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OPTIMIZATION OF SUNFLOWER NUTRITION USING ELEMENTS OF PRECISION AGRICULTURAL PRODUCTION

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This article presents the results of scientific research aimed at resolving the issue of inefficient agricultural resource utilization under the traditional fertilization system. The traditional approach often ignores the spatial variability of soil and climatic conditions, which leads to nutrient deficiencies in high-productivity zones and nutrient excesses in low-productivity ones. The aim of this research was the scientific justification of a system of variable-rate foliar feeding of sunflower based on the delineation of intra-field productivity zones. The study was conducted in 2025 on the fields of Chkalov Agricultural LLC in the Left-Bank Forest-Steppe of Ukraine (Cherkasy oblast) on typical heavy-loam chernozem. The object of the study was the yield formation process of the Sumatra HTS sunflower hybrid. Using the GeoPard Agriculture satellite platform at the 6–8 leaves stage (BBCH 16-18), the experimental field was zoned by NDVI into three stationary zones: high (NDVI ~0.75), medium (NDVI ~0.69), and low (NDVI ~0.62) productivity. Within the delineated zones, the effectiveness of two foliar applications (at BBCH 16–18 and BBCH 51) of the complex fertilizer 'Avangard Complex Sunflower' at rates of 1.5 and 2.0 L/ha was studied. It was established that in the full flowering stage, the maximum NDVI (0.97) was recorded in the high-productivity zone at an application rate of 2.0 L/ha. The maximum yield was also obtained in this zone – 3.24 t/ha, which provided an additional yield increase of 13.7% (0.39 t/ha) compared to the control. A pronounced compensatory effect was proven on plots with a lower natural potential: in the low-productivity zone, the application of 2.0 L/ha increased yield by 10.6% (to 2.71 t/ha), which allowed for full equalization with the control of the medium-productivity zone (2.70 t/ha).

Key words: *sunflower, precision agriculture, vegetation index, NDVI, foliar application, typical chernozem, yield, economic efficiency, Avangard Complex Sunflower, spatial field heterogeneity.*

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Панчук Т.В., Бикін А.В., Кучер Л.І. Оптимізація живлення соняшнику за використання елементів прецизійного агровиробництва

У статті представлено результати наукових досліджень, спрямованих на вирішення проблеми неефективного використання агроресурсів за традиційної системи удобрення. Традиційний підхід часто не враховує просторову мінливість ґрунтово-кліматичних умов, що зумовлює дефіцит живлення на високопродуктивних ділянках поля та його надлишок на низькопродуктивних. Метою дослідження стало наукове обґрунтування системи диференційованого позакореневого підживлення соняшнику на основі виділення внутрішньопольових зон продуктивності. Дослідження проводили у 2025 році на території СТОВ ім. Чкалова в умовах Лівобережного Лісостепу України (Черкаська область) на чорноземах типових важкосуглинкових. Об'єкт дослідження – процес формування врожайності гібриду соняшнику Sumatra HTS. За допомогою супутникової платформи GeoPard Agriculture на етапі 6–8 листків (BBCH 16-18) дослідний масив диференційовано за індексом NDVI на три стаціонарні зони: високої (NDVI ~0,75), середньої (NDVI ~0,69) та низької (NDVI ~0,62) продуктивності. У межах виділених зон вивчали ефективність дворазового (BBCH 16-18 та BBCH 51) підживлення комплексним добривом «Авангард Комплекс Соняшник» нормами 1,5 і 2,0 л/га. Встановлено, що у фазу повного цвітіння максимальний індекс NDVI (0,97) зафіксовано у високопродуктивній зоні за норми внесення 2,0 л/га. Максимальну врожайність також отримано у цій зоні – 3,24 т/га, що забезпечило додатковий приріст на 13,7 % (0,39 т/га) порівняно з контролем. Доведено виражений компенсаторний ефект на ділянках із гіршим природним потенціалом: у зоні низької продуктивності внесення 2,0 л/га підвищило врожайність на 10,6 % (до 2,71 т/га), що дозволило повністю зрівняти її з контролем середньопродуктивної зони (2,70 т/га).

