic exposure to phytoplasmas can reduce the chlorophyll content and plant resistance to abiotic stresses, and in severe cases – cause plant death. S. Ahmad *et al.* (2019) noted that this leads to limited nutrient transport in the plant. According to the current protocols, phytoplasmas are included in the diagnostic protocols of the European and Mediterranean plant protection organisation EPPO Global Database (2023), which are regulated by the relevant standards. In particular, these include: PM 7/62 (3) '*Candidatus Phytoplasma mali*', '*Ca. P. pyri*' and '*Ca. P. prunorum*' and PM 7/150 (1) '*Candidatus Phytoplasma phoenicium*'. According to the requirements of the EPPO Global Database, mandatory testing for the presence of phytoplasmas is provided for such stypes of fruit crops as pome, stone, and vine. According to A. Konup *et al.* (2019), the correlation of the main groups of infectious diseases was determined in viticulture. It was found that among the detected pathologies of the vine, about 10% are viral diseases, approximately 25% are bacterial cancer, while the dominant share, about 65%, is phytoplasma diseases. Phytoplasma is also common in orchards of the Czech Republic. L. Valentová *et al.* (2022) found that phytoplasma is common in 80% of the pear samples examined. In general, according to the EPPO Global Database, this disease is widespread throughout the European continent.

Special attention is drawn to the risk of spreading phytoplasmas through vegetative reproduction, in particular during vaccination, which creates a threat of infection of both rootstocks and inoculations, as noted by R. Wang *et al.* (2024). This makes it relevant to investigate the effect of phytoplasma damage on the functional state of rootstocks, which is important for ensuring the effectiveness of grafting and preserving the productivity of garden crops. In the context of potential or existing phytoplasma damage, it is advisable to assess the physiological suitability of the rootstock used for grafting. The choice of rootstock P-HL-A as an object of research is conditioned by the need to determine its ability to maintain functional indicators and stability during intensive agrotechnical grafting. The rootstock is characterised by a reduced growth force, which is approximately

60% relative to wild mazzard cherry seedlings. It is recommended for use in intensive plantings in conditions of irrigation, the use of supporting structures, and high soil fertility. It is characterised by a high level of compatibility with most varieties and is characterised by a good ability to vegetative reproduction by both green cuttings and cultivation methods *in vitro*. The scientific originality consists in a comprehensive analysis of the effect of phytoplasma infection on the functional state of the P-HL-A rootstock of Czech selection in practical growing. The results obtained allow assessing the risks associated with the use of contaminated materials and develop recommendations for the use of healthy rootstocks to ensure successful grafting and maintain high productivity of garden crops.

The purpose of this study was to evaluate the physiological suitability of the P-HL-A rootstock under conditions of potential or existing phytoplasma infection during intensive agrotechnical grafting.

LITERATURE REVIEW

Contemporary studies demonstrate a significant influence of both biotic and abiotic stress factors on fruit crops and emphasise the complex interaction of these factors in agroecological conditions and their impact on the physiological state of plants. One of these factors is phytoplasma diseases, which can manifest typical symptoms or remain asymptomatic depending on the concentration of the pathogen in the plant tissues, the type of plant and its growing conditions. Phytoplasma diseases are an important pathogenic factor for both perennial and annual plants. They are characterised by the ability to spread unevenly through host tissues, which makes it difficult to accurately assess the degree of damage and the dynamics of disease development. In particular, the study by V. Singh *et al.* (2018), demonstrates that in sesame plants, phytoplasma concentrations in the early stages of infection positively correlate with disease severity. In later stages, there is a decrease in the level of the pathogen. In addition, significant changes in phytoplasma concentrations were recorded between the upper and lower parts of plants, with the distribution pattern varying from the early to late stages of infection development. These

data confirm the uneven distribution of phytoplasma in plant tissues, regardless of their age and life expectancy. Morphological changes that accompany phytoplasmic infections are also well documented in potato and tomato plants. Y. Arocha *et al.* (2007) noted that the disease begins with the development of additional lateral shoots that quickly lengthen and sprout through the top of the plant, giving it a branched appearance. In addition, there is a decrease in the size of the leaves, their twisting and yellowing. These symptoms reflect a violation of the hormonal balance of the plant, which leads to changes in normal growth and development and are typical of phytoplasma infections. The study by S. Ahmad *et al.* (2019) showed that phytoplasma infection in sesame seeds causes significant changes in plant metabolism and antioxidant protection, including increased activity of catalase, superoxide dismutase, and peroxidase enzymes, increased levels of phenols, proteins, proline, and glycynbetaine, and an increase in malone dialdehyde and hydrogen peroxide while reducing soluble sugars.

There are also studies that note the negative impact of phytoplasma infection on the physiological state of the plant, in particular, on a decrease in photosynthetic activity. For example, A. Bertaccini *et al.* (2014) and V. Kuyan (2016) indicated that phytoplasma infection leads to a significant decrease in the content of chlorophyll and carotenoids in apple leaves, disrupting photosynthesis. In addition, there is a decrease in the level of soluble proteins, in particular ribulose-1.5-bisphosphate carboxylase, and a decrease in the activity of photosystem 2 and nitrate reductase. Infection also reduced the content of specific thylakoid membrane proteins involved in water photolysis. The most relevant one for this study was the paper by Y. Tan *et al.* (2015), who investigated the effects of phytoplasma infection on sweet cherry trees. In the course of the study, characteristic morphological changes in the leaf blade and shoots were described, in particular, shortening of internodes, reducing the size of leaves, their yellowing, wrinkling, and twisting. In addition, a negative effect on plant physiological processes was recorded: infected leaves were characterised by a decrease in the chlorophyll content, a

significant decrease in the evaporation rate, a decrease in stomatal opening (Gs), an increase in the concentration of CO₂ in the intercellular space (Ci), and a decrease in intracellular resistance (Ls). Phytoplasma infection also led to significant changes in the hormonal balance in the leaves: an increase in cytokinin (ZT) levels was noted, while a decrease in the concentrations of gibberellins (GA) and abscisic acid (ABA). Elevated ZT levels stimulate abnormal cell growth and the development of additional shoots, while reduced GA and ABA inhibit normal leaf and stem development and reduce the plant's stress tolerance. Thus, the effect of phytoplasma on leaf morphology and development is mainly conditioned by a violation of hormonal regulation, and not just mechanical tissue damage. The negative effect on plant physiological processes was confirmed by X. Bai *et al.* (2009). In particular, G. Asudi *et al.* (2021) showed that NGS phytoplasma infects napier grass, disrupting the morphoanatomic structure of phloem and the transport of photosynthetic products, leading to inhibition of growth, leaf chlorosis, and activation of defence mechanisms through the accumulation of reactive oxygen species.

Given the significant influence of phytoplasma infections on the morphology, physiological processes, and hormonal balance of plants, an important aspect of their study is understanding the mechanisms of spread of these pathogens in cultivated plants, because it is the transmission routes that determine the rate of infection and the effectiveness of disease control measures. According to R. Tedeschi & A. Alma (2006), the main vector of pathogen transmission is cicadas. Simultaneously, an effective plant protection system can reduce transmission of infection through vector insects. But the infection that occurs during agrotechnical procedures, such as vaccinations, is almost impossible to limit.

Since grafting is one of the key methods of propagation of planting material, it is also one of the main ways of spreading pathogens, in particular phytoplasmas. According to K. Caglayan *et al.* (2023), phytoplasma transmission during grafting was recorded in pears, jujuba, and grapes. Research by S.-H. Lee *et al.* (2012) showed that it takes about 28 days to detect phytoplasma in a plant after grafting. It was found

that at the initial stages, phytoplasma particles are localised mainly in the root system, and after 82 days the infectious agent spreads to all organs of the plant.

Thus, numerous research results confirm that phytoplasma infections have a complex negative impact on the morphology, physiological state, and hormonal balance of plants, disrupting their normal growth, development, and resistance to stress factors. Given that grafting is one of the most common methods of propagation of planting material, but simultaneously one of the main ways of spreading phytoplasmas, it is particularly important to study their impact on the quality of the rootstock and its ability to ensure the water and physiological balance of the bud.

MATERIALS AND METHODS

Location and objects of research. The study was conducted in 2025 at the Research and Breeding Institute of Pomology "Holovousy" (Czech Republic), in the Department of the Fruit genetic resources. Rootstock for cherries and sweet cherries P-HL-A was used as the object of research. The presence of European Stone Fruit Yellows (ESFY) phytoplasma in plant material was preliminarily confirmed by polymerase chain reaction (PCR). According to the results of molecular diagnostics, all samples were classified into three conditional groups depending on the number of amplification cycles: PP (potentially positive), + (weakly positive), ++ (clearly positive). Plants in which the pathogen was not detected were used as a control group. Sampling was carried out in the third ten days of July, immediately before the start of budding, in order to assess the physiological state of the rootstocks before budding. Tissues were taken from four opposite sides of each plant at the same height, which ensured the representativeness of the samples. The experiment was performed in four repetitions, each of which included two plants.

Determination of plant water deficiency. To assess the water regime of the leaf tissue, turgescence properties were analysed using die-cuts. From the leaf blade, avoiding the main veins, 10 disk die-cuts were obtained using a drill with a diameter of 8 mm. The samples were weighed (raw mass before immersion), then placed in

distilled water in Petri dishes for 2 hours. After incubation, the leaf discs were carefully drained with filter paper and re-weighed (raw weight after immersion). To control the complete water saturation, the die-cuts were again submerged in water for 30 minutes and re-weighed. The samples were then dried in a drying cabinet for 40 minutes at 120°C, after which the dry weight was determined.

Based on the obtained data, the following indicators were calculated:

n Initial water content (g): raw weight before immersion – dry weight.

n Amount of water in the state of turgescence (g): raw weight after immersion – dry weight.

n Water deficit (%): ((amount of water in the turgescence state – initial water content) / amount of water in the turgescence state) × 100.

n Relative turgescence (%): ((crude weight before immersion – dry weight) / (crude weight after immersion – dry weight)) × 100.

n Relative turgescence deficit (%): 100 – relative turgescence.

Determination of green pigments in the plant. The samples were ground using liquid nitrogen in the presence of a small amount of MgCO₃, 20 mg of the resulting material was taken from ependorf-type tubes, after which 1.5 ml of methanol was added. After short-term stirring, the tubes were centrifuged for 5 minutes at 16,000 g. The content of chlorophyll a, chlorophyll b, and carotenoids in the supernatant was determined by the Wellburn method using a Genesys 180 spectrophotometer (USA).

Statistical processing of results. Statistical processing of experimental data was performed using Minitab 19 software suite (Minitab LLC, 2019). Before performing a univariate analysis of variance (ANOVA), the data were checked for normality using the Kolmogorov-Smirnov criterion. Statistically significant differences between the mean values were determined using the Tukey test at a significance level of $p \leq 0.05$.

Ethical standards. The study was conducted in accordance with the ethical standards of the Convention on Biological Diversity (1992) and Convention on the Trade in Endangered Species of Wild Fauna and Flora (1976). Only plant material (P-HL-A rootstock) was used in the work,

without the involvement of animal or human experiments.

RESULTS AND DISCUSSION

Lack of water limits plant productivity and yields in various ecosystems and agriculture. In addition to the ability to survive acute drought stress, which depends on the genotypic characteristics of the plant, the strength and duration of exposure, the speed and efficiency of recovery also play an important role in determining productivity. A study of the effect of phytoplasma infection on water deficiency in plants showed that all the samples under study were in a state of water stress. The standard value of water deficiency (WD) for physiologically healthy plants is 5-10%, while in the presented study, even control, uninfected samples showed WD at the level of 23.9%. The results show that even control, uninfected plants experienced severe water stress, since the level of their water deficiency significantly exceeded the physiological norm. Infected samples, depending on the degree of infectious load, had a significantly higher level of water deficiency – from 31.6 to 37.5%, which indicates a reduced adaptive ability of such plants to arid conditions. This indicates a direct effect of the pathogen on the water balance of plants.

In particular, the water deficit in PP samples (potentially positive) exceeded the control value by 7.7%, in + samples (weakly positive) – by 8.9%, and in ++ samples (clearly positive), respectively, by 13.7%. Although the analysis of variance did not reveal a statistically significant difference between individual infection groups, there is a clear tendency for water deficiency to increase with increasing infectious load. This indicates a negative effect of phytoplasma infection on the water balance of rootstocks, which may have adverse effects on bud survival during grafting (Table 1).

An important indicator of the water status of plants is relative turgescence (RT), which characterises the ability of cells to maintain turgor under stressful conditions. According to the generally accepted classification by M. Laxa *et al.* (2019), RT values in the range of 60-70% indicate moderate water scarcity. The results showed that control samples with a RT score of 76.1% were in a state of minor water stress. Simultaneously, plants infected with phytoplasma showed

lower RT values – from 62.4 to 68.4%, depending on the degree of infection, which indicates the development of moderate or even severe water deficiency. This condition potentially disrupts the physiological and biochemical processes in the plant, in particular metabolism, water

exchange, and transport of assimilants, and can have a negative impact on the overall functioning of the plant. Analysis of relative turgescence deficiency (RTD) indicators shows an increased need for water in infected plants to maintain a normal functional state.

Table 1. Physiological state of plants under conditions of varying degrees of phytoplasma infection (2025)

Indicator Sample	Water deficit indicators, %			Indicators of pigments, mg/g			
	WD ¹	RT ²	RTD ³	<i>a</i>	<i>b</i>	<i>a+b</i>	<i>karot.</i>
P-HL-A (k)	23.9±5.5 a	76.1±1.0 a	23.9±1.0 a	0.48±0.15 a	0.11±0.03 a	0.59±0.18 a	0.21±0.06 a
P-HL-A (pp)	31.6±6.2 b	68.4±5.6 b	31.6±5.9 b	0.32±0.14 a	0.08±0.03 a	0.40±0.17 a	0.15±0.04 a
P-HL-A (+)	32.1±5.7 b	67.9±6.2 b	32.1±6.2 b	0.32±0.07 a	0.09±0.02 a	0.41±0.09 a	0.15±0.03 a
P-HL-A (++)	37.6±1.0 b	62.4±5.5 b	37.6±5.5 b	0.40±0.22 a	0.11±0.04 a	0.52±0.24 a	0.17±0.08 a

Note: ± – standard deviation; alphabetic symbols indicate the difference between the options; ¹ – water scarcity; ² – relative turgescence; ³ – relative turgescence deficit
Source: compiled by the authors

Similar trends were recorded in the study by A. Bertaccini *et al.* (2014) on sesame (*Sesamum indicum*), where phytoplasma infection resulted in a statistically significant decrease in tissue water content by 11.4% compared to uninfected plants. Similar results were obtained in the study by L. Pavliuk *et al.* (2025), which showed that the water content in the leaf tissues of plants infected with PNRSV and PDV of the 'Nizhnist' cherry variety decreased by 20%. At the same time, when PDV was monoinfected in the 'Bohuslavka' variety and PNRSV in the 'Ksenia' variety, the water content in the infected samples was slightly higher by 1.4% and 5.7%, respectively, but these differences are statistically insignificant. According to the available literature data, this study is one of the few that evaluated the effect of phytoplasma on the water balance of plants. Due to the limited nature of such studies, unambiguous conclusions about the specific effects of the pathogen on different plant species remain difficult. However, it can be assumed that infection with phytoplasma has a more negative effect on plants of the genus *Prunus* compared to monoinfection with viral pathogens.

