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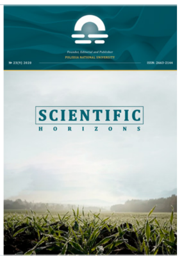

Formation of soybean yield depending on varietal characteristics and agrotechnological practices based on predictive modelling

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Abstract. The article presented the results of a two-year field experiment investigating the influence of varietal characteristics, agrotechnological practices, and weather conditions on soybean yield using predictive modelling. The relevance of the study stems from the need to improve the stability of soya bean yields in the context of climate change and the importance of using biological plant protection products (biofungicides). The aim was to establish the effectiveness of various pre-sowing seed treatment schemes and foliar application of fungicides and micronutrients, as well as to develop mathematical models for predicting soyabean yield depending on weather conditions. Field studies were conducted in 2024-2025 at the Training and Production Centre of Bila Tserkva National Agrarian University using soybean varieties 'RGT Salsa' and 'RGT Saidina'. The experiment included 50 variants. It was established that the highest average yield (2.71 t/ha) was obtained for the variety 'RGT Saidina' under the combined use of the fungicides Maxim XL, Apron XL, the inoculant BioMAG Soya, and double application of the fungicide Kolosal Pro with micronutrient fertilisers Intermag Molybdenum and Quantum Bor Active at the budding stage (BBCH 51-59) and the flowering stage (BBCH 60-69). Under this scheme, variants with the biofungicide Fitosporin-M Soya provided a yield of 2.65 t/ha, confirming the high effectiveness of biological protection. Mathematical modelling revealed a high level of agreement between actual and calculated data (error up to 0.07 t/ha). Cluster analysis of the 50 studied variants based on soybean grain yield identified three main groups according to productivity level. The first cluster included variants with yields above 2.5 t/ha, most of which combined the use of the inoculant BioMAG Soya with the fungicides Maxim XL (1.0 L/t) + Apron XL (0.5 L/t), as well as the fungicide Kolosal Pro and micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active. The practical value

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of the results lies in identifying optimal combinations of biological and chemical fungicides, inoculants, and micronutrient fertilisers to increase soybean productivity, as well as in the possibility of forecasting yield based on climatic indicators

Keywords: inoculation; fungicides; variety; micronutrient fertilisers; climatic conditions; clustering

INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) is one of the most important grain legume crops in the world, playing a key role in providing protein and vegetable oils for both the food and feed sectors. W.M. Singer *et al*. (2023) and D.B. Shelke *et al*. (2023) noted that the growing demand for this crop necessitates improving the efficiency of its cultivation through the enhancement of agrotechnologies. In this context, optimisation of soybean growing conditions in modern agroecosystems is of particular importance. Under current conditions of climatic instability and agricultural intensification, optimisation of agronomic practices for soybean cultivation becomes especially significant. In particular, according to O. Milenko *et al.* (2022), an important direction is the study of the influence of varietal characteristics in combination with different schemes of seed treatment with fungicides and inoculants, as well as foliar application of fungicides and micronutrient fertilisers. As noted by I. Prymak *et al*. (2025), determining the effectiveness of these measures makes it possible to increase yield, improve product quality, and reduce risks associated with adverse weather conditions.

At the same time, the effectiveness of these agrotechnical measures largely depends on the influence of abiotic factors, particularly water regime. Leguminous crops are highly sensitive to drought, both during vegetative and reproductive stages of development. The yield of agricultural crops, including legumes, is the result of a complex interaction between the genetic potential of the plant and a set of environmental factors. Grain productivity of legumes is also determined by symbiotic performance, which depends on the efficiency of symbiosis formed with highly active and virulent strains of nodule bacteria. In the studies of M. Nadeem *et al.* (2019), the efficiency of legume-rhizobial symbiosis under unfavourable growing conditions depends on the ability of the host plant to induce its antioxidant defence systems. This leads to adaptive changes in plant metabolism and increases their tolerance. The most noticeable effects of drought conditions on legumes include reduced germination, delayed growth, severe damage to the photosynthetic apparatus, decreased photosynthetic productivity, and reduced nutrient uptake. Accordingly, the study of plant responses and the formation of adaptive potential in crops, particularly soybean, under climate change conditions has both economic and agronomic significance.

Given the need to account for climatic factors on soya bean yields, the role various forecasting methods is increasing. One of the promising approaches to improving soybean productivity is the application of elements of mathematical modelling, which allows prediction of potential yield depending on climatic conditions. This is particularly relevant in view of increasing weather variability, which often makes it difficult to assess risks in advance and plan cultivation technologies. Crop yield modelling is an important tool for evaluating the impact of climatic factors on productivity. Researchers such as H. Chen *et al.* (2020) have used statistical methods together with process-based models to assess the impact of climate change on crop yields.