Ключові слова: *соняшник, точне землеробство, вегетаційний індекс, NDVI, позакореневе підживлення, чорнозем типовий, урожайність, економічна ефективність, Авангард Комплекс Соняшник, просторова неоднорідність поля.*

Introduction. Sunflower is one of the main oilseed crops globally and a strategically important crop for the economy of Ukraine. Obtaining stable and high sunflower yields is a priority task for the agricultural sector, especially under increasing food demand and the necessity for rational use of natural and technological resources. The application of mineral fertilizers plays a decisive role in sunflower yield formation; however, under the traditional fertilization approach based on average rates applied across the entire field area, this approach is often insufficiently effective [1]. Scientific and field studies demonstrate that almost every field has significant heterogeneity (spatial variability) in soil agrochemical parameters, topography, and moisture availability [2]. The application of uniform fertilizer rates across areas with varying fertility potentials leads to the inefficient use of agricultural resources: in low-potential areas, fertilizers are not fully absorbed, while in high-potential areas, a nutrient deficiency occurs, limiting potential yield. This not only reduces the economic efficiency of production but also poses significant environmental risks, including groundwater pollution and soil acidification.

One of the most promising approaches to resolving this issue is the implementation of precision farming elements, which rely on satellite monitoring data, geographic information systems (GIS), and variable rate technology (VRT). These technologies allow for the management of spatial variability in soil and climatic conditions within a specific field [3]. Optimizing the sunflower nutrition system using such approaches is a highly relevant scientific and practical task aimed at increasing yields, improving product quality, and raising the economic efficiency of crop cultivation while simultaneously reducing the anthropogenic load on the environment.

Literature Review. The theoretical and practical foundations of precision agricultural production, as well as the specifics of mineral nutrition in sunflower, have been studied by many leading Ukrainian and foreign scientists. Research by H. I. Demydas and O. M. Tsymbaliuk has demonstrated that incorporating elements of precision agriculture

into field crop cultivation technologies significantly optimizes the expenditure of material and technical resources [4]. O. A. Romanenko et al. in their works covered in detail the economic efficiency of precision farming systems, noting a rapid growth in profitability due to resource differentiation [5]. The use of unmanned aerial vehicles and satellite technologies for crop monitoring is of great importance, as described in detail by V. H. Mikheiev and other researchers [6]. B. Ya. Panasiuk and L. V. Hubenko highlight the important role of the economic evaluation of precision farming technologies prior to their direct implementation in production [7].

In the field of agrotechnical and engineering solutions, significant contributions were made by S. M. Moroz and V. M. Bulhakov, who researched automated guidance systems and satellite positioning of agricultural machinery [8, 9]. The study of the spatial variability of soil properties using electromagnetic scanning is addressed in the works of V. V. Dehtiarov [10]. The specifics of yield mapping as a key tool of precision farming are highlighted by B. O. Voroniuk and H. A. Holub [11]. The integration of multi-temporal spatial data into geographic information systems (GIS) has been investigated by A. V. Kokhan [12].

The principles of mineral nutrition and the physiological requirements of sunflower for nutrient elements were thoroughly developed by H. M. Hospodarenko [13], A. V. Bykin [14], and are also covered in agrochemistry textbooks by A. T. Martyniuk [15]. The influence of nitrogen and sulfur nutrition on the productivity of sunflower hybrids was studied by I. Shevchenko [16] and H. M. Hospodarenko [17], who indicated a close correlation between the nitrogen background and the photosynthetic activity of the leaf apparatus.

Despite the substantial body of scientific work in precision farming and mineral nutrition, the optimization of the sunflower nutrition system based on the integrated use of remote sensing data (NDVI index) and variable-rate foliar feeding with microelements in the specific soil and climatic zones of the Left-Bank Forest-Steppe of Ukraine remains insufficiently studied. Most research focuses on the primary (soil-applied) variable-rate application of nitrogen, phosphorus, or potassium, whereas the adaptive application of complex microfertilizers (specifically boron and accompanying mesoelements) depending on the delineated productivity zones requires further scientific justification and practical validation.