Water deficiency, as a rule, negatively affects the photosynthetic apparatus of plants, in

particular, the content of chlorophylls and carotenoids. As part of the study, a decrease in the concentration of these pigments in infected plants was observed compared to the control. However, the results of the analysis of variance did not reveal statistically significant differences. In general, the degree of reduction in the content of photosynthetic pigments ranged from 11.9 to 33.3%, depending on the type of pigment and the level of infection. The chlorophyll a content in PP (potentially positive) and + (weakly positive) samples was reduced by 33.3% compared to the control, while in ++ (clearly positive) samples it was only 16.7% lower. A similar trend was found for chlorophyll b: in PP (potentially positive) and + (weakly positive) samples, a decrease of 27.3 and 18.2%, respectively, was observed, while in ++ (clearly positive) the content of chlorophyll b was at the level of control plants not infected with phytoplasma. Despite this, the total amount of green pigments (chlorophyll a + b) in all infected groups remained lower compared to the negative control. A similar trend was recorded in terms of carotenoid content: in PP (potentially positive) and + (weakly positive) samples, it was reduced by 28.6%, and in ++ (clearly positive) – by 19% compared to the control. A decrease in

the level of pigments in samples with a higher concentration of the pathogen can be explained by the stress response of the plant, which occurs at the initial stages of infection. During this period, the most pronounced symptoms of the lesion and the negative impact of the pathogen on physiological processes, including photosynthesis. In the future, under conditions of prolonged exposure to the pathogen, the plant can partially adapt to the state of infection, which can reduce the severity of symptoms.

Studies by other researchers indicate a more pronounced negative effect of phytoplasma infection compared to the results recorded on the P-HL-A rhizome. Thus, according to S. Zafari *et al.* (2012), infected lime leaves showed a 70.9% decrease in chlorophyll a, 97.2% in chlorophyll b, and 98.7% in carotenoids. In addition, some studies indicate that the level of pigments in infected plants may depend on the age of the plant. For example, older apricot plants showed a 48.5% decrease in chlorophyll a, 50% decrease in chlorophyll b, and 43.1% decrease in carotenoids (Trempetić *et al.*, 2025). Young plants reacted less strongly to infection: a decrease in chlorophyll a was 7.3%, chlorophyll b – 14.3%, and carotenoids – 3.2% compared to healthy plants. The timing of the study also played an important role, since a greater decrease in photosynthetic pigments was recorded in the second half of the growing season. Therefore, it can be assumed that the chlorophyll content on the rootstock under study has already reached the maximum point of decrease and, given the sampling period, no further decrease should be expected. Another confirmation of the negative effect of phytoplasma on the plant was the study by Y. Tan *et al.* (2015), who showed that when sweet cherries were infected with subgroup B phytoplasma (16srv-B), the chlorophyll content decreased by 51-56% depending on the type of pigment. The ratio of chlorophyll a/b in infected leaves was reduced, while the ratio of carotenoids to the total content of chlorophylls increased compared to the control. Similar results were obtained by M. Bertamini *et al.* (2002) in studies on grapes and apple trees, which also recorded a decrease in the level of photosynthetic pigments in plants infected by phytoplasma.

Thus, phytoplasma infection simultaneously worsened the water status and photosynthetic characteristics of plants, which negatively affected their survival rate and productivity. In some cases, its effect was more pronounced than with monoinfection with viral pathogens. This highlights the importance of systematic monitoring of the infectious load and the introduction of adaptive agrotechnical measures to reduce the stress effect of the pathogen and maintain stable crop productivity.

CONCLUSIONS

The study showed that phytoplasma infection significantly affects the water status and photosynthetic activity of P-HL-A rootstock plants. Even control, uninfected plants showed a water deficiency of 23.9%, which significantly exceeds the standard values for physiologically healthy plants (5-10%). Infected samples, depending on the degree of infectious load, had an even higher water deficit: in PP (potentially positive) and + (weakly positive) samples, it was 31.6-32.1%, and in ++ (clearly positive) – 37.6%. The relative turgescence (RT) in the control samples remained at 76.1%, indicating a slight water stress, while in infected plants RT decreased to 62.4-68.4%, indicating moderate or severe water deficiency.

Simultaneously, phytoplasma infection negatively affected the photosynthetic apparatus. Chlorophyll a in PP (potentially positive) and + (weakly positive) samples decreased by 33.3%, chlorophyll b – by 18-27%, and in ++ (clearly positive) samples, the decrease was less, which indicates partial adaptation of the plant to long-term exposure to the pathogen. The carotenoid content in PP (potentially positive) and + (weakly positive) samples decreased by 28.6 %, and in ++ (clearly positive) – by 19% compared to the control. These changes indicate that at the initial stages of infection, the plant experiences the greatest stress, but over time, partial compensation of damage is possible.

Thus, phytoplasma infection simultaneously disrupts the water balance and reduces the concentration of photosynthetic pigments, which negatively affects the physiological state, photosynthesis, and potential productivity of plants. The results highlighted the importance of

monitoring the infectious load and implementing agrotechnical measures to minimise stress consequences, preserve rootstock survival, and maintain overall crop productivity. Further study of the combined effects of phytoplasma infection and abiotic stress on rootstock productivity and survival is important.

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CONFLICT OF INTEREST

None.

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Оцінка фізіологічного стану підщепи P-HL-A за умов інфікування фітоплазмою

Анотація. Актуальність дослідження обумовлена значним впливом фітоплазмових інфекцій на продуктивність та фізіологічний стан підщеп садових культур, що створює ризики для приживлюваності та розвитку бруньок під час щеплення та їхнього подальшого росту. Метою роботи було оцінити фізіологічну придатність підщепи P-HL-A за умов потенційного або наявного інфікування фітоплазмою у період проведення окулірування. Для досягнення цієї мети застосовувалися методи молекулярної діагностики, а саме полімеразної ланцюгової реакції (ПЛР) в реальному часі для визначення наявності патогену, аналіз тургесцентності листових тканин для оцінки водного дефіциту, а також спектрофотометричне визначення фотосинтетичних пігментів (хлорофілів та каротиноїдів). Було досліджено зміни водного режиму та функціонального стану фотосинтетичного апарату підщеп P-HL-A залежно від ступеня інфікування. Було встановлено, що фітоплазмове ураження спричиняє водний дефіцит у межах 31,6-37,5 % та зниження відносної тургесцентності до 62,4-68,4 %, що свідчило про розвиток помірного водного стресу. Було проаналізовано вміст фотосинтетичних пігментів, який знижувався на 11,9-33,3 % залежно від типу пігменту та рівня інфекційного навантаження. Було узагальнено, що початковий вплив патогену проявлявся зниженням тургору клітин та фотосинтетичної активності, що може негативно впливати на приживлюваність бруньок під час щеплення. Практична цінність роботи полягає в тому, що отримані результати можуть бути використані садівниками, агрономами та науковцями у розсадниках та дослідних станціях для оптимізації агротехнічних заходів, контролю фітоплазмових інфекцій та підвищення ефективності розмноження плодкових культур

Ключові слова: водний дефіцит; фотосинтез; тургесцентність клітин; хлорофіл; каротиноїди

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Varietal spectral differences in winter wheat plants according to satellite monitoring data

Abstract. The paper reflected the results of investigating the spectral features of winter wheat plants of various varieties, which was a component of the implementation of conventional remote monitoring technologies in precision agricultural production. It was based on empirical data for determining the characteristic spectral characteristics of different varieties and evaluating them using remote sensing data (RS). The purpose of the study was to establish the possibility of identifying varietal differences of winter wheat based on the spectral characteristics of plants obtained from open sources of satellite monitoring data. For this purpose, open data from the Sentinel-2 satellite was used, which provided relatively high spatial and spectral resolution. The analysis covered key wheat growing periods, and spectral differences were investigated using the RGB additive colour model and vegetation indices SAVI (soil-adjusted vegetation index), NDVI (normalised difference vegetation index), ARVI (atmospherically resistant vegetation index). The results of the study indicated the presence of significant spectral differences between winter wheat varieties due to their genetic diversity and response to agroecological conditions. It was found that spectral profiles and indices of photosynthetic activity of different varieties correlated with indicators of productivity and resistance to biotic and abiotic stresses. The obtained data helped not only to differentiate wheat varieties by spectral characteristics, but also to use them to

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build models for predicting yield and evaluating adaptive properties in climate change conditions. The informative value of satellite data for optimising winter wheat cultivation technologies and improving the efficiency of breeding programmes was shown. Such studies were promising in the development of precision agricultural production technologies, ensuring prompt and objective assessment of the state of crops over large areas, tracking the phenology of a particular wheat variety, and in breeding research

Keywords: winter grain crops; varietal differences; remote monitoring of agrophytocoenoses; vegetation indices; spectral characteristics of plants

INTRODUCTION

Accurate observation of wheat phenology in close real time is critical for both agricultural technologies and breeding programmes. It allows effectively managing crops, choosing the most productive varieties, increasing grain yield and quality, and provides a scientific basis for sustainable wheat production. Remote sensing (RS) technologies, data digitisation, and big data management are finding practical application in crop production and therefore require methodological support. Management of agrophytocoenoses has acquired new approaches, agronomists need means of monitoring the state of crops, the quality and timeliness of technological operations, especially in large areas. Winter wheat crops require constant research for each new variety, considering biological features, noticeable differences in plant colour, and the reaction to agroecological factors. A separate important criterion remains the organogenesis of various varieties of winter wheat, depending on the time of sowing and growth conditions, considering the widespread late harvesting of predecessor crops. Remote satellite monitoring is relevant for solving this issue, which allows agricultural producers to receive constant updates about the situation in any field of the farm without the need for personal presence. The main advantage of satellite monitoring is the scale of the survey and the efficiency of data on the state of crops over large areas, which is several times different from ground-based measurements, which are local.

A. Zvonar (2020) presented a new approach to monitoring wheat phenology during the growing season using sequential RGB images and an integrated KNN-CNN-RF model. The

researcher demonstrated that the combination of machine learning and deep learning algorithms allows accurately and timely determining the phenological phases of wheat, which is especially valuable for breeding programmes and crop management. The technique has proven its effectiveness in comparison with conventional approaches, providing higher accuracy and stability of results.

Methodologies for monitoring the phenology of cultivated plants, with the establishment of dependencies on external parameters, are based on the following criteria. Based on the plant parameters of the variety, as shown in the paper by U. Akumaga *et al.* (2023) that combined data from ground-based phenological studies with the leaf area index (LAI) obtained from satellite images of the Planet Fusion platform, also by R. Zhang *et al.* (2024) that proposed a two-step deep learning framework called PhenoNet for accurate and efficient classification of key wheat phenophases in real time. Based on spectral features: in their research papers on the description of crop phenology, the teams of researchers presented the results of selecting optimal variants of the shape model (SMF-S) based on the time series data of the vegetation index (Liu *et al.*, 2022). A model using the time series normalised difference vegetation index (NDVI) and normalised difference red edge index (NDRE) obtained from multispectral UAV images was able to accurately determine full ear emergence dates for more than 1,000 rice varieties (Liu *et al.*, 2023). Machine learning models were based on the characteristics of radar polarisation.

G. Song *et al.* (2022) presented an approach to monitoring leaf phenology in tropical

rainforests using deep learning techniques. The researchers used super-pixel classification of time series of images of tree tents, which allowed improving the accuracy of tracking changes in vegetation. The results showed that artificial intelligence combined with remote images significantly improves the ability to assess the seasonal dynamics of plant development. This study is a valuable example of the use of modern image analysis algorithms for monitoring the state of crops and optimising agricultural technologies in accordance with the principles of precision farming. The paper by D. Cann *et al.* (2023) examined the role of phenology in the adaptation of winter wheat to various climatic conditions. The researchers showed that varying the duration of the development phases significantly affects the yield and stability of crop productivity in a variable environment. The study highlighted the importance of considering the phenological characteristics of varieties to improve the effectiveness of agricultural technologies and breeding programmes. These results are useful for precision farming, as they demonstrate the possibility of optimising fertilisation and crop management systems considering the biological rhythms of plants.

The purpose of the study was to determine the information content and feasibility of using images in the RGB additive colour model, vegetation indices NDVI, SAVI, ARVI for investigating varietal spectral differences in the agrophytocoenosis of winter wheat using remote sensing.

LITERATURE REVIEW

In crop production, variety replacement is a consistently relevant measure, and the latest technologies for monitoring agrophytocoenoses should consider this. Varietal spectral differences of even the most popular cultivated plants are poorly understood, but researchers continue to look for ways to obtain objective data. In studies of varietal differences of winter wheat in recent years, the main focus has shifted towards high – frequency phenotyping – the use of UAVs with multi- and hyperspectral sensors, a combination of ground-based spectrometers and satellite data, and the

use of deep learning methods. Hyperspectral models for monitoring the chlorophyll density (ChD) of winter wheat were constructed using eight machine learning algorithms. A combination of algorithms for intelligent analysis of wheat plant traits and machine learning was used as a hyperspectral imaging system. J. Ma *et al.* (2022) reviewed the use of hyperspectral images to assess the protein content of wheat grains, summarised modern methods for collecting, processing, and analysing spectral data, highlighting the advantages of this technology over conventional laboratory approaches. The researchers noted the prospects of integrating hyperspectral systems into high-performance phenotyping and breeding programmes, and their importance for improving the accuracy of grain quality assessment in production conditions.

Crop growth models such as Crop-Grow, WOFOST, APSIM, and others predict crop phenology based on variety parameters and environmental conditions. However, their application is difficult due to the need to calibrate the parameters of each variety. This is most difficult to do for new varieties. Phenology can also be controlled based on polarised traits that are sensitive to the morphological parameters of crops. D. Vincke *et al.* (2022) proposed a combination of crop shape and growth models for determining the phenological phases of soybeans. The method demonstrates promise for monitoring field crops in precision farming. The authors used near-infrared hyperspectral imaging to assess the presence of grains in wheat ears. This approach allows improving the accuracy of yield forecasting. R. Zhang *et al.* (2024) developed the lightweight two-step PhenoNet neural network for real-time classification of wheat phenological phases, making it convenient for agricultural practice. A. Zvonar (2020) proposed a method for monitoring wheat phenology for breeding tests using a combination of KNN-CNN-RF models based on RGB images. The solution is effective for analysing a large number of samples. J. Campoy *et al.* (2023) created a remote sensing model for predicting wheat and barley yields that works both at the level of field and within the field, improving the accuracy of productivity estimates.

Multispectral cameras in combination with time series allows tracking growth dynamics, are used for crop forecasting and classification of varieties, and operational monitoring of large areas. Thus, X. Lyu *et al.* (2024) used aerial (UAV-hyperspectral) images to distinguish between winter wheat varieties and deep learning (ENVINet5) and SVM methods to process the data. The conducted studies showed a close relationship (R^2 to ≈ 0.96), and the developed method was recommended for classifying the varieties under study. However, the proposed method has limitations in the area of application and requires specialised ground equipment and, accordingly, trained specialists. The use of satellite survey data to study various indicators of agrophytocoenoses of winter wheat showed both positive and unsatisfactory results. W. Cai *et al.* (2022) presented a new multiple phenological spectral trait (Mpsf) for mapping winter wheat. The researchers used multi-phenological indices: NDVI, NDVI₆, GNDVI (Green NDVI), EVI (Enhanced Vegetation Index), BSI (Bare Soil Index), PSRI (Plant Senescence Reflection Index) to search for objective identification of wheat and individual other crops, and integration of the main growth phases. Important, according to the researcher, are the presented results of studies of the informative value of individual Sentinel2 spectral channels to evaluate wheat growth: rededge 705 and 740 nm, near-infrared NIR 783, 865 nm, calculated LAI indices (Revill *et al.*, 2019); VSWIR multispectral and hyperspectral data (Pancorbo *et al.*, 2025). It was shown that the red-edge/SWIR, NDSI indices significantly increase the accuracy of assessing the biophysical properties and yield of the variety. Varieties can have different photopigmentation and structural properties of plants. The spectral features of plants were considered by researchers in the study of nitrogen supply, with the analysis of protein content of the resulting grain (Camino *et al.*, 2018; Aranguren *et al.*, 2020). The micronutrient nutrition was considered in the study of the potential of hyperspectral imaging. Grain quality prediction models based on the spectral reflectivity of flour showed very promising results ($r^2 > 0.60$) for Mg, Mo, and Zn (Hu *et al.*, 2021).

Based on Sentinel-2 time series and indices a method for classifying plant stresses was developed, which allowed, in particular, distinguishing diseased plants from nitrogen deficiency (Shi *et al.*, 2023). The researchers noted the possibility of using this method for varietal differentiation, if varieties respond differently to stress. Hyperspectral data were used for early diagnosis of biological stress in wheat plants, characteristics that determine grain quality and moisture content (Xie *et al.*, 2024; Wang *et al.*, 2024; Sun *et al.*, 2025).