At the same time, the development of such models is associated with a number of methodological difficulties. As noted by L.B. Jaques *et al.* (2022), attempts to develop physiologically based soybean yield models over large areas have been complicated by the lack of a growth-stage model capable of accounting for these responses and applicable across a wide geographical and climatic range. T.D. Setiyono *et al.* (2021) developed a soybean phenological model, which uses nonlinear functions of temperature and photoperiod and separates flowering induction and post-induction phases to simulate flowering time. In the studies of J.Q. Zhang *et al*. (2019), the artificial neural network method provided the highest accuracy in predicting soybean phenological development stages, indicating that this approach can be effectively applied in modelling. However, according to A. Moreira *et al.* (2023) and K.R. Hopper (2023), the problem of modelling soybean growth and yield lies in the complexity of accurately describing plant responses to stress factors (drought, temperature anomalies) and the specific nature of symbiotic nitrogen fixation, which often leads to errors in traditional models under changing climatic conditions. In addition, existing systems require continuous and complex calibration for new varieties and local growing conditions.

Thus, improving the efficiency of soybean cultivation requires a comprehensive approach that incorporates both technica and analytical tools. Comprehensive studies of soybean cultivation technology components are necessary to achieve a balance between plant protection against harmful organisms, preservation of nitrogen-fixing potential, and maintenance of resilience to abiotic stress factors. The development of mathematical models for specific soil and climatic conditions makes it possible to predict the influence of weather on plant development and forecast yield. This enables the adaptation of soybean cultivation techniques, minimise climatic risks and ensure stable economic efficiency. The aim of the research was to establish the effectiveness of various pre-sowing seed treatment regimens using fungicides and inoculants, and the foliar application of fungicides and micronutrients, as well as to develop mathematical models for forecasting soyabean yield depending on weather conditions.

LITERATURE REVIEW

Under current climate change conditions, according to the Food and Agriculture Organisation of the United Nations (FAO, 2021), crop yields could fall by more than 50% of their potential productivity, which could pose serious food security challenges. As noted in their works by G.L. Hartman *et al*. (2011) and A.Y. Bandara *et al*. (2020), realising the potential productivity of leguminous crops is one of the main tasks in ensuring their high yield and is determined by a harmonious combination of all modern methods: organisational and economic, agrotechnical, immunological, biological and chemical. Among agrotechnical measures, pre-sowing seed treatment is of particular importance. As noted by N. Strom *et al*. (2020), one of the important technological practices used in soybean cultivation is pre-sowing seed treatment with fungicides, as yield losses due to damage to soybeans by phytopathogens can reach up to 40%. Subsequent studies focused on combining various elements of this technology. Studies by J.R. Rathjen *et al*. (2020) and Z. Getachew & L. Abeble (2021) investigated the combined use of seed inoculation with nodule-forming bacteria and fungicides to regulate the metabolism of leguminous crops and enhance their tolerance to fungal diseases and productivity. And according to data obtained by I. Fedoruk *et al*. (2021), combining the inoculation process with the use of micronutrient fertilisers in cultivation technology yields significant results and increases soyabean yield. This is linked to the specific functioning of the symbiotic system of leguminous crops. Research by O. Mazur *et al*. (2025) established that to maximise the development of the symbiotic system's parameters – including the number and mass of nodules, their intensive functioning with the formation of the highest levels of total and active symbiotic potential, as well as the amount of biologically fixed nitrogen – it is necessary to combine pre-sowing seed treatment (with the HighCot Super inoculant, Wonder Micro microfertiliser and Maxim XL seed dressing) with foliar feeding using chelated fertilisers containing macro- and microelements (Wonder Yellow and Wonder Blue), alongside the application of mineral fertilisers at the standard rate of $N_{20}P_{20}S_9$.

Practical aspects of implementing these processes are reflected in the results of field studies. According to V. Petrychenko *et al*. (2024), the use of pre-sowing seed treatment with a bacterial preparation based on nodule-forming bacterial strains had a lesser effect on laboratory germination and a greater effect on the germination energy of soyabeans. The highest value was obtained for the Slavna soyabean variety – 93.4% – when using nitrogen-fixing bacteria (Rhizolin + Rhizosavei) in pre-sowing seed treatment. S. Didorenko *et al*. (2023), under agroclimatic conditions of Kazakhstan, found that treating soybean seeds with molybdenum and cobalt salts before sowing is economically beneficial for the early-maturing variety Ivushka and the mid-maturing variety Lastivka. For the early-maturing variety Birlik KV, the highest profitability was recorded with combined seed treatment using the nitrogen-fixing inoculant HiStick and Mo and Co salts. In the soybean variety Zhansaya, additional seed treatments reduced production profitability.