Research Objective. The objective of this study is the scientific justification and development of methods to optimize the mineral nutrition system of sunflower by delineating intra-field productivity zones via remote sensing (NDVI index) and applying variable-rate foliar feeding with a complex fertilizer in typical chernozems of the Left-Bank Forest-Steppe of Ukraine.

Materials and Methods. The field experiment was established in 2025 on the land utilized by Chkalov Agricultural LLC (Zolotonoša Raion, Cherkasy Oblast, Zhovnyne village). This region belongs to the Central Left-Bank Forest-Steppe of Ukraine, which is characterized by favorable soil conditions, with highly fertile typical chernozems prevailing. The soil cover of the experimental plot is represented by a typical heavy-loam chernozem on loess parent materials.

The sunflower planting material was the Sumatra HTS hybrid (Syngenta), adapted for ExpressSun (HTS) technology with the use of tribenuron-methyl-based herbicides. The plant density at harvest was 55,000 plants/ha, with a row spacing of 70 cm. The preceding crop in the rotation was winter wheat.

Field zoning by productivity level was conducted at the 6–8 true leaves stage of sunflower (BBCH 16-18) using the GeoPard Agriculture satellite platform. Based on

the calculated Normalized Difference Vegetation Index (NDVI), the crop field was differentiated into three stationary zones: high, medium, and low productivity. Within each delineated zone, a field experiment was set up according to the scheme presented in Table 1. The plot size for each experimental treatment was 50 m², with three replications.

Table 1

Experimental design in the delineated field productivity zones

Productivity Zone (by NDVI)	Treatment	Foliar Feeding Scheme
High productivity (NDVI ~ 0.75)	1	No foliar feeding (Control)
High productivity (NDVI ~ 0.75)	2	Avangard Sunflower – 2.0 L/ha (twice: BBCH 16-18 and BBCH 51)
High productivity (NDVI ~ 0.75)	3	Avangard Sunflower – 1.5 L/ha (twice: BBCH 16-18 and BBCH 51)
Medium productivity (NDVI ~ 0.69)	4	No foliar feeding (Control)
Medium productivity (NDVI ~ 0.69)	5	Avangard Sunflower – 2.0 L/ha (twice)
Medium productivity (NDVI ~ 0.69)	6	Avangard Sunflower – 1.5 L/ha (twice)
Low productivity (NDVI ~ 0.62)	7	No foliar feeding (Control)
Low productivity (NDVI ~ 0.62)	8	Avangard Sunflower – 2.0 L/ha (twice)
Low productivity (NDVI ~ 0.62)	9	Avangard Sunflower – 1.5 L/ha (twice)

Foliar feeding was carried out using the complex concentrated fertilizer 'Avangard® Complex Sunflower', which contains a balanced set of macro- and micronutrients in an easily digestible chelated form (specifically boron, sulfur, zinc, iron, manganese, copper, molybdenum, and cobalt). Treatments were applied using a backpack sprayer at the 6–8 leaves stage (BBCH 16–18) and at the budding, or 'star' stage (BBCH 51) according to the scheme. Harvesting was done manually from each plot at full maturity, followed by conversion to 100% purity and a 10% standard seed moisture content.

Results and Discussion. Remote monitoring of sunflower crop state by NDVI. Analysis of satellite imagery using the GeoPard Agriculture platform at the initial stages of sunflower development (6–8 leaves stage, BBCH 16–18) showed a high level of crop spatial variability. In the high-productivity zone, the average NDVI index was 0.75, reflecting the intensive accumulation of vegetative biomass and high chlorophyll content. The medium-productivity zone was characterized by moderate development, with a vegetation index of 0.69. The lowest level of plant development was noted in the low-productivity zone, where the NDVI was only 0.62, indicating growth suppression and the presence of limiting soil-related factors.