Therefore, previous studies have shown the feasibility of using satellite remote sensing methods, which opens up prospects for timely detection of stress factors, assessment of organogenesis dynamics, and ensuring effective management of agrophytocoenoses over large areas. Varietal spectral characteristics were studied mainly from ground platforms and UAVs, which has advantages in accuracy, but loses scale and availability. The question remains of developing a scientific basis for improving technologies for growing winter wheat and increasing its productivity in the precision farming system. Scientific data indicate the relevance and prospects of studying the spectral varietal features of winter wheat, and the informative value of such characteristics for solving practical technological problems.

MATERIALS AND METHODS

Studies of wheat growth and development were conducted during two seasons – 2021 and 2022 and performed on production areas occupied by winter wheat. The field with a total area of 40.5 hectares was located in the Boryspil District of the Kyiv Oblast, near the national highway H08. Four varieties of winter wheat were grown within the field, as shown in Figure 1: 'Tobak' (9.8 ha), 'Akhim' (9.2 ha), 'Milton' (6.8 ha), and 'Royal' (6.2 ha). Varieties 'Tobak' and 'Akhim' are modern medium-ripened (growing season 270–280 days) varieties of soft, awnless winter wheat, lutescence variant, intensive type, produced by German company Saaten-Union. 'Milton' and 'Royal' varieties are intensive medium-early winter wheat varieties, an erythrosperrum variant, produced by Canadian origin (Seed Grain Company).



Figure 1. Field location (coordinates 50°27'33"N 31°00'34"E; left) and winter wheat varieties (right)
Note: 'Tobak', 'Akhim', 'Milton', 'Royal'
Source: Google Earth (n.d.)

Reproduction of varieties – elite. Potatoes were the predecessor crop, allowing wheat to be sown on time. The topography of the field was mostly flat, which eliminates the cancellation of growing conditions. The soil cover and technical background of the agrophytocoenosis were uniform, which enabled a comparison of exclusively varietal differences. The EOS Land Viewer platform of the European Space Agency (ESA), which is part of the space mission for remote sensing of the Earth, specialised for crop production tasks was used to perform satellite monitoring. Images of the Sentinel 2 satellite obtained from the Copernicus Open Access Hub (DataHUB) archive were used. The Sentinel-2 was equipped with the MSI multispectral Instrument, which provided shooting in 13 spectral channels with a spatial resolution of 10, 20, and 60 m and a repeat cycle of about 5 days. The choice of this satellite was conditioned by its free access to data, the highest spatial resolution of images among available satellites (10m/pixel). The use of various indices helped to comprehensively assess the state of crops and spatial heterogeneity of the field. The study used combinations of spectral channels that are most sensitive to changes in plant photosynthetic activity and chlorophyll status: B4 (Red, 665 nm, 10 m) – chlorophyll uptake; B8 (NIR, 842 nm, 10 m) – leaf cover reflection; B5, B6, B7 (Red Edge, 705–783 nm, 20 m) were additionally used to assess the physiological state of plants. Vegetation indices were calculated based on these channels, in particular: NDVI ($B8 - B4 / B8 + B4$), SAVI ($B8 + B4 + L(B8 - B4) \cdot (1 + L)$), ARVI

($B8 + (B4 - \gamma \cdot (B4 - B2))B8 - (B4 - \gamma \cdot (B4 - B2))$). This combination of spectral channels and vegetation indices helped to track the growth characteristics of winter wheat at different stages of vegetation and assess the spatial heterogeneity of crops.

Satellite image dates were selected considering the local time zone (UTC + 2 / UTC + 3), minimal cloud cover, and compliance with key phenological phases of winter wheat development. In the autumn period (germination and tillering, BBCH 10–29), indices were analysed to assess the density of seedlings, uniformity of development, and the influence of stress factors at the initial stages of growth. In the spring period (stem elongation – heading, BBCH 30–59), the main attention was paid to the dynamics of indices reflecting photosynthetic activity and chlorophyll content, as well as to monitoring the water status of plants. The assessment of plant condition based on satellite images was carried out by the author as an expert. Before processing the data, atmospheric correction (L2A level, Bottom-of-Atmosphere) was performed, which reduced the impact of atmospheric conditions on reflection, including georeferencing and cloud masking using the Scene Classification Layer (SCL) built into Sentinel-2 products.

Verification of compliance of the results was carried out by ground-based morphological and biometric studies (BBCH stages, visual assessment of the state of crops, features of soil cover and microrelief). The growing season of the territory was determined by the transition of the average daily temperature through 5°C, as accepted

in crop production. This approach helped not only to identify varietal differences in the dynamics of vegetation indices, but also to identify the influence of soil and technological factors on the heterogeneity of the field. The study was conducted in accordance with the ethical standards of Convention on Biological Diversity (1992) and Convention on the Trade in Endangered Species of Wild Fauna and Flora (1976).

RESULTS AND DISCUSSION

For the completeness of spectral analysis of winter crop agrophytocoenoses within the framework of remote monitoring, the author suggests it is appropriate to use data from the autumn and spring periods of winter wheat vegetation. Autumn vegetation, according to scientific data, should last 40-60 days, so that the plants have time to gain the necessary amount of effective

temperatures (300-350°C) before the end of the growing season, that is, a stable transition below 5°C. Due to the completeness of the autumn growing season, plants have time to accumulate the necessary amount of plastic substances for the wintering period, which increases their stress resistance.

In the experimental field, plants entered winter in the initial early tillering stage (BBCH 20). Figure 2 shows images of the autumn vegetation of winter wheat, at the time of the first ground survey and plant accounting. The plants were in the leaf development phase (BBCH 10). The first image shows the state of plants in the visible spectrum. Sparse vegetation with the presence of open ground was identified. Light spots are clearly distinguished on the varieties 'Milton' and 'Royal', which can be explained by the soil heterogeneity of the part of the field they occupy.

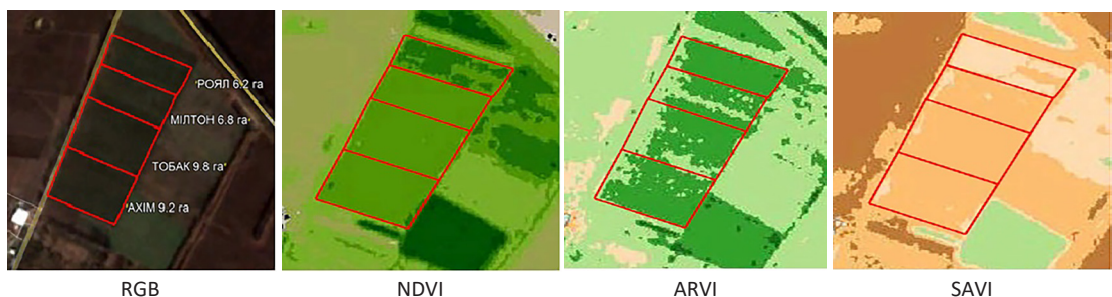


Figure 2. Index images of satellite survey data of winter wheat agrophytocoenoses (BBCH 10, survey date 13.11.2021)

Note: 'Tobak', 'Akhim', 'Milton', 'Royal'; RGB – additive colour model; NDVI – normalised difference vegetation index; ARVI – atmospherically resistant vegetation index; SAVI – soil-adjusted vegetation index

Source: EOS data analytics (n.d.)

Analysis of index images showed that the 'Royal' variety differed from others in higher values. Homogeneous elementary plots for each variety were used to compare the index values. This characteristic NDVI value for the 'Royal' variety was 0.38, for other varieties it was 0.31-0.33. This allowed assuming that this variety is characterised by a more intensive beginning of growth processes at the autumn stage of vegetation. Reflection of a high index indicator on a plot with the 'Royal' variety was observed for 80-85% of the territory. Ground-based phenological studies have established that it was on the site under the 'Royal' variety that the density

of the projection vegetation cover was 32-38, for other varieties in this field – it did not reach 30%. This explains the low information content of NDVI, because this index is sensitive to projective vegetation cover.

ARVI, which is not very sensitive to atmospheric factors (such as aerosols), was chosen for data analysis due to its ability to adjust for autumn weather conditions. Compared to other vegetation indices, its values were most variable, in particular in the areas of the varieties 'Achim', 'Tobak', and 'Milton'. The largest gradient of the index values was observed for the varieties 'Tobak' and 'Milton', ground-based

studies did not show a correlation of these differences with the topography of the territory, and therefore, it is possible to assume that they are conditioned by spectral characteristics. Attention is drawn to the special feature of the ARVI and SAVI index images of land plots near the forest belt. The values of these indices in such marginal zones were poorly correlated with ground-based biometric studies, so, in the according to the author, marginal zones should not be considered in the spectral analysis of agrophytocoenoses. The total coverage of the agrophytocoenosis in these two indices for

the varieties 'Achim', 'Tobak', and 'Milton' in the SAVI index was uniform. There is a clear reflection of soil or technological heterogeneity for the 'Milton' variety in the form of a strip, which later, in May, became more noticeable. Satellite monitoring of the state of agrophytocoenoses is almost not used in winter due to weather conditions, a pause in the growing season of the crop, and therefore low relevance. The availability of a clear image without snow cover allowed analysing the agrophytocoenosis in its winter dormancy state, which was done on 2 January 2022. The results are shown in Figure 3.

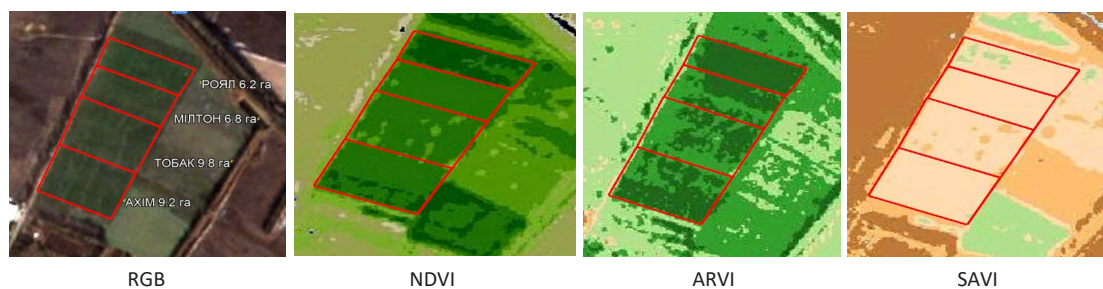


Figure 3. Satellite monitoring of winter wheat crops in the tillering phase (BBCH 20, survey date 02.01.2022)

Note: 'Tobak', 'Akhim', 'Milton', 'Royal'; RGB – additive colour model; NDVI – normalised difference vegetation index; ARVI – atmospherically resistant vegetation index; SAVI – soil-adjusted vegetation index

Source: EOS data analytics (n.d.)

The image in the visible part of the optical spectrum with a uniform green colour reflects the steady development of winter wheat varieties. In terms of NDVI value, the leadership was maintained by the 'Royal' variety – approximately 80% of the area, the index value was higher compared to other varieties. Varieties 'Milton' and 'Tobak' had a more uniform index coverage, but on the part of the field with these varieties, relief differences ("saucers") were clearly traced, where plants with significantly worse development were identified. The development of zones of higher indices for the variety 'Achim' was noted. According to the results of the construction of ARVI, the leading position was occupied by the 'Royal' variety. Other varieties had visually similar index values, and soil heterogeneities are reflected. Plants of other varieties, except 'Royal', developed worse in areas near the forest belt. In

second place in terms of Index indicators was the 'Achim' variety. Spectral analysis showed low information content of SAVI for the task at hand. This is conditioned by the specifics of its work with poorly visible soil at this stage, although the "falling" terrain zones on the 'Tobak' variety are quite clearly identified.

During the spring resumption of wheat vegetation, it is difficult to assess the state of production areas of agrophytocoenoses, namely, the number of damaged plants, the tillering coefficient, the rate of active growth for planning agricultural operations, etc. The date of the first spring monitoring, based on the quality of the satellite images received, was set for 23 March 2022. The conditions of the month allowed plants to begin spring tillering, and the warming at the end of March – beginning of April became a factor in the resumption of vegetation (Fig. 4).

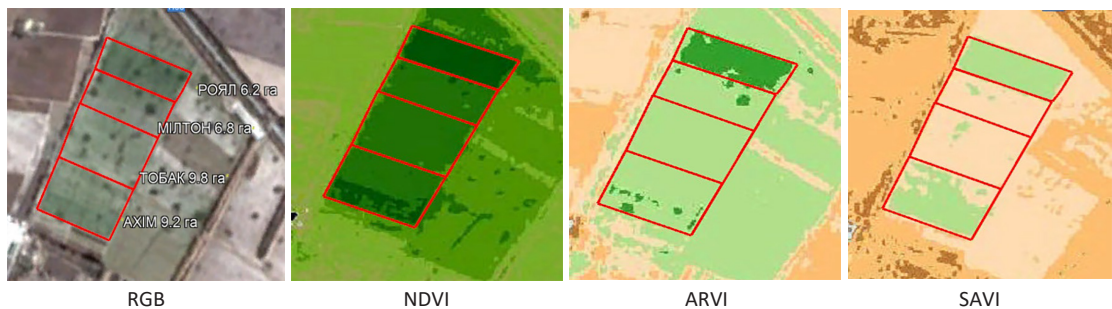


Figure 4. Satellite monitoring of winter wheat crops in the tillering phase (BBCH 20, survey date 23.03.2022)

Note: 'Tobak', 'Akhim', 'Milton', 'Royal'; RGB – additive colour model; NDVI – normalised difference vegetation index; ARVI – atmospherically resistant vegetation index; SAVI – soil-adjusted vegetation index

Source: EOS data analytics (n.d.)

The visible spectrum shows that most of the area of the 'Royal' variety has a relatively greener colour. In the field, changes in the terrain are noticeable in the form of depressions, the so-called "saucers". Soil heterogeneity is visually apparent. In addition, for the 'Achim' variety, there is a zone (about 25% coverage) with higher index indicators. Comparing the index values with the data of 02.01.22, it can be concluded that the plants are at rest or that the slow passage of spring tillering processes is not available for satellite recording. Considering the distribution of the NDVI index, the active development of crops of the 'Royal' variety and ¼ part of the 'Achim' variety plot is clearly reflected. The existing zone of more active plant development in the 'Achim' variety has a sharp transition, which indicates technological reasons. Varieties 'Milton' and 'Tobak' develop uniformly, without dividing into zones. The ARVI vegetation index also showed the most active development of plants of the 'Royal' variety and part of the 'Achim' variety plot for the period of the end of March. There is a noticeable active development of areas with a decrease in the 'Milton' variety, which explains the presence of more moisture. Analysing the SAVI indicators, which consider the presence of soil in the image, a similar distribution of areas with active vegetation by variety was obtained: the most developed varieties are 'Royal' and 'Achim', and the area of more productive zones on the site of the latter variety increased to 75%.

The next remote monitoring date was May 7, 2022. Due to cloudy and rainy weather in April, monitoring was not carried out, and a similar problem was observed in May. A special feature of this period is the intensive growth of plants, in fact, the approach of plants to the peak of vegetative mass development. Wheat at the stage of stem elongation (BBCH 30), actively growing, plants of bright green colour. For photosynthesis, the amount of solar activity at this time is sufficient. Agrophytocoenosis is aligned by spectral characteristics. For this time of monitoring, the visible spectrum image turned out to be more informative than the index ones. The picture shows a clear difference in the colour of the 'Milton' variety, compared with others: the plants have a lighter colour. Considering the yield of this variety later, the authors were convinced of the assumption that the colour of the plants was associated with its physiological characteristics, and not with low photosynthetic activity. As a result of constructing the SAVI index, a well-defined green band was obtained on the 'Milton' variety, which correlates with the images of previous monitoring and may be associated with changes in terrain and better water supply.

The next observation of the condition of winter wheat plants was carried out on 21 June 2022 during the flowering phase – grain formation (BBCH 60-70). The NDVI values were relatively higher for the varieties 'Achim' and 'Tobak', but the specifics of plant colour during this growing season should be considered.