Alongside biological factors, the plant nutrition system plays an important role. According to the work of S. Bagale (2021), effective management of the soybean nutrition regime helps to provide the necessary nutrients for the plant without causing a significant reduction in yield, and also helps the crop to withstand biotic and abiotic stresses. A total of fifteen nutrients are required for the growth and development of soya. These nutrients can be classified as micro- and macronutrients. Macronutrients required in quantities >0.01% include nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca) and magnesium (Mg). They perform structural and functional roles in plants. Similarly, soya also requires micronutrients, but in quantities of <0.01%. These are copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), boron (B), chlorine (Cl), molybdenum (Mo) and nickel (Ni). These micronutrients perform enzymatic and cellular regulatory functions. In practice, the supply of these elements to plants is often achieved through foliar fertilisation. According to studies by V. Petrychenko *et al*. (2016), the most effective way to provide plants with micronutrients is foliar feeding during the growing season at critical stages of soybean development: the 3-5 trifoliate leaf stage, budding, and pod formation. In this way, up to 100% of the plant's micronutrient requirements can be satisfied.

The effectiveness of such approaches is confirmed by a number of experimental studies. A.V. Golodna *et al*. (2024) found that foliar feeding of soybean plants with the organo-mineral fertiliser Khelprost Soya at the branching and budding stages, against the background of fertilisation $N_{15}P_{45}K_{60}$ + N_{30} and pre-sowing seed treatment, increased yield to 3.67 and 3.74 t/ha (by 23.2% and 25.5%, respectively) and provided a yield increase compared to the absolute control of 0.69 t/ha and 0.76 t/ha. Fertilisation at the flowering stage ensured soybean seed yield at the level of 3.62 t/ha, with a yield increase of 0.64 t/ha. Under the conditions of the Forest-Steppe of Ukraine, according to M.P. Baida (2025), higher yields of the soybean variety Arata were obtained with the combined use of YaraVita

Mono Molitrac at the budding stage (0.25 L/ha) and the micronutrient fertiliser Radostym – 2.35 t/ha, as well as in variants combining YaraVita Mono Molitrac at the budding stage (0.25 L/ha) and at the flowering stage (0.25 L/ha) with growth regulators Biosil and Radostym – 2.34 t/ha and 2.35 t/ha, respectively. The yield of the soybean variety Cordoba under these same treatment combinations was 2.40 t/ha, 2.41 t/ha, and 2.45 t/ha, respectively. In the southern part of the Western Forest-Steppe of Ukraine, D.V. Kozyrsky *et al.* (2025) reported that double foliar feeding with the preparation Fulvohumin resulted in a yield increase of 0.18-0.37 t/ha compared to the base fertilisation variant $N_{30}P_{60}K_{60}$. Foliar fertilisation with Fulvohumin in combination with fungicidal protection ensured a greater realisation of the productivity potential of soybean varieties than the application of these technological elements separately. Yield increases amounted to 0.35 t/ha for the variety Samorodok, 0.43 and 0.41 t/ha for Rohiznianka and Triada, respectively, and 0.65 t/ha for the variety Azymut.

An important criterion for evaluating the effectiveness of agrotechnologies is not only yield but also the economic feasibility of their application. Under the conditions of the Forest-Steppe of Ukraine, M. Grabovskyi *et al.* (2025) found that the maximum conditional net profit and profitability were achieved in the soybean varieties Amadea and Aurelina in the variant with pre-sowing seed treatment using fungicides containing the active ingredients fipronil, thiophanate-methyl, and pyraclostrobin (2 L/t), along with the application of fungicides pyraclostrobin and epoxiconazole during the growing season. The use of these preparations contributed to a statistically significant increase in soybean yield.