Repeated satellite sensing during the full flowering stage of sunflower (BBCH 65–67) demonstrated significant changes in the optical characteristics of the crop as a result of the foliar applications. In the high-productivity zone, NDVI values for the treatment with 2.0 L/ha of fertilizer increased to the maximum level of 0.97. In the medium-productivity zone, this parameter reached 0.82. The most dynamic growth was recorded in the low-productivity zone, where the foliar feeding of 2.0 L/ha (treatment 8) increased the NDVI index to 0.80, which practically equalized the crop condition with that of the medium-productivity zone. This indicates a high compensatory capacity of

the applied fertilizer, which allowed the plants to overcome stressful conditions and maximize photosynthetic processes.

Influence of nutrition conditions on sunflower yield and structure. The final criterion for evaluating any agrotechnical practice is crop yield and its structural elements, which reflect the potential of each individual plant. Analysis of sunflower yield across the studied treatments confirmed the high efficiency of variable-rate foliar feeding against the background of soil heterogeneity (Table 2).

Table 2

Influence of nutrition conditions on the yield of the Sumatra HTS sunflower hybrid

Productivity zone	Treatment	Application rate	Yield, t/ha	Increase, t/ha	Increase, %
High	1	Control	2.85	-	-
	2	2.0 L/ha	3.24	0.39	13.7
	3	1.5 L/ha	3.08	0.23	8.1
Medium	4	Control	2.70	-	-
	5	2.0 L/ha	3.01	0.31	11.5
	6	1.5 L/ha	2.86	0.16	5.9
Low	7	Control	2.45	-	-
	8	2.0 L/ha	2.71	0.26	10.6
	9	1.5 L/ha	2.58	0.13	5.3

The data in Table 2 demonstrate that on the control plots without foliar feeding (treatments 1, 4, and 7), the sunflower yield directly depended on the natural potential of each zone, decreasing from 2.85 t/ha in the high-productivity zone to 2.45 t/ha in the low-productivity zone. The application of foliar feeding with the 'Avangard Complex Sunflower' fertilizer provided a significant and statistically reliable increase in yield in all treatments without exception.

The maximum yield in the experiment was recorded in the high-productivity zone for treatment 2, using 2.0 L/ha of fertilizer, reaching 3.24 t/ha, which provided an additional seed harvest of 0.39 t/ha (or 13.7%) compared to the control. However, the most important aspect of adaptive management is the feeding effect on less fertile plots: in the low-productivity zone, with the application of 2.0 L/ha of fertilizer (treatment 8), a yield of 2.71 t/ha was obtained, which is an increase of 10.6% compared to the control of that zone, practically equalizing productivity with the control of the medium-productivity zone (2.70 t/ha). This further confirms that variable-rate foliar nutrition serves as an effective tool for mitigating the negative impact of field spatial variability and enhancing its overall productivity.

Conclusions and Prospects for Further Research. Summarizing the results of the conducted field studies, it is worth emphasizing the shift in approaches to forming high sunflower productivity. The obtained data confirm that variable-rate nutrition management based on vegetation indices (NDVI) is no less important for optimizing growth processes and yield formation than the physical volume of applied agrochemicals. Based on this, the following conclusions are formulated:

1. Remote monitoring of sunflower crop state by NDVI at the 6–8 leaves stage (BBCH 16–18) allows for the reliable identification of spatial field heterogeneity, delineating zones with high (NDVI ~0.75), medium (NDVI ~0.69), and low (NDVI ~0.62) plant development potential.

2. The application of double foliar feeding with the complex fertilizer 'Avangard Complex Sunflower' guarantees a reliable yield increase across all delineated zones. The highest yield of the Sumatra HTS hybrid (3.24 t/ha) was obtained in the high-productivity zone at a rate of 2.0 L/ha, providing a maximum increase of 0.39 t/ha (13.7%) compared to the control.

3. Variable-rate micronutrient application demonstrates a high compensatory effect in areas with poorer soil conditions. In the low-productivity zone, the application of a 2.0 L/ha rate increased the yield to 2.71 t/ha, which practically equalized this index with the productivity of the control treatment in the medium-productivity zone (2.70 t/ha).

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