Varieties 'Royal' and 'Milton' have earlier maturation periods, because they developed faster by several microstages of BBCH, which was proved

by biometric records. The dynamics of the NDVI value during the entire monitoring was presented graphically (Fig. 5).

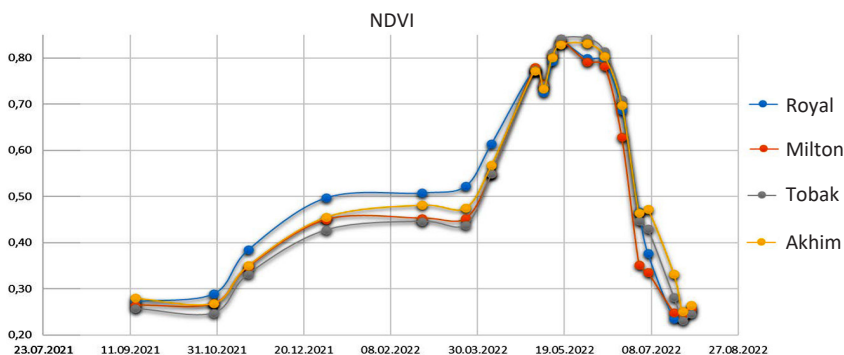


Figure 5. Graph of distribution of NDVI index values of different winter wheat varieties, 2022

Note: 'Tobak', 'Akhim', 'Milton', 'Royal'; NDVI – normalised difference vegetation index

Source: EOS data analytics (n.d.)

SAVI analysis fully confirmed the distribution of sites according to the intensity of photosynthetic activity of the leaf apparatus. The leaders are the varieties 'Achim' and 'Tobak'. Plants in all areas were delayed in growth in areas near the forest belt. The filling of winter wheat grains is closely linked to the activity of the photosynthetic apparatus of the flag leaf. The importance of remote monitoring at this time is extremely high. The information that can be obtained about the state of crops will indicate the physiological characteristics of varieties regarding the duration of active activity of the flag leaf. Even after analysing the visible spectrum image, one can see a change in the colour of all varieties, namely a decrease in the intensity of the green colour. It is noticeable that the 'Milton' variety has the lightest colour.

According to NDVI, areas of the 'Royal' and 'Milton' varieties are distinguished, which have a low level of vegetation, in contrast to small areas of low relief, where there is a delay in development. It should be noted that the beginning of a decrease in the value of the NDVI index for other varieties ('Tobak', 'Achim'). Thus, for the 'Achim' variety, the zones of low vegetation are 50%, and for the 'Tobak' variety – 35-40%. For comparison, the area of such zones for 'Royal' is 70%, and for 'Milton' – 85%. According to ground-based studies, approximately 85% of plants of the

'Milton' variety as of 21 June 2022 were in the stage of grain formation, the second place was taken by the 'Royal' variety (67%), and flowering was completed in other varieties.

Consequently, index images of satellite monitoring data made it possible to identify early-maturing varieties 'Royal' and 'Milton' with the greatest manifestation in the latter. At the next stage of monitoring (06.07), the activity of the photosynthetic apparatus of both varieties almost did occur, plants are approaching the end of the grain maturation phase (Fig. 6). Photosynthetic activity of the upper tier of 'Tobak' and 'Achim' varieties was also observed at this time, judging by the distribution of vegetation indices. This suggests that the accumulation of a larger amount of active temperatures may affect the amount of assimilating substances in the grain and further affect its qualitative composition.

The results of the conducted studies confirmed the conclusions of X. Liu *et al.* (2023) that a hyperspectral remote sensing system can potentially be used to classify winter wheat varieties, and it provides a benchmark for classifying crops with weak intra-class differences. However, the researchers investigated the spectral differences of wheat from the UAV platform. Satellite monitoring has fundamentally different parameters, especially for free access data, but in terms of efficiency, scale, and availability,

it significantly exceeds all other types. The results obtained showed the informative nature of satellite data for determining varietal differences, and therefore the prospects of such an area. High information content of multispectral images of Sentinel-2B was shown by M. Memon *et al.* (2023) to accurately estimate and map the percentage of wheat straw cover WSC compared to Landsat-8 data in a large-scale agricultural region. The researchers support their results with improved temporal and spatial data, but do not distinguish between wheat varieties.

W. Cai *et al.* (2022) developed and used the generated new multi-factor spectral features as output data for the ONE-Class Support Vector Machine (OCSVM) for mapping winter wheat. However, the developed system showed positive results for phenological studies, without distinguishing wheat varieties or varietal types. Similar conclusions were also made by R. Zhang *et al.* (2024), who noted that combining multispectral satellite data with machine learning significantly improves the accuracy of crop condition identification and crop yield estimation.

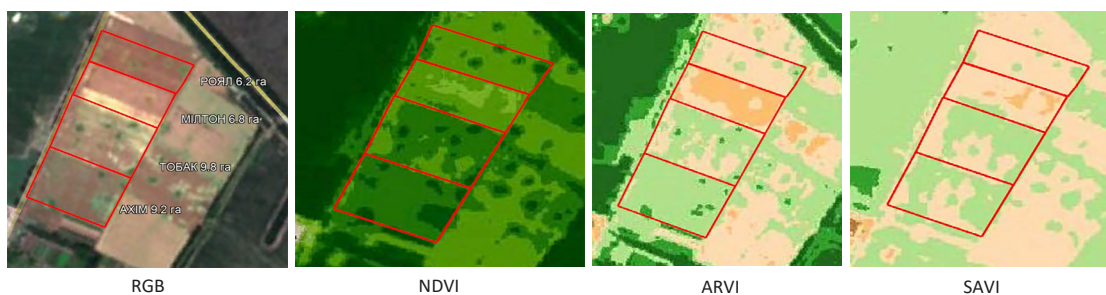


Figure 6. Satellite monitoring of winter wheat crops in the tillering phase (BBCH 80, survey date 06.07.2022)

Note: 'Tobak', 'Akhim', 'Milton', 'Royal'; RGB – additive colour model; NDVI – normalised difference vegetation index; ARVI – atmospherically resistant vegetation index; SAVI – soil-adjusted vegetation index

Source: EOS data analytics (n.d.)

O. Tarariko *et al.* (2019) noted a significant differentiation of the reflective characteristics of crops in the ear emergence phase and full ripeness, which allows identification based on remote survey materials. Hyperspectral imaging (narrow bands, near and middle parts of the infrared spectrum – NIR/MIR) allows the most accurate detection of spectral differences between varieties, especially in critical phenophases (stem elongation – flowering). Free access satellite technologies have a number of limitations. Compared to shooting with UAVs, the data has a fundamentally lower ability to distinguish images and is limited in use in the presence of clouds. Therefore, it is appropriate to use the opportunity to conduct a series of experiments due to the large coverage area and calibrate the data based on ground measurements (Opryshko *et al.*, 2024). Previous studies of the spectral characteristics of plants have established dependencies, formed a hypothesis about the possibility

of developing vegetation indices based on an alternative model of colour formation, which will be more resistant to changes in lighting.

Thus, the results of the conducted research confirmed that Sentinel-2 satellite multispectral data can be an effective tool for classifying wheat varieties, providing an optimal balance between accuracy, scale, and availability of monitoring. Satellite monitoring allowed assessing the growth dynamics and development of winter wheat varieties, identify early-maturing varieties and reflect spatial heterogeneities of the agrophytocoenosis. NDVI, ARVI, and SAVI data confirmed their informative value for varietal differentiation, although they are inferior in resolution to hyperspectral UAV images. Together with ground-based measurements, satellite data provide a large-scale and operational tool for precision farming, which allows assessing the condition of crops in a timely manner and predicting yields.

CONCLUSIONS

Monitoring with Sentinel-2 helped to identify winter wheat varieties by spectral differences that occur at different stages of vegetation. The recorded stable spectral signatures allowed working remotely with individual varieties of winter wheat, in particular, to identify the stages of vegetation of different varieties. Interpretation of satellite data by EOS LandViewer through vegetation indices NDVI, SAVI, ARVI allowed assessing the general state of phytocoenoses of winter wheat and conducting phenological studies with reference to varietal characteristics. Thus, in the range of vegetation indices NDVI, SAVI, ARVI, the early beginning of autumn vegetation of the 'Royal' variety was established, which was confirmed by ground studies. The NDVI value for the 'Royal' variety was 0.38, for other varieties it was in the range of 0.31-0.33. Index maps and other vegetation indicators identified varieties with higher photosynthetic activity, which may be related to potential productivity and adaptability to climatic conditions. Thus, in the BBCH 80 stage (shooting date 06.07.2022) for early-maturing varieties of Canadian selection 'Royal' and 'Milton', the activity of the photosynthetic apparatus was not recorded, ground observations showed approaching the end of the grain maturation phase. Photosynthetic activity of the upper tier of German varieties 'Tobak' and 'Achim' continued, which showed the distribution of vegetation index values and was confirmed by ground-based studies.

The informative value of satellite monitoring for identifying varietal characteristics of

winter wheat depended on the growing season. Regardless of the variety, during the stem elongation – beginning of ear emergence, the wheat agrophytocoenosis acquires a uniform intense green colour, varietal differences are visually recorded by ground surveys, but are practically not identifiable by satellite imagery. The results obtained confirmed the prospects of using satellite data for variety assessment and monitoring of agrophytocoenoses on a large scale, breeding work and digital agriculture, in particular in precision technologies. Further research, according to the authors, should be aimed at verifying satellite data with ground-based observations and refining processing algorithms to improve the accuracy of variety identification.

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CONFLICT OF INTEREST

None.

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Сортові спектральні відміни рослин пшениці озимої за даними супутникового моніторингу

Анотація. Стаття відобразила результати вивчення спектральних особливостей рослин пшениці озимої різних сортів, що є складовою імплементації традиційних технологій дистанційного моніторингу в технології прецизійного агровиробництва. В основу покладені емпіричні дані визначення характерних спектральних характеристик різних сортів та оцінка їх із використанням даних дистанційного зондування Землі (ДЗЗ). Метою роботи було встановити можливість ідентифікації сортових відмін пшениці озимої за спектральними

характеристиками рослин, отриманими із відкритих джерел даних супутникового моніторингу. Для цього використовувались відкриті дані супутника Sentinel-2, які забезпечили порівняно високі просторову та спектральну роздільність. Аналіз охоплював ключові періоди вегетації пшениці, а спектральні відмінності досліджувались за допомогою адитивної колірної моделі RGB і вегетаційних індексів SAVI (soil-adjusted vegetation index), NDVI (normalised difference vegetation index), ARVI (atmospherically resistant vegetation index). Результати дослідження свідчили про наявність істотних спектральних розбіжностей між сортами пшениці озимої, що зумовлені їхньою генетичною різноманітністю та реакцією на агроекологічні умови. Встановлено, що спектральні профілі та індекси фотосинтетичної активності різних сортів корелювали з показниками продуктивності та стійкості до біотичних і абіотичних стресів. Отримані дані дозволили не лише диференціювати сорти пшениці за спектральними характеристиками, а й використовувати для побудови моделей прогнозування врожайності, оцінювання адаптивних властивостей в умовах змін клімату. Показано інформативність супутникових даних для оптимізації технологій вирощування пшениці озимої, підвищення ефективності селекційних програм. Такі дослідження є перспективними у розвитку технологій прецизійного агровиробництва, забезпечуючи оперативність та об'єктивність оцінки стану посівів на великих площах, відстеження фенології конкретного сорту пшениці, а також у селекційних дослідженнях

Ключові слова: озимі зернові культури; сортові відміни; дистанційний моніторинг агрофітоценозів; вегетаційні індекси; спектральні характеристики рослин

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Effect of foliar application of biological products on sunflower productivity in the north-eastern part of the forest-steppe of Ukraine

Abstract. Sunflower production required new technological approaches that involve not only the use of intensive hybrids, fertiliser systems, and innovative equipment, but also ensuring a comprehensive interaction of the main agrotechnological factors. The purpose of the study was to

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establish the effect of foliar application of biological products due to their stimulating and protective effect on the development of the productivity of sunflower plants embedded in the genotype. A field method was used to investigate the interaction of research objects with natural, laboratory, and mathematical and statistical factors. It was found that foliar application of biological products showed a tendency to stimulate plant growth. The highest plant height (+5 cm) in the five leaf phase over the years of research was observed in the variant treated with Azotohelp. Foliar dressing with Organic Balance biologics affected an increase in the basket diameter by 3.25 cm compared to the control version, Organic Balance Monophosphorus – by 3.55 cm, and Azotohelp – by 3.8 cm. The weight of 1,000 grains with the use of Organic Balance increased by 5.2 g, Organic Balance Monophosphorus – 3.2 g, Azotohelp – 3.7 g. Foliar applications of biologics increased the weight of seeds from the basket by 4.9, 6.9, and 9.7 g, respectively. However, an increase in the diameter of the basket, the number and weight of seeds in it, and the weight of 1,000 grains, led to an increase in yield, which was confirmed by a high correlation ($r = 0.80-0.99$) between these indicators. Notably, the greater influence of Organic Balance Monophosphorus biologics on the development of sunflower yield was found in hot weather conditions in 2021 compared to more favourable conditions in 2022-2023. On average, over three years of research, the biological yield of sunflower seeds with foliar application of biologics exceeded the control option by 0.3-0.54 t/ha. The highest productivity of sunflower was formed by foliar dressing with Azotohelp biologics and amounted to 3.7 t/ha with a control level of 3.16 t/ha, an increase of 0.54 t/ha, or 17.1%. These results can be used to optimise intensive sunflower cultivation technology, which will contribute to better plant nutrition, reduce the pesticide load, and increase sunflower yield

Keywords: oilseeds; yield; fertilisers; Azotohelp; Organic Balance; Organic Balance Monophosphorus

INTRODUCTION

Sunflower is one of the most important oilseeds in Ukraine, in particular in the left-bank forest-steppe, where it occupies a leading place among agricultural crops in terms of profitability. However, intensive sunflower cultivation, crop rotation violations, climate changes, and anthropogenic impact lead to soil degradation, reduced fertility, and disruption of water and nutrient regimes, which makes it difficult to obtain stable and high yields. Simultaneously, in the context of increasing climate risk, especially droughts and high temperatures, there is an urgent need to introduce effective and environmentally friendly approaches to plant nutrition (Adeleke *et al.*, 2022; Pavlichenko *et al.*, 2023). V. Pichura *et al.* (2023) noted that one of the promising areas is the use of biological preparations containing growth stimulants, anti-stress agents, amino acids, and other active components that can increase plant resistance to adverse conditions, activate physiological and biochemical processes, and improve crop productivity. Therefore, the study of the impact of foliar application of biologics is extremely relevant, both for science

and for practice, since it is aimed at reducing the risks of agricultural production, improving the efficiency of using natural resources.

A. Rozhkov & V. Roenko (2025) emphasised the growing role of applying biologics to vegetative plants, which reduces the dependence of the crop on environmental factors, allows optimising resource-saving cultivation technologies and using the natural potential of this oilseed crop. They suggested that the introduction of biologics do not pollute the environment, showing a high selective effect, are convenient for production and has inexhaustible resources for constantly increasing production volumes. O. Laslo (2022) and O. Kovalenko *et al.* (2022) noted that foliar dressing acts as an additional method to root nutrition and ensures that nutrients are instantly absorbed and distributed inside plants through the leaves. O. Averchev & N. Vasylenko (2023) emphasised the importance of using biologics with protective and growth-stimulating functions that contribute to the implementation of potential opportunities inherent in the crop, including certain

immune responses, increases plant productivity, and the implementation of genotypic makings of varieties and hybrids. O. Tsyliuryk *et al.* (2021) emphasised that the treatment of plant seeds with growth-regulating drugs has established an effect on the growth and development of sunflower and revealed the possibility of reducing the duration of stressful conditions with a versatile degree of adverse effects. The researchers also noted that one of the measures to increase plant resistance is the use of biologics that are environmentally safe, intensify physiological processes in plants, increase resistance, and increase the yield of agricultural crops.

According to the observations of J. Akua-ku *et al.* (2020), B. Basile *et al.* (2021), the physiological effect of using biologics consists in the activation of the vital activity of plant cells, increase in the permeability of intercellular membranes, and acceleration of their biochemical reactions, which contributes to the intensification of nutrition, respiration, and photosynthesis. The high efficiency of using drugs for regulating the growth and development of plants of biological origin is determined, purposefully reducing stressful situations by reducing their duration, rational use of natural resources, and the development of a larger amount of dry mass, which, accordingly, leads to an increase in productivity and an improvement in product quality. However, the versatile effect of microbial preparations with foliar application is poorly investigated.

The purpose of the study was to establish the influence of foliar use of biologics, Azotohelp, Organic Balance and Organic Balance Monophosphorus in sunflower crops on the development of crops and individual plant productivity in the conditions of the north-eastern part of the forest-steppe of Ukraine.

MATERIALS AND METHODS

The research was conducted in the grain-row crop rotation of the Department of Agriculture of the Institute of Agriculture of the North-East of the National Academy of Agrarian Sciences in 2021-2023. The soil in the area under study was typical low-humus, slightly leached, coarse-grained, medium-loamy chernozem with the following agrochemical indicators of the arable layer: humus according to D. Tyurin – 4.2-4.8%;

salt pH – 6.0; water pH – 7.9; easily hydrolysed nitrogen content according to D. Kornfeld – 107; mobile P_2O_5 and K_2O according to N. Chirikov, respectively, 62.7 and 67.5 mg per 1 kg of soil. Granulometric composition of the soil according to J. Kaczynski – coarse-grained, medium loamy: physical clay (particles 0.05-0.01) – 49.1-52.1%, silt (particles less than 0.001 mm) – 23.4-25.5% in a layer of 0-20 cm weight

The research was conducted according to generally accepted methodological approaches in the field of agronomy (Rozhkov *et al.*, 2016). The area of the sowing plot in one repetition of each individual variant was 94.5 m², the area on which the harvest was recorded (without side and end protective strips) was 45.5 m², the repetition was four times, and the plots were arranged using the randomised repetition method. Crop accounting was carried out by continuous threshing of grain from each site, followed by recalculation to 8% of the basic humidity. The weight of 1,000 grains was determined by DSTU 4138-2002 (2004). The obtained results were processed by variance and correlation methods of analysis using Excel-16.0 software suite.

The cultivation technology was generally accepted for this zone, except for the techniques that were studied. Mineral fertilisers were applied in the spring, under pre-sowing cultivation with the rate of $N_{32}P_{32}K_{32}$ on all variants. The effectiveness of foliar application of biologics was studied in sunflower crops of the 'Esman' variety. Treatment of plants was carried out in the phase of 2-3 pairs of true leaves in a crop with a working solution consumption rate of 200 l/ha according to the following scheme: control (treatment of plants with water); Organic Balance 0.5 l/ha; Organic Balance Monophosphorus 0.5 l/ha; Azotohelp 0.5 l/ha.

Organic Balance – biologics based on bacteria with nitrogen-fixing, phosphorus and potassium mobilising and fungicidal properties, the action of which is to provide plants with an immunostimulating and protective effect. Composition of the biological product: *Bacillus velezensis*, *Agrobacterium pusense*, *Paenibacillus polymyxa*, *Enterococcus hirae*, *Lactobacillus delbrueckii* sp. *Bulgaricus*. Organic Balance Monophosphorus – biologics based on phosphorus mobilising bacteria, the action of which

consists in providing prolonged nutrition of plants with mobile forms of phosphorus, fungicidal and bactericidal plant protection. Composition of the biological product: live cells of phosphorus mobilising and fungicidal and bactericidal properties of bacteria, biologically active substances: phytohormones, amino acids, and vitamins. The total number of viable producer microorganisms was not less than 1.0×10^9 CFU/cm³. Azotohelp KS – a biological product based on associative nitrogen-fixing bacteria, which consists in fixing molecular nitrogen from the atmosphere by nitrogen-fixing bacteria and transferring it to a form accessible to plants, synthesising growth-stimulating substances. Composition of biologics: live cells of *Agrobacterium pusense*, vitamins, phytohormones, amino acids, and other physiologically active substances. Total number of viable cells – not less than 1.0×10^9 CFU/cm³.

Weather conditions during the research years were satisfactory for plant growth and development. The spring was somewhat colder than usual. A decrease in air temperature was observed in April 2021-2022 and May in 2022. Summers during the research years were hotter compared to the long-term average. Thus, the excess temperature in the summer was from 0.5 to 4.9°C. At the beginning of autumn in September, it got slightly colder in 2021-2022 (respectively -0.6°C and -1.8°C below normal) In April, there was an excessive amount of precipitation during the research years, (+14...+67 mm), and May turned out to be dry in 2022-2023, the hydrothermal coefficient (HC) was 0.7, 0.4, respectively. The availability of plants with available moisture in the soil was formed due to precipitation that took place in April. In summer, dry conditions were observed in 2021, in July (HC – 0.1), and in 2022 in August (HC – 0.3). The summer of 2023 was characterised by a sufficient

supply of moisture to plants. In early autumn 2021, 2023, in September, high air temperatures and low precipitation contributed to the harvest, and in 2022, harvesting was difficult due to heavy rains in the second and third ten days of September, the excess of precipitation was 75.6 mm. The contrast of weather conditions during the growing season during the years of research (decrease and increase in temperatures, lack of moisture) in the north-eastern part of the forest-steppe of Ukraine helped to more fully investigate the effectiveness of foliar application of biologics in sunflower crops. The study was conducted in accordance with the ethical standards of Convention on Biological Diversity (1992) and Convention on the Trade in Endangered Species of Wild Fauna and Flora (1976).

RESULTS AND DISCUSSION

The growth and development of plants took place without any special deviations and corresponded to the varietal characteristics of sunflower. Thus, full shoots appeared on day 12 after sowing on all variants of the experiment in 2021, on day 21 in 2022 and on day 9 in 2023. The negative impact of a decrease in the average daily air temperature (by 2.3°C) in May 2022 on the duration of seed germination and the uniformity of seedlings. The duration of inter-phase periods of germination – the first pair of true leaves – five leaf phase – flowering – maturation depended on climatic conditions and amounted to 5, 29, 19, 63 days on all variants of the experiment in 2021; in 2022 – 6, 28, 26, 75 days; in 2023 – 11, 29, 28, 50 days, respectively. Under these conditions, it was found that the use of biologics did not change the duration of the passage of plants, both individual phases of growth and development, and the growing season as a whole, which in 2021 was 116, in 2022 – 135, and in 2023 – 118 days (Table 1).

Table 1. Dates of the main phases of growth and development of sunflower plants

Phases of plant growth and development	Years of research		
	2021	2022	2023
Sowing	10.05	06.05	15.05
Germination	22.05	27.05	24.05
First pair of true leaves	27.05	03.06	05.06
Five leaf phase	25.06	01.07	03.07

Table 1, Continued

Phases of plant growth and development	Years of research		
	2021	2022	2023
Flowering	14.07	27.07	31.07
Maturation	15.09	10.10	19.09

Source: compiled by the authors

In the process of studying the effect of treating the vegetative mass of plants with biologics, observations of growth processes were carried out. The height of sunflower plants in the five leaf phase in 2021 ranged from 68 to 74 cm in 2022 from 70 to 73 cm, and in 2023 – 60-65 cm (Fig. 1). Foliar dressing with biologics showed a tendency to stimulate plant growth. In 2021, this trend was more pronounced due to a warmer and wetter spring, compared to 2022 and 2023. The highest height of plants in the five leaf phase over the

years of research was observed in the variant where Azotohelp treatment was performed, the increase compared to the control was 2-5%. The best development of the photosynthetic apparatus of plants at this stage was one of the significant factors in the development of their productivity. The difference in plant height persisted until the end of the growing season (maturation phase): plants of the control variant in 2021 and 2023 were lower by 3-9% and 3-8%, and in 2022 by 1-4%, compared to treated biologics.

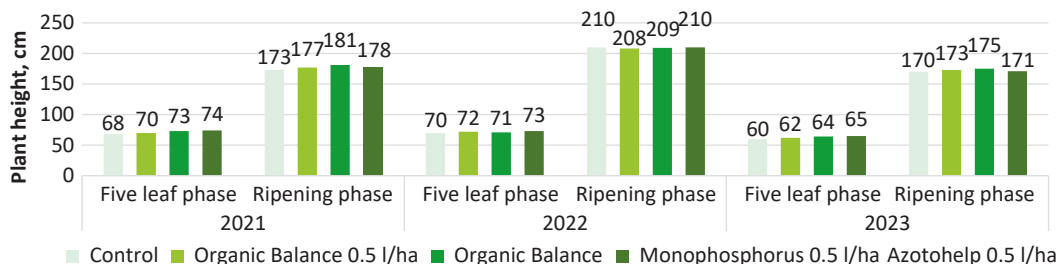


Figure 1. Height of sunflower plants with the foliar application of biologics

Source: compiled by the authors

One of the main indicators that affect the development of sunflower productivity was the basket diameter, the weight of seeds from the basket, and the weight of 1,000 grains. The results of experimental data indicate that foliar dressing with biologics increased the diameter of the basket. Thus, the introduction of Organic Balance on average for three years of research increased this indicator compared to the control version by 3.25 cm, Organic Balance Monophosphorus – by 3.55 cm, and Azotohelp – by 3.8 cm.

A significant role in the development of

yield was played by the weight of 1,000 grains, which characterises the fullness of seeds and directly affects the weight of grain in the basket and plant productivity. It was found that on average for three years, the weight of 1,000 grains in the version using Organic Balance increased by 5.2 g, Organic Balance Monophosphorus – 3.2 g, Azotohelp – 3.7 g, compared to the control. Naturally, an increase in the weight of 1,000 grains due to foliar application of biologics led to an increase in the weight of seeds from the basket by 4.9, 6.9, and 9.7 g, respectively (Table 2).

Table 2. Structural indicators of sunflower yield with the foliar application of biologics (average for 2021-2023)

Option	Basket diameter, cm	Weight of grains from the basket, g	Weight of 1,000 grains, g
1. Control	18.6	53.9	54.8
2. Organic Balance 0.5 l/ha	21.1	58.8	59.1

Table 2, Continued

Option	Basket diameter, cm	Weight of grains from the basket, g	Weight of 1,000 grains, g
3. Organic Balance Monophosphorus 0.5 l/ha	21.1	60.8	58.0
4. Azotohelp 0.5 l/ha	21.9	63.6	58.5

Source: compiled by the authors

The results obtained demonstrate that the treatment of plants with Organic Balance, Organic Balance Monophosphorus, Azotohelp preparations, improving biological and economic productivity indicators, had a positive effect on sunflower yield, which was confirmed by the close relationship between these indicators. Thus, an increase in the diameter of the basket, the number and weight of seeds in it, and the weight of 1,000 grains, is highly correlated with yield ($r =$

0.80-0.99) (Table 3). An integral indicator of the effectiveness of a particular element of technology is the yield of the crop. However, the weather conditions of the year also have a significant impact on the crop development. Thus, according to the results of accounting in 2021, a mathematically significant increase (+0.3, +0.7, +0.64 t/ha, respectively) to the control variant was obtained at all variants of the experiment where foliar dressing with biologics was carried out (Table 4).

Table 3. Correlation coefficients of valuable biological and economic characteristics of sunflower with the foliar application of biologics (average for 2021-2023)

Indicators	Basket diameter, cm	Number of seeds in the basket, units	Weight of grains from the basket, g	Weight of 1,000 grains, g
Number of seeds in the basket, units	0.77	-	-	-
Weight of grains from the basket, g	0.96	0.91	-	-
Weight of 1,000 grains, g	0.93	0.49	0.8	-
Yield, t/ha	0.96	0.9	0.99	0.8

Source: compiled by the authors

Table 4. Sunflower yield with the foliar application of biologics

No.	Option	Yield, t/ha					Lewis stability coefficient, Ksfn
		2021	2022	2023	Average for 2021-2023	\pm to control, t/ha	
1	Control	3.05	3.27	3.16	3.16	-	1.07
2	Organic Balance 0.5 l/ha	3.35	3.57	3.41	3.44	0.28	1.07
3	Organic Balance Monophosphorus 0.5 l/ha	3.75	3.33	3.42	3.5	0.34	1.13
4	Azotohelp 0.5 l/ha	3.69	3.7	3.78	3.72	0.56	1.02
LSD ₀₅		0.28	0.21	0.21			

Source: compiled by the authors

In the climatic conditions of 2022, a significant increase in yield was formed when plants were treated with Organic Balance (+0.3 t/ha) and Azotohelp (+0.43 t/ha) biologics. The use of biologics in 2023 significantly increased this indicator in all variants (+0.25 t/ha, +0.26 t/ha, and +0.62 t/ha, respectively). Notably, the advantage of the positive effect of Organic Balance Monophosphorus on the development of sunflower yield under hot weather conditions in

2021 (+0.6 t/ha) compared to favourable conditions for agricultural crops in 2022-2023 (+0.06, +0.26 t/ha, respectively). On average, over three years of research, the biological yield of sunflower seeds with the foliar application of biologics exceeded the control option by 0.3-0.54 t/ha. The highest productivity of sunflower was formed by foliar dressing with Azotohelp and amounted to 3.7 t/ha at the control level of 3.16 t/ha, respectively, the increase was 0.54 t/ha,

or 171%. This option, according to the Lewis coefficient (1.02), turned out to be the most stable in terms of yield.

It was determined that similar patterns regarding the positive use of biologics were confirmed by studies on other cultures. In particular on winter wheat, A. Bahan & V. Gurba (2025) noted that the use of microbiological preparations in technologies for growing winter wheat helped to increase the supply of nutrients to plants, which stimulated the development of plants during the growing season, and, as a result, increased the length of the ear to the control option by 4.1%, and productivity by 3-12%. A. Datsko *et al.* (2022) noted that the productivity of winter wheat increased compared to the control variant by 2-7% with the use of Azotohelp, by 8% with Organic Balance, and by 10% with Organic Balance Monophosphorus. According to V. Polishchuk *et al.* (2025), foliar application of biologics in 'Granada' potato crops contributed to higher yields compared to the control option when using biologics, the yield increase against the background of 50 tonnes of manure was 6-11%, and with the mineral fertiliser system $N_{50}P_{40}K_{70}$ – 3-8%. V. Bilyi & V. Knysh (2021) noted that double foliar application of biologics increased corn yield relative to control by 26-30%.

The findings by K. Geetha *et al.* (2018) and A. Bahan *et al.* (2023) showed that the treatment of sunflower seeds with biologics had a significant impact on its sowing qualities, there was an increase in the length of the root and sprout, and the weight of 100 sprouts during germination in hybrids, compared with the control. D. Chuyko *et al.* (2020) indicated a positive effect of double foliar application of biologics on the line-sterile analogues of the Sh808A genotype, increasing yield by 19%, plant productivity – by 17%. O. Kovalenko *et al.* (2020) noted that the foliar application of biologics contributes to the mobilisation and optimisation of plant nutrition elements, improvement of growth processes, and high sunflower seed productivity, an increase relative to control by 5-13%. A. Panfilova *et al.* (2024) noted that the use of biologics Azotofit and Organic Balance on various sunflower hybrids improved biological performance, which, in turn, increased productivity by 5-10 and 3-12%, respectively, and the oil content – by 0.9-1.8%.

The study investigated the use of biologics specifically for foliar application, which is important in increasing the biological potential of the crop, considering the weather features of the growing season. The proposed agricultural measure is effective and necessary in contemporary agricultural technologies; however, in the context of climate change, it requires further scientific research.

CONCLUSIONS

In the conditions of the north-eastern part of the forest-steppe zone of Ukraine, on typical low-humus medium loamy chernozems, it is advisable to use foliar application of biological products to increase the efficiency of intensive sunflower cultivation technology. Foliar application of biologics contributed to the activation of physiological and biochemical processes, stimulation of plant growth and development, which was manifested in an increase in the height of sunflower plants by 3-7%, the diameter of the basket by 16.9-19.8% of the weight of 1,000 grains by 8.4-12.1%, and an increase in yield by 9.5-17.1% compared to the control. A high correlation ($r = 0.80-0.99$) was obtained between the elements of productivity (basket diameter, number and weight of grains, weight of 1,000 grains) and yield, which confirms their decisive role in the development of the level of crop productivity.

The greatest increase in the yield of sunflower plants was provided by foliar application of Azotohelp, which increased productivity by 0.54 t/ha (17%) relative to the control (3.16 t/ha) and was characterised by the highest stability according to the Lewis coefficient (1.02). Organic Balance Monophosphorus showed a particularly positive effect in arid conditions in 2021, which indicates an increase in plant resistance to abiotic stresses and the prospects for using biologic preparations in the context of climate change.

The use of biologics not only increased the yield of sunflower, but also allowed optimising plant nutrition, reducing the pesticide load, and increasing the efficiency of intensive sunflower cultivation technology, which meets the requirements of contemporary ecological farming. The use of biologics contributed not only to increasing yields, but also to improving

environmental sustainability and reducing the impact of sunflower cultivation on the environment. The results of the study showed the potential of integrating biologics into precise and sustainable farming systems, which increases both productivity and resource efficiency. In further studies of foliar application of biologics on sunflower, it is advisable to expand the research of the growth-regulating effect of biologics, their role in reducing the duration of stress states, influence on photosynthetic activity, and

features of the development of productivity of agrophytocoenoses.

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Вплив фоліарного внесення біопрепаратів на продуктивність соняшника в умовах північно-східної частини Лісостепу України

Анотація. Виробництво соняшнику вимагає нових технологічних підходів, що передбачають не лише використання інтенсивних гібридів, систем удобрення й інноваційної техніки, а також забезпечення комплексної взаємодії основних агротехнологічних чинників. Метою дослідження було встановити вплив фоліарного внесення біопрепаратів завдяки їх стимулюючій та захисній дії на реалізацію продуктивності рослин соняшнику закладених в генотипі. У дослідженні було застосовано польовий метод для вивчення взаємодії об'єктів досліджень з природними факторами, лабораторний, а також математико-статистичний. Встановлено, що за фоліарного підживлення біопрепаратами простежилась тенденція до стимуляції росту рослин. Найбільша висота рослин (+5 см) у фазу зірочки за роки досліджень спостерігалася на варіанті, де проводили обробку Азотохелпом. Позакореневі підживлення біопрепаратом Органік баланс вплинули на збільшення діаметра кошика порівняно до контрольного варіанту на 3,25 см, Органік баланс монофосфор – на 3,55 см, а Азотохелп – на 3,8 см. Водночас маса 1000 зерен, за застосування Органік баланс зростала на 5,2 г, Органік баланс монофосфор – 3,2 г, Азотохелп – 3,7 г. Фоліарні внесення біопрепаратів підвищували масу насіння з кошика відповідно на 4,9, 6,9 та 9,7 г. Втім, збільшення діаметру кошика, кількості та маси насінин в ньому, а також маси 1000 насінин, зумовило підвищення врожайності, що

підтвердилось високою кореляцією ($r = 0,80-0,99$) між даними показниками. Слід відмітити, що більший вплив біопрепарату Органік баланс монофосфор на формування урожайності соняшника виявлено за спекотних погодних умов 2021 р. порівняно з більш сприятливими умовами 2022-2023 рр. В середньому за три роки досліджень біологічна урожайність соняшника за фоліарного внесення біопрепаратів перевищила контрольний варіант на 0,3-0,54 т/га. Найвища продуктивність соняшника формувалася за позакореневого підживлення біопрепаратом Азотохелп і складала 3,7 т/га за рівня на контролі 3,16 т/га, приріст склав 0,54 т/га, або 17,1 %. Дані результати можуть бути використані для оптимізації інтенсивної технології вирощування соняшника, що сприятиме кращому живленню рослин, зниженню пестицидного навантаження та підвищення врожайності соняшника

Ключові слова: олійні культури; урожайність; добрива; Азотохелп; Органік баланс; Органік баланс монофосфор

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Photosynthetic activity of oat crops under combined application of mineral fertilisers and biological preparation

Abstract. The effectiveness of photosynthesis in oat crops with the combined use of mineral fertilisers and biological products in order to reduce mineral fertiliser rates and increase productivity is extremely relevant. The aim of the study was to establish the effectiveness of the combined use of mineral fertilisers and biological preparations by activating the photosynthetic activity of oat crops and their productivity. The study was conducted using field, laboratory and mathematical methods of analysis. The research results were statistically calculated and interpreted. The results of research on the formation of leaf surface area and net photosynthetic productivity of the 'Ivory' oat variety in the right-bank forest-steppe zone of Ukraine depending on fertiliser rates, pre-sowing treatment of seeds with biological preparations of phosphate-mobilising action Polymixobacterin based on the bacterium *Paenibacillus polymyxa*, and Mycofix based on the mycorrhizal fungus *Glomus*

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intraradices using treated and untreated seeds. With combined treatment of seeds with a fungicide and Mycofix, the maximum leaf area was formed – 44.6-64.5 thousand m²/ha depending on the fertilisation background. When sowing with treated seeds against the background of N₉₀P₉₀K₉₀, 60.9 thousand m²/ha of leaf area was formed, and when treated with fungicide and additional treatment with Polimixobacterin or Mycofix against a background of N₉₀P₆₀K₉₀, 61.3 and 63.9 thousand m²/ha, respectively. With a reduction in phosphorus to N₉₀P₃₀K₉₀ and seed treatment according to the same scheme, the leaf area was 61.0 and 63.2 thousand m²/ha, respectively, at the BBCH 62-65 stage. A close positive correlation was established – the correlation coefficient between yield and leaf area at the BBCH 63-64 stage was 0.87-0.89. The practical value of the study was to establish a compensatory effect of the combined use of biological preparations and mineral fertilisers, which made it possible to reduce fertiliser application rates without reducing the photosynthetic activity of crops and oat yield

Keywords: leaf area; net photosynthetic productivity; fertiliser rates; Polymixobacterin; Mycofix; yield

INTRODUCTION

The relevance of the study was associated with the search for ways to increase the production of a valuable crop – oats (*Avena sativa*). Oats are a versatile crop, in particular, oat grain is a valuable raw material for the production of dietary and baby food products. The production of such grain requires the use of technologies that reduce the use of chemical fertilisers while activating the genetic potential of varieties through the use of biological preparations.

Oats have a fairly short growing season, during which intensive synthesis of organic matter occurs through photosynthesis. The directions for improving the efficiency of photosynthesis are quite different from the modelling of the selection genome, according to N. Smith *et al.* (2019) and F. Morales *et al.* (2020), as indicated by O. Todosiichuk (2024), crop cultivation technologies that increase leaf surface area, effective transpiration and solar energy absorption. M. Duda *et al.* (2021) emphasise that one of the main technological factors determining the intensification of photosynthesis and increased disease resistance is the fertilisation system, dry matter accumulation, and yield formation with targeted grain quality. When producing such grain, it is necessary to adhere to technologies that reduce the use of chemical fertilisers while activating the genetic potential of varieties through the use of biological preparations. Research by A. Kravchenko *et al.* (2023) demonstrates that F2 hybrids of naked oats exhibit transgressive variability in productive traits,

which opens up prospects for increasing yield through breeding and agrotechnical measures. This emphasises that increasing the productivity of oats is possible not only through external agrotechnical factors, but also through the use of the internal potential of plants, which opens up additional opportunities for optimising cultivation technologies.

For a long time, it was believed, as emphasised by M. Stepanenko (2023), that global plant growth on the planet is largely limited by nitrogen supply – more so than by other nutrients. At the same time, research results are emerging, in particular from J. Paz-Ares *et al.* (2022) and S. Wang *et al.* (2025), which analytically prove that over the last four decades, phosphorus has been a stronger constraint on global photosynthesis than nitrogen. V. Volkogon (2023) argues that chemical fertilisers and pesticides are widely used to ensure food security and increase crop productivity. At the same time, V. Volkogon *et al.* (2019) emphasise that the reckless use of agrochemicals in turn leads to environmental pollution, which poses a threat to public health and soil degradation, deterioration of their chemical and biological condition. To increase the efficiency of mineral fertilisers applied to crops, scientists suggest combining the use of mineral fertilisers with microbial preparations for seed inoculation. The research is unquestionably novel in that it is the first study conducted on oats using a combination of mineral fertilisers, biological preparations, pre-sowing

seed treatment, which made it possible to establish the possibility of controlling the photosynthetic activity of oat crops and compensatory reduction of mineral fertiliser rates through their combined use with biological preparations and seed treatment.

The aim of the study was to establish the effectiveness of the combined use of mineral fertilisers and biological preparations through the photosynthetic activity of oat crops. The objectives of the study were to identify: the characteristics of the formation of the leaf surface area of oat plants and the net productivity of photosynthesis depending on the rates of mineral fertilisers, pre-sowing treatment of seeds with biological preparations and seed dressing; the compensatory effect of biological preparations and other nutritional components, pre-sowing seed treatment on the formation of leaf surface area and net photosynthetic productivity of oat crops at reduced rates of mineral fertilisers, in particular phosphorus fertilisers; correlation dependencies between the photosynthetic activity of oat crops and yield depending on the factors studied.

LITERATURE REVIEW

Photosynthesis – the only process in the biosphere that allows the Sun's energy to be absorbed and ensures the existence of both plants and all heterotrophic organisms. N. Smith *et al.* (2019) emphasise that primary photosynthetic production sets an absolute upper limit for all heterotrophs and modern agricultural production. The photosynthetic apparatus, its architecture, spatial and temporal parameters, optical and biological properties for autotrophic organisms, all other things being equal, are the main source of energy for their vital functions and a determining factor in their productivity. L. Hu *et al.* (2019) and X. Song *et al.* (2019) indicate that the activity of photosynthetic processes in plants depends on the species and variety characteristics of crops, soil and climatic conditions, and the level of nutrient availability. As R. Kholodchenko (2014) points out, photosynthesis processes, the rate of increase in leaf area and respiration have a direct impact on plant growth and development, determining the rate of organic matter accumulation, structure and yield.

D. Lawlor (1995) argues that there are two main ways to increase dry matter accumulation through photosynthesis: extending the growing season; increasing the efficiency of light absorption and conversion by crops, which can be achieved by increasing the leaf surface area. The extension of the growing season is achieved through genetic mechanisms, as well as through a fertilisation system, which at the same time significantly affects the formation of the leaf surface area and its activity, as proven by the research of R. Kholodchenko (2014). H. Tian *et al.* (2022) emphasise the importance of studying and increasing the photosynthetic activity of oats not only through the leaf surface, but also through other plant organs, especially the ear during grain filling, which is an important strategy for increasing crop yields, especially under stressful conditions. Oats are a moisture-loving crop, and drought significantly reduces the photosynthetic capacity of plants, leading to crop loss, although according to V. Sadras *et al.* (2017), non-leaf organs such as flower scales can compensate for this by increasing their photosynthetic contribution.

Scientists such as H. Zeng *et al.* (2024) show that droughts disrupt the internal physiological processes of plants, such as photosynthesis, reducing plant metabolism and causing premature ageing, which leads to lower yields. K. Jużoń *et al.* (2020) and H. Tian *et al.* (2022) show that drought causes accelerated degradation of photosynthetic components (chlorophyll, Rubisco, photosystem II, etc.) in the flag leaves of cereal crops. B. Zhao *et al.* (2021) prove that drought causes a 31-69% loss of oat grain yield. Compared to sufficient water supply, grain yield decreased by 36, 69 and 44% in the 'Shadow' variety and by 31, 33 and 41% in the 'Bia' variety under severe stress at the stages of stem elongation, heading or after flowering. Under conditions of sufficient water supply, the 'Shadow' variety showed a 13-16% longer leaf area functioning period and had a significantly larger leaf area at the heading and post-flowering stages, resulting in 13-20% more spikelets per panicle and 13-21% higher grain yield than the 'Bia' variety. Water stress at the heading stage for the 'Shadow' variety and at the post-flowering stage for the 'Bia' variety was detrimental to grain yield due to a

decrease in the grain weight/leaf area ratio, duration of functioning and a decrease in leaf area.

Optimising the nutrition of oat plants helps to realise the biological potential of varieties at a higher level. S. Wang *et al.* (2025), based on the analysis of more than 80,000 field observations of nutrient elements in leaves, created a long-term global dataset on nitrogen (N) and phosphorus (P) concentrations in leaves during 1980-2017. A more intense decrease in phosphorus concentration in leaves ($-0.80 \pm 0.008\%$ year⁻¹) than in N concentration ($-0.31 \pm 0.002\%$ year⁻¹) was observed. This decline led to an increase in terrestrial areas with limited phosphorus content in leaves and a large-scale reduction in plant photosynthesis, more than 1.5 times stronger than the reduction due to lower nitrogen content in leaves. The increasing trend in global photosynthesis over the past four decades has been reduced by approximately 17.2% and 6.7% due to the reduction in phosphorus and nitrogen content in leaves, respectively. This stronger phosphorus limitation of global photosynthesis implies a weakening of terrestrial carbon sinks due to emerging phosphorus limitations and calls for more stringent strategies to reduce anthropogenic emissions to mitigate climate warming. S. Xu *et al.* (2020) also show a significant response of plants to the ratio of carbon, nitrogen, and phosphorus content in leaves and CO₂ uptake in relation to climate change and air emissions. Carbon accumulation in leaves mainly comes from the balance between photosynthesis and leaf respiration, a topic that remains insufficiently studied.

V. Volkogon *et al.* (2019) emphasise the extreme importance of improving the efficiency of phosphorus fertiliser use. According to J. Paz-Ares *et al.* (2022), the inefficiency of phosphorus fertilisers is related to their properties: only 15-25% is absorbed by plants, and the rest is washed away, causing soil degradation and water eutrophication. N. Smith *et al.* (2019) prove that by applying bacterial inoculation to cereal seeds, it is possible to improve their phosphorus supply and increase yields. Similar conclusions regarding the use of bacteria and their effectiveness when used in combination with mineral fertilisers were also reached by E. Kuter *et al.* (2023). According to S. Kumar *et al.* (2022) and

K. Marchenko (2022), beneficial mechanisms for improving plant growth include increasing nutrient availability, modulating phytohormones, biocontrol of phytopathogens, and mitigating biotic and abiotic stresses. At the same time, according to P. Murgese *et al.* (2020), O. Fasusi *et al.* (2021), and S. Nacoon *et al.* (2021), the use of beneficial microbiomes as biofertilisers in sustainable agricultural practices has become an innovative and environmentally friendly technology for improving soil fertility and plant growth. B. Glick & E. Gamalaro (2021) point out that microbes, which are phylogenetically diverse and multifaceted, interact with plants in various ways: symbiosis, parasitism, commensalism, amensalism, and neutralism. At the same time, as A. Potapov & M. Hrabovsky (2023) point out, the growth of these microbes depends on plant photosynthesis, while simultaneously influencing plant growth, which is why they are collectively referred to as the plant microbiome.

A. Johnston *et al.* (2014) found that the determining factor in the mobilisation of phosphorus for plants is the activity of soil microbiota, namely microorganisms that have the potential to convert poorly soluble soil phosphates into a form accessible to plants and produce physiologically active substances. The hyphae of mycorrhizal fungi are able to penetrate plant root cells, forming vesicles (swelling) and arbuscules (tree-like branches). Once established in the root system of a plant, mycorrhizal fungi multiply and spread into the surrounding soil in the form of a large mass of absorbent threads, increasing the plant's absorption of water and nutrients (Brisson *et al.*, 2022). However, these studies are insufficient, especially given the establishment of the photosynthetic activity of oat plants and their productivity depending on a complex of environmental factors, cultivation technologies and soils.

MATERIALS AND METHODS

The research was conducted in 2019-2021 in a demonstration and production experiment by the Vitagro group of companies, Agrarian Company 2004 (experimental field 5/3 of the "Tovtry" Cluster, Lisovody village, Horodok municipal community, Khmelnytskyi district, Khmelnytskyi region. Geolocation: 49°09'35.8"N

26°28'32.9'E). A field experiment was set up to achieve the set goal. The soil of the experimental plots is podzolised chernozem, which is considered favourable for the formation of highly productive crops. The soil humus content is 3.7-3.9%; alkali-hydrolysed nitrogen – 108-115 mg/kg of soil; mobile phosphorus – 170-180; exchangeable potassium – 115-120 mg/kg of soil. The soil solution reaction is neutral – pH 6.8-7.1; hydrolytic acidity is low – 0.60-0.80 mg – eq/100 g of soil; the sum of absorbed bases is 38-42 mg – eq/100 g of soil. The main physical and water properties of the soil are good: specific gravity – 2.55 g/cm³, bulk density – 1.20-1.25 g/cm³, porosity – 55%. The maximum hygroscopicity was 5.1%; the minimum moisture capacity was 23.0%, and the total moisture capacity was 51.0%.

The field experiment was set up in accordance with the methodological requirements for conducting experiments (Rozhkov *et al.*, 2016).

The area of the sowing plot was 50.4 m². The experiment was repeated three times, with the variants arranged sequentially. The study was conducted in accordance with the ethical standards of the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1976). According to the experiment scheme, mineral fertilisers were applied in the form of ammonium nitrate, simple granulated superphosphate, and granulated potassium chloride (Table 1). The full fertiliser rate was based on an equal ratio of nitrogen:phosphorus:potassium (N: P: K). Subsequently, for each full dose of nutrients, the phosphorus dose was reduced in increments of 30 kg/ha a.i. in order to determine the level of compensatory capacity of phosphate-mobilising biological products. The main application of fertilisers was carried out during pre-sowing soil cultivation.

Table 1. Scheme of the field experiment

Fertilisation, kg/ha a.i. – Factor A		Seed treatment – Factor B		Biopreparation treatment – Factor C	
Variant designation	Rate	Variant designation	Treatment	Variant designation	Seed treatment
K	Control (no fertilisers)	K1	Without treatment	K1	Control (no seed treatment)
U 1	N ₃₀ P ₃₀ K ₃₀			K1P	Polymixobacterin
U 2	N ₃₀ K ₃₀			K1M	Mycofix
U 3	N ₆₀ P ₆₀ K ₆₀ O	K2	Seeds treated	K2	Control with seed dressing
U 4	N ₆₀ P ₃₀ K ₆₀			K2N	Seed treatment + Polymixobacterin
U 5	N ₉₀ P ₉₀ K ₉₀			K2M	Seed treatment + Mycofix
U 6	N ₉₀ P ₆₀ K ₉₀				
U 7	N ₉₀ P ₃₀ K ₉₀				

Source: scheme developed by the authors

For pre-sowing seed treatment, in accordance with the experimental design, Vincit 050 SC seed treatment was used at a rate of 2.0 l/t; phosphate-mobilising biological products: Polymixobacterin and Mycofix. The active ingredient of Polymixobacterin is phosphate-mobilising bacteria *Paenibacillus polymyxa* KB (Patent No. 99009 Ukraine), whose mechanism of action is related to the ability of bacteria to produce gluconic, acetic, succinic, uronic, lactic, butyric and other acids, as well as the enzyme phosphatase, which promotes the dissolution of poorly soluble minerals and the hydrolysis of organic phosphates

in soil and fertilisers, resulting in the release of phosphorus into the soil. acids, as well as the enzyme phosphatase, which promotes the dissolution of poorly soluble minerals and the hydrolysis of organic phosphates in soil and fertilisers, thereby activating the process of phosphorus assimilation by plants. In addition to their effect on the dissolution of phosphorus compounds, *Paenibacillus polymyxa* KB bacteria produce phytohormonal substances that stimulate plant growth and development, influence the formation and development of the root system and its absorptive capacity, which also optimises phosphate uptake.

The Mycofix mycorrhizal inoculant (mycorrhizant) was developed by the British company Legume Technology Ltd. The mycorrhizal inoculant is based on the mycorrhizal fungus *Glomus intraradices* (CMCCROC7) – living vegetative cells, spores of the mycorrhizal fungus – 1% (minimum 2000 propagules (spores)/gram), with the remaining 99% being an extract of the marine alga *Ascophyllum nodosum* with a naturally low content of micro- and macroelements (surface-active substances). On the day of sowing, the seeds were treated according to the experimental scheme (Table 1). During the growing season in the field experiment, plant samples of oats were selected at the stages of plant growth and development: BBCH 27-29 (end of tillering), BBCH 37-39 (emergence of the flag leaf), BBCH 52-55 (formation of the panicle – appearance of 20-50% of the panicle – panicle node still in the leaf sheath).

To determine the leaf area of oats and calculate the net photosynthetic productivity, samples were taken at certain macro- or micro-stages in two non-contiguous replicates of 0.33 running metres, in which the wet weight, dry matter content and leaf area were determined. All leaves were separated from the sample and weighed. Ten leaves were selected, tightly folded together, and 10 punctures were made with a laboratory sampler of a specified diameter and calculated area – 100 “cuts” were selected, which were immediately weighed. The leaf surface area of the selected sample was determined by proportional ratio and converted to hectares. The net photosynthetic productivity of crops was determined by measuring the absolutely dry mass of plants in grams per 1 m² at the same stage (phase) as the determination of leaf surface area. The net photosynthetic productivity (NPP) of plants was calculated using formula (1):

$$NPP = \frac{Us_1 - Us_2}{0.5(L_1 + L_2)T}, \quad (1)$$

where Us_1 and Us_2 – dry matter of plants at the studied stages of development, g/m²; L_1 and L_2 – the average leaf area of plants during the studied period of development.

Laboratory tests were conducted in the scientific and production laboratory of Vitagro Partner TM Bayton (LLC “Ahrokhim Tekhnologii”).

Oat cultivation technology. The experiment involved growing the ‘Ivory’ oat variety, bred by Saaten Union and registered in 2011. The variety belongs to the early maturing group. The sowing rate was 3.5 million viable seeds per hectare. The predecessor in the experiment was soybeans. After harvesting the predecessor, disc harrowing was carried out with a Rubin 12 (Lemken) heavy harrow to a depth of 14-16 cm in two passes. Fertilisers were applied with a Kuhn MDS 19.1 R2 mounted mineral fertiliser spreader during pre-sowing cultivation according to the experiment scheme. Pre-sowing cultivation was carried out with an AP-3 Europak unit. Sowing was carried out with a Horsch Pronto 6 DC PPF (Germany) seeder to a depth of 3.0-3.5 cm.

The protection system included a number of measures. During microstudies BBCH 21-29 (macrostage 2: tillering), the crops were treated with a tank mixture: herbicide protection – Pride (TM Bayton (2-ethylhexyl ester 2,4-D, 452, 42 g/l florasulam, 6.25 g/l) – 0.6 l/ha; fungicide protection – Duncan (TM Bayton Carbendazim, 250 g/l, Flutriafol, 125 g/l) – 0.6 l/ha; insecticide protection TOP (TM Bayton (Lambda-cyhalothrin, 50 g/l) – 0.2 l/ha. In microstage BBCH 41-49 (macrostage 4: panicle formation), oat crops were treated with a tank mixture: fungicide protection – Platon (TM Bayton (Prochloraz, 300 g/l + tebuconazole, 140 g/l + cyproconazole, 50 g/l) – 0.8 l/ha; insecticide protection – Shocker (TM Bayton (Imidacloprid, 300 g/l + lambda-cyhalothrin, 100 g/l) – 0.15 l/ha.

RESULTS AND DISCUSSION

The formation of the optimal leaf area directly depends on the technology used to grow crops, as indicated by D. Liubyt'ska & R. Mialkovskiy (2024). K. Marchenko (2022) asserts that the best conditions for high yields are created by forming a larger leaf surface area, longer vegetation period, and photosynthetic potential. For the synthesis of organic matter and the formation of vegetative and generative organs, it is important that the total leaf surface area of the crop is optimal. The optimal area is considered to be one that ensures maximum gas exchange in plants. N. Smith et al. (2019) prove that the optimal size of the assimilation apparatus, which ensures intensive absorption of solar energy and high

photosynthetic productivity, is between 40 and 45 thousand m²/ha. Further growth of leaf area slightly increases photosynthetically active radiation and causes a decrease in net photosynthetic productivity due to the shading of leaves in the middle and lower tiers.

It has been established that the leaf area changed significantly depending on the plant fertilisation system, which caused both the intensification of photosynthesis and changes in plant parameters, in particular the size of the leaf area. The use of mineral fertilisers in various fertilisation schemes contributed to an increase in leaf surface area at all microstages of plant development, compared to the control variant, where fertilisers were not used. Oat plants form leaf surface area quite intensively already in the early stages of development, unlike other spring cereals, responding positively to fertiliser application. Thus, at microstages

BBCH 27-29, the leaf area ranged from 11.6 to 31.8 thousand m²/ha (Table 2). When sowing with untreated seeds, an area of 11.6 to 25.0 thousand m²/ha was formed, depending on the nutrient background; when treating seeds with Polymixobacterin – 12.5-28.1; when treating seeds with Mycofix – 12.5-29.1. When sowing with treated seeds, 13.3-30.3 thousand m²/ha of leaf surface area was formed; with additional treatment with Polymixobacterin – 13.7-13.3 thousand m²/ha; with additional treatment with Mycofix – 13.6-31.8 thousand m²/ha. The application of complete mineral fertiliser ensured increased growth intensity of the leaf surface of oats. In particular, in the 'Buh' variety, with intensive fertiliser application, the leaf surface area, depending on the fertilisation option, was: in the tillering phase 12.6-14.7; at the booting stage – 51.6-59.1; at milk ripeness 23.3-33.1 thousand m²/ha.

Table 2. Leaf area of sown oat depending on fertilisation and seed treatment, tillering stage (BBCH 27-29), thousand m²/ha

Fertiliser rate, kg/ha a.i.	Seed treatment									
	Untreated (K1)					Treated (K2)				
	Biopreparation seed treatment ¹									
	K1	P	M	Mean	+/- from fertiliser	K2	P	M	Mean	+/- from fertiliser
Control	11.6 ²	12.5	12.5	12.2	0.6	13.3 ³	13.7	13.6	13.5	-
N ₃₀ K ₃₀	15.4	16.2	16.8	16.1	4.5	17.5	17.9	18.3	17.9	4.6
N ₃₀ P ₃₀ K ₃₀	18.5	20.0	20.5	19.7	8.1	21.1	21.6	21.6	21.4	8.1
N ₆₀ P ₆₀ K ₆₀	24.0	25.0	26.0	25.0	13.4	28.1	27.8	28.6	28.2	14.9
N ₆₀ P ₃₀ K ₆₀	21.8	23.2	23.9	23.0	11.4	24.0	25.3	26.0	25.1	11.8
N ₉₀ P ₃₀ K ₉₀	25.0	26.3	27.4	26.2	14.6	27.3	28.0	29.2	28.2	14.9
N ₉₀ P ₆₀ K ₉₀	25.7	27.6	28.1	27.1	15.5	29.2	29.9	30.2	29.8	16.5
N ₉₀ P ₉₀ K ₉₀	27.0	28.1	29.1	28.1	16.5	30.3	31.3	31.8	31.1	17.8
HIP	1.2	1.2	1.3	1.4		1.3	1.3	1.2	1.4	

Note: ¹P – Polymixobacterin; M – Mycofix; ² and ³ – controls according to fertiliser norms for untreated and treated seeds, respectively; average for 2019-2021

Source: authors' research results

The process of leaf mass growth in oats is accelerated – already in the phase of plant emergence, the photosynthetic surface of oats increased almost twice – on average over the years of research from 11.6 in the tillering phase (BBCH 27-29) to 21.3 thousand m²/ha in the booting phase (BBCH 37-39) in the variant without

fertilisers, and from 31.8 to 40.6 thousand m²/ha, respectively, with fertilisation and combined seed treatment with the Mikofix fungicide. At the same time, according to M. Stepanenko (2023), maize in the milk ripeness phase had a maximum leaf area of 35.7-42.1 thousand m²/ha, significantly inferior to oats (Tables 2, 3, 4).

Table 3. Leaf area of sown oats depending on fertilisation and seed treatment, booting stage (BBCH 37-39), thousand m²/ha

Fertiliser rate, kg/ha a.i.	Seed treatment									
	Untreated (K1)					Treated (K1)				
	Biopreparation seed treatment ¹									
	K1	P	M	Mean	+/- from fertiliser	K2	P	M	Mean	+/- from fertiliser
Control	21.3 ²	23.0	23.7	22.7	1.4	23.7 ³	25.1	25.4	24.7	-
N ₃₀ K ₃₀	25.6	27.2	27.8	26.9	5.6	28.3	29.7	30.7	29.6	5.9
N ₃₀ P ₃₀ K ₃₀	27.5	29.5	30.1	29.0	7.7	30.7	31.5	32.4	31.5	7.8
N ₆₀ P ₆₀ K ₆₀	32.5	35.5	36.5	34.8	13.5	38.1	38.4	38.7	38.4	14.7
N ₆₀ P ₃₀ K ₆₀	31.0	34.2	34.9	33.4	12.1	34.9	36.0	36.4	35.8	12.1
N ₉₀ P ₃₀ K ₉₀	32.9	35.0	36.7	34.9	13.6	35.6	36.7	38.2	36.8	13.1
N ₉₀ P ₆₀ K ₉₀	33.7	35.7	36.8	35.4	14.1	36.9	38.2	39.4	38.2	14.5
N ₉₀ P ₉₀ K ₉₀	34.5	36.8	38.4	36.6	15.3	37.8	39.4	40.6	39.3	15.6
HIP										

Note: ¹P – Polymixobacterin; M – Mycofix; ² and ³ – controls according to fertiliser norms for untreated and treated seeds, respectively; average for 2019-2021

Source: authors' research results

The assimilation surface of crops reached its maximum value during the flowering phase (BBCH 62-64). The range of changes in leaf surface area was from 38.1 thousand m²/ha in the control variant (without

fertilisers and without seed treatment) to 63.2-64.5 thousand m²/ha when applying N₉₀P₃₀K₉₀, N₉₀P₆₀K₉₀, N₉₀P₉₀K₉₀ and sowing with seeds treated with a fungicide and Mycofix (Table 4).

Table 4. Leaf area of sown oats depending on fertilisation and seed treatment, beginning of flowering phase (BBCH 62-64), thousand m²/ha

Fertiliser rate, kg/ha a.i., Factor A	Seed treatment, Factor B									
	Untreated (K1)					Treated (K2)				
	Biopreparation seed treatment ¹ , Factor C									
	K1	P	M	Mean	+/- from fertiliser	K2	P	M	Mean	+/- from fertiliser
Control	38.1 ²	41.3	42.0	40.5	-	42.3 ³	44.0	44.6	43.6	-
N ₃₀ K ₃₀	41.3	44.7	45.3	43.8	5.7	45.9	47.3	49.3	47.5	5.2
N ₃₀ P ₃₀ K ₃₀	43.5	46.7	48.3	46.2	8.1	48.0	49.1	50.1	49.1	6.8
N ₆₀ P ₆₀ K ₆₀	53.1	56.4	57.9	55.8	17.7	57.5	58.1	60.3	58.6	16.3
N ₆₀ P ₃₀ K ₆₀	50.9	53.8	58.4	54.4	16.3	54.8	56.9	59.3	57.0	14.7
N ₉₀ P ₃₀ K ₉₀	54.2	58.7	60.5	57.8	19.7	59.2	61.0	63.2	61.1	18.8
N ₉₀ P ₆₀ K ₉₀	54.7	57.8	60.2	57.6	19.5	59.8	61.3	63.9	61.7	19.4
N ₉₀ P ₉₀ K ₉₀	57.1	59.6	62.1	59.6	21.5	60.9	63.0	64.5	62.8	20.5
HIP	2.0	1.9	1.9	2.1	-	2.1	2.0	2.0	2.2	-

Note: ¹P – Polymixobacterin; M – Mycofix; ² and ³ – controls according to fertiliser norms for untreated and treated seeds, respectively; average for 2019-2021

Source: authors' research results

Mineral fertilisers contributed to significant increases in leaf area. Thus, in the variant without fertiliser application and sowing with treated seeds, the assimilation area during the

flowering phase was 42.3 thousand m²/ha, while with the application of N₉₀P₉₀K₉₀ and the same seed treatment, it was 60.9 thousand m², or an increase of 43%. When sowing with non-treated

seeds, the leaf surface area increased by 49.9%, or by 19.0 thousand m²/ha, depending on the fertiliser rate. Similar results were obtained by M. Stepanenko (2023) in studies with corn to determine the effectiveness of new biological fertilisers. Pre-sowing seed treatment had a positive effect on the formation of leaf area. Thus, when seeds were treated only with a fungicide, the leaf area increased by 3.8-5.1 thousand m², depending on the fertilisation background, compared to similar nutrition backgrounds, but when sowing with untreated seeds. The growth is partly due to higher field germination of seeds and the formation of denser agrocenoses. Slightly higher increases compared to the control variant (untreated seeds) were achieved by treatment with the preparation Mikofix – 4.0-7.5 thousand m²/ha; with the preparation Polymixobacterin – 2.4-4.5 thousand m²/ha. With combined treatment of seeds with a fungicide and Mikofix, the maximum leaf area was obtained – 44.6-64.5 thousand m²/ha depending on the fertilisation background, which is 6.5-9.1 thousand m²/ha more than the control variant, and 2.3-4.0 thousand m²/ha when treating seeds only with a fungicide. Similar results regarding the effectiveness of the combined use of the protection system and fertilisers were obtained in studies with sugar beet crops (Potapov & Hrabovskiy, 2023).

The compensatory effect of biological preparations was significant both against the background of different fertiliser rates and when using treated seeds for sowing compared

to untreated seeds. The largest leaf area of oat crops was formed with the combined use of reduced fertiliser rates, in particular phosphorus, and seed treatment with phosphorus-mobilising preparations, compared to variants where full fertilisation with increased phosphorus rates was applied. Thus, when sowing with treated seeds against the background of N₉₀P₉₀K₉₀, 60.9 thousand m²/ha of leaf surface area was formed, while when sowing with treated seeds and additional treatment with Polymixobacterin or Mycofix against the background of N₉₀P₆₀K₉₀, 61.3 and 63.9 thousand m²/ha were formed, respectively. With a reduction in phosphorus by 60 kg/ha of active ingredient – to N₉₀P₃₀K₉₀ and seed treatment according to the same scheme, the leaf area was 61.0 and 63.2 thousand m²/ha, respectively, at the BBCH 62-65 stage.

Thus, S. Ribou *et al.* (2013) and V. Volkogon *et al.* (2019) also assert that it is possible to reduce the rate of technical nitrogen through the use of biological products without reducing crop yields, which is realistic for low and medium mineral agro-backgrounds in the experiment. The intensity of plant foliage functioning is determined by net photosynthetic productivity (NPP). Net photosynthetic productivity is determined by both the dynamics of biomass accumulation by crops and the leaf area. NPP and leaf area are closely related. The results of the studies indicate a significant influence of mineral fertilisers, pre-sowing seed treatment and weather conditions of the year on the net productivity of crops (Table 5).

Table 5. Net photosynthetic productivity of oat crops depending on the level of mineral nutrition and seed treatment, period – stages BBCH 27-64 g/m² per day

Fertiliser rate, kg/ha a.i., Factor A	Seed treatment, Factor B										Gains from absolute control
	Untreated					Treated					
	Biopreparation seed treatment ¹ , Factor C										
	-	P	M	Mean	+/-from fertiliser	-	P	M	Mean	+/-from fertiliser	
2019											
Control	1.68 ²	1.85	1.80	1.78	-	1.93 ³	1.95	1.92	1.93	-	0.25
N ₃₀ K ₃₀	2.12	2.27	2.31	2.23	0.55	2.42	2.48	2.52	2.47	0.54	0.79
N ₃₀ P ₃₀ K ₃₀	2.18	2.35	2.42	2.32	0.64	2.44	2.53	2.53	2.50	0.57	0.82
N ₆₀ P ₆₀ K ₆₀	2.85	2.99	3.05	2.96	1.28	3.11	3.28	3.36	3.25	1.32	1.57
N ₆₀ P ₃₀ K ₆₀	2.64	2.85	2.90	2.80	1.12	3.04	3.09	3.12	3.08	1.15	1.40
N ₉₀ P ₃₀ K ₉₀	3.01	3.31	3.40	3.24	1.56	3.49	3.58	3.64	3.57	1.64	1.89
N ₉₀ P ₆₀ K ₉₀	3.18	3.40	3.43	3.34	1.66	3.82	3.72	3.91	3.82	1.89	2.14
N ₉₀ P ₉₀ K ₉₀	3.21	3.31	3.37	3.30	1.62	3.79	3.82	3.85	3.82	1.89	2.14

Table 5, Continued

Fertiliser rate, kg/ ha a.i., Factor A	Seed treatment, Factor B										Gains from absolute control
	Untreated					Treated					
	Biopreparation seed treatment ¹ , Factor C										
	-	P	M	Mean	+/-from fertiliser	-	P	M	Mean	+/-from fertiliser	
2020											
Control	2.80 ²	3.00	3.02	2.94	-	3.14 ³	3.28	3.30	3.24	-	0.24
N ₃₀ K ₃₀	2.91	3.11	3.14	3.05	0.25	3.23	3.38	3.40	3.34	0.20	0.34
N ₃₀ P ₃₀ K ₃₀	3.09	3.37	3.40	3.29	0.49	3.49	3.62	3.65	3.59	0.45	0.59
N ₆₀ P ₆₀ K ₆₀	3.12	3.24	3.37	3.24	0.44	3.46	3.56	3.71	3.58	0.44	0.58
N ₆₀ P ₃₀ K ₆₀	3.10	3.29	3.41	3.27	0.47	3.38	3.63	3.72	3.58	0.44	0.58
N ₉₀ P ₃₀ K ₉₀	3.22	3.35	3.41	3.33	0.53	3.48	3.61	3.80	3.63	0.49	0.63
N ₉₀ P ₆₀ K ₉₀	3.30	3.56	3.63	3.50	0.70	3.66	3.76	3.86	3.76	0.62	0.76
N ₉₀ P ₉₀ K ₉₀	3.51	3.69	3.79	3.66	0.86	3.93	4.07	4.11	4.04	0.90	1.04
2021											
Control	2.22 ²	2.33	2.42	2.32	-	2.42 ³	2.46	2.62	2.50	-	0.28
N ₃₀ K ₃₀	2.31	2.43	2.56	2.43	0.21	2.61	2.66	2.73	2.67	0.25	0.45
N ₃₀ P ₃₀ K ₃₀	2.34	2.43	2.55	2.44	0.22	2.57	2.62	2.67	2.62	0.20	0.40
N ₆₀ P ₆₀ K ₆₀	3.08	3.26	3.30	3.21	0.99	3.48	3.57	3.60	3.55	1.13	1.33
N ₆₀ P ₃₀ K ₆₀	3.00	3.18	3.30	3.16	0.94	3.27	3.51	3.60	3.46	1.04	1.24
N ₉₀ P ₃₀ K ₉₀	3.17	3.33	3.39	3.30	1.08	3.52	3.42	3.61	3.52	1.10	1.30
N ₉₀ P ₆₀ K ₉₀	3.24	3.40	3.53	3.39	1.17	3.50	3.63	3.76	3.63	1.21	1.41
N ₉₀ P ₉₀ K ₉₀	3.33	3.46	3.63	3.47	1.25	3.56	3.76	3.86	3.73	1.31	1.51
2019-2021											
Control	2.23 ²	2.39	2.41	2.34	-	2.50 ³	2.56	2.61	2.56	-	0.33
N ₃₀ K ₃₀	2.45	2.6	2.67	2.57	0.12	2.75	2.84	2.88	2.82	0.32	0.59
N ₃₀ P ₃₀ K ₃₀	2.54	2.72	2.79	2.68	0.14	2.84	2.92	2.95	2.90	0.40	0.67
N ₆₀ P ₆₀ K ₆₀	3.02	3.17	3.24	3.14	0.12	3.35	3.47	3.56	3.46	0.96	1.23
N ₆₀ P ₃₀ K ₆₀	2.91	3.11	3.20	3.07	0.16	3.23	3.41	3.48	3.37	0.87	1.14
N ₉₀ P ₃₀ K ₉₀	3.13	3.33	3.40	3.29	0.16	3.50	3.54	3.69	3.58	1.08	1.35
N ₉₀ P ₆₀ K ₉₀	3.24	3.46	3.53	3.41	0.17	3.66	3.70	3.84	3.73	1.23	1.50
N ₉₀ P ₉₀ K ₉₀	3.35	3.49	3.60	3.48	0.13	3.76	3.88	3.94	3.86	1.36	1.63
HIP for the factor:											
A	0.18	0.18	0.19	0.21		0.19	0.21	0.20	0.22		
B						0.16	1.16	0.15	0.17		
C	0.05	0.04	0.05	0.6		0.06	0.05	0.06	0.07		

Note: ¹P – Polymixobacterin; M – Mycofix; ² – absolute control by year and control for untreated seeds; ³ – controls by year for treated seeds

Source: results of authors' research and calculations

During the years of research, the highest NPP was in 2020 and 2021, and the lowest was in the dry year of 2019. The negative impact of drought on the photosynthetic activity of oats is also indicated by V. Sadras *et al.* (2017). B. Zhao *et al.* (2021) prove that drought causes a 31-69% loss of oat grain yield. At the beginning of vegetation, the NPP increases sharply until the booting stage. The assimilation surface area

of the crop also increases sharply during this period. Further, the rate of increase in the size of the photosynthetic surface decreases, and, accordingly, the NPP also begins to decrease. Thus, when growing oats without fertilisers, the NPP was 2.23-2.61 g/m² per day, depending on seed treatment, while the application of complete mineral fertiliser increased it to 3.35-3.94 g/m² per day, or by 50-51%. The highest net

photosynthetic productivity was observed when sowing with treated seeds in combination with the mycorrhizal preparation Mycofix against the background of $N_{90}P_{90}K_{90}$ – 3.94 g/m² per day, which is 0.59 g/m² per day more than the control variant (without treatment) and 0.42 g/m² per day more than with only treated seeds. In the variants where phosphorus fertiliser rates were reduced by 30 and 60 kg/ha a.i., and the seeds were treated with a fungicide and biological preparations, the NPP of the crops provided an increase to the level of treatment with only a fungicide against the background of full fertilisation, which proves the significant phosphate-mobilising and growth-stimulating effect of the studied biological preparations.

The results of the study coincide with the conclusions of V. Volkogon *et al.* (2019) that the combined use of microbial preparations with reduced fertiliser rates is an important strategy for managing and reducing environmental problems by reducing the use of chemical fertilisers. At the same time, unlike publications that justify the complete replacement of mineral fertilisers with agronomically valuable microorganisms, the results of the study are equivalent to the conclusions of V. Volkogon (2023) regarding the effective combination of mineral and biological factors in fertilising agricultural crops as a solution in which both resources can synergistically interact to improve nutrition and provide other biological functions necessary for the harmonious development of plants. Calculations of the correlation between yield and leaf area at variable rates of fertilisers and biological products revealed a very close positive correlation. The correlation coefficient between yield and leaf area at the BBCH 63-64 stage for sowing with untreated seeds was 0.87, and for sowing with treated seeds – 0.89.

CONCLUSIONS

Sown oat responds positively to the application of mineral fertilisers, which is manifested in an increase in leaf area. Photosynthetic activity of crops is activated as a whole due to an increase in net photosynthetic productivity. Oats intensively form leaf surface area already in the early microstages of development, effectively using the applied nutrients. The compensatory effect

of the use of biological preparations is significant both against the background of different fertiliser rates and when using treated seeds for sowing compared to untreated seeds. The largest leaf area of oat crops was formed with the combined use of reduced fertiliser rates, in particular phosphorus, and seed treatment with phosphorus-mobilising preparations, compared to variants where full fertilisation with increased phosphorus rates was applied. When sowing with treated seeds against the background of $N_{90}P_{90}K_{90}$, 60.9 thousand m²/ha of leaf surface area was formed, and with treated seeds and additional treatment with Polimixobacterin or Mycofix against a background of $N_{90}P_{60}K_{90}$ – 61.3 and 63.9 thousand m²/ha, respectively. With a reduction in phosphorus to $N_{90}P_{30}K_{90}$ and seed treatment according to the same scheme, the leaf area was 61.0 and 63.2 thousand m²/ha, respectively, at the BBCH 62-65 stage.

Pre-sowing seed treatment contributes to the formation of a larger leaf area – when seeds were treated with a fungicide, the leaf area increased by 3.8-5.1 thousand m², depending on the fertilisation background, compared to untreated seeds. Increases over the control variant (untreated seeds) were achieved by treating the seeds with Mikofix – 4.0-7.5 thousand m²/ha; with Polimixobacterin – 2.4-4.5 thousand m²/ha. With combined treatment of seeds with a fungicide and Mikofix, the maximum leaf area was obtained – 44.6-64.5 thousand m²/ha, depending on the fertilisation background, or 6.5-9.1 thousand m²/ha more compared to the control variant and 2.3-4.0 thousand m²/ha compared to the control variant and by 2.3-4.0 thousand m²/ha compared to seed treatment with only a fungicide. A very close positive correlation was established between yield and leaf surface area at variable rates of fertilisers and biological products – the correlation coefficient at the BBCH 63-64 stage for sowing with untreated seeds was 0.87, and 0.89 for sowing with treated seeds. The prospect for further research lies in the need to conduct agrochemical and microbiological analysis of the soil with calculations of the balance of nutrients and their availability to plants.

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Фотосинтетична активність посівів вівса посівного за комбінованого застосування мінеральних добрив та біопрепаратів

Анотація. Ефективність фотосинтезу посівів вівса посівного за комбінованого використання мінеральних добрив та біопрепаратів з метою зниження норм мінеральних добрив та підвищення продуктивності є надзвичайно актуальною. Метою дослідження було встановлення ефективності комбінованого використання мінеральних добрив та біологічних препаратів шляхом активізації фотосинтетичної діяльності посівів вівса та його продуктивності. Дослідження проведенні з використанням польового, лабораторних та математичних методів аналізування. Результати досліджень статистично обраховані

та інтерпретовані. Представлено результати досліджень з формування площі листкової поверхні та чистої продуктивності фотосинтезу вівса посівного сорту 'Айворі' в умовах правобережного лісостепу України залежно від норм добрив, передпосівної обробки насіння біологічними препаратами фосфатмобілізуючої дії Поліміксобактерин на основі бактерії *Paenibacillus polymyxa*, та Мікофікс на основі мікоризного гриба *Glomus intraradices* з використанням протруєного і непротруєного насіння. За сумісної обробки насіння протруєником та Мікофіксом формувалась максимальна площа листкової поверхні – 44,6-64,5 тис. м²/га залежно від фону удобрення. За сівби протруєним насінням на фоні N₉₀P₉₀K₉₀ формувалося 60,9 тис. м²/га площі листкової поверхні, а протруєним насінням та додаткової обробки Поліміксобактерин або Мікофікс на фоні N₉₀P₆₀K₉₀ – 61,3 та 63,9 тис. м²/га відповідно. За зменшення фосфору до N₉₀P₃₀K₉₀ та обробки насіння за тією ж схемою, листкова площа становила відповідно 61,0 та 63,2 тис. м²/га на стадії ВВСН 62-65. Встановлено тісний позитивний кореляційний зв'язок – коефіцієнт кореляції між урожайністю і площею листкової поверхні на стадії ВВСН 63-64 – 0,87-0,89. Практична цінність дослідження полягала у встановленні компенсаційного ефекту за комбінованого застосування біологічних препаратів та мінеральних добрив, що дозволило знижувати норми внесення добрив без зниження фотосинтетичної активності посівів та урожайності вівса

Ключові слова: площа листкової поверхні; чиста продуктивність фотосинтезу; норми добрив; Поліміксобактерин; Мікофікс; урожайність

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