Alongside mineral nutrition, seed inoculation is an important factor in increasing productivity. In the study by Ya.O. Yarovyi (2024), it was shown that, on average over three years, soybean yield increased from 2.50 to 3.03 t/ha with the application of N_{30} and up to 3.19 t/ha with N_{60}. The application of complete mineral fertilisers at rates of $N_{30}P_{30}K_{30}$ increased this value to 3.20 t/ha (by 6%), and $N_{60}P_{60}K_{60}$ to 3.40 t/ha (by 7%) compared to nitrogen-only systems. The use of inoculation contributed to a yield increase of 0.38-0.41 t/ha depending on the experimental variant. In the north-eastern Forest-Steppe of Ukraine, A. Melnyk *et al.* (2022) obtained the highest soybean yield (3.02 t/ha) under the application of calculated fertiliser rates ($N_{30}P_{60}K_{90}$): with foliar fertilisation using Wuxal Microplant + Wuxal Combi Plus + Wuxal Aminoplant, yields reached 3.45 t/ha for the variety Lissabon and 3.22 t/ha for Diadema Podillia, which is 1.24-1.41 t/ha higher compared to the absolute control; with the use of fertilisers Basfoliar 36 Extra + Solu Bor + Basfoliar 6-12-6, the variety Kyoto achieved 3.37 t/ha, which is 1.35 t/ha higher than the absolute control.

MATERIALS AND METHODS

The research was conducted in 2024-2025 at the Training and Production Centre of Bila Tserkva National Agrarian University. Experimental design: Factor A – varieties: 'RGT Salsa' and 'RGT Saidina'. Factor B – pre-sowing seed treatment with fungicides and inoculants. 1. Control: no treatment. 2. Fungicide Maxim XL (1.0 L/t) + Apron XL (0.5 L/t) + inoculant RhizoStart (2.0 kg/t). 3. Fungicide Maxim XL (1.0 L/t) + Apron XL (0.5 L/t) + inoculant BioMAG Soya (3.0 kg/t). 4. Inoculant RhizoStart (2.0 kg/t) + biofungicide Ekostern Trichoderma, SC (1.5 L/t). 5. Inoculant BioMAG Soya (3.0 kg/t) + biofungicide Ekostern Trichoderma, SC (1.5 L/t). Factor C – fungicides and micronutrient fertilisers applied during the growing season. 1. Control: no application. 2. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 3. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69). 4. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 5. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69).

The arrangement of treatments in the experiment was systematic and sequential. The total plot area was 70 m^2, with an accounting area of 56 m^2. The experiment was conducted in triplicate. Soybean cultivation practices, apart from the studied factors, followed those generally accepted for the Right-Bank Forest-Steppe of Ukraine. The research was carried out in accordance with the methodological recommendations of V.V. Volkodav (2001). Pre-sowing seed treatment with Maxim XL (1.0 L/t), Apron XL (0.5 L/t), and Ekostern Trichoderma, SC (1.5 L/t) was performed in advance, 5-7 days prior to sowing, while inoculation with RhizoStart (2 kg/t) and BioMAG Soya (3 kg/t) was carried out on the day of sowing, in accordance with the manufacturers' recommendations for product use. Seeds and soybean crops in the control treatments were treated with water. Application of fungicides and micronutrient fertilisers was carried out using a knapsack sprayer, in accordance with the application rates recommended by the manufacturers and the working solution rates at the appropriate growth and development stages of the crop.

Yield assessment of soybean varieties was conducted by plot harvesting, followed by grain cleaning and recalculation to 100% purity and 14% moisture content. Statistical processing of the research results was performed using analysis of variance and correlation–regression analysis with the application software Excel and Statistica 12.0. Clustering of soybean yield data was carried out using the method of J.H. Ward (1963) based on Euclidean distances, which minimises the increase in within-group variance at each stage of cluster merging. This method allows for the formation of compact and clearly separated groups of objects according to similar characteristics, making it particularly effective for the analysis of quantitative agronomic data, including yield. During the study, the requirements of the Convention on Biological Diversity (1992) were observed.

RESULTS

The data in Table 1 showed that for the soybean variety 'RGT Salsa', in the control treatment without seed treatment and foliar application of preparations, grain yield amounted to 1.34 t/ha in 2024 and 2.51 t/ha in 2025, with an average value of 1.92 t/ha. The highest yield in 2024-2025 was obtained in the experimental variant with pre-sowing seed treatment using Maxim XL + Apron XL + BioMAG Soya and double application during the growing season of the fungicide Kolosal Pro (0.5 L/ha) with micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) and Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69), reaching 1.82 and 3.13 t/ha, respectively, with an average value of 2.48 t/ha.

***Table 1**. Grain yield of the soybean variety 'RGT Salsa' depending on the applied agrotechnological measures (average for 2024-2025), t/ha*

Pre-sowing seed treatment with fungicides and inoculants (B)	Fungicides and micronutrient fertilisers (C)*	2024	2025	Average
Control	1	1.34	2.51	1.92
	2	1.57	2.82	2.19
	3	1.68	2.96	2.32
	4	1.50	2.75	2.13
	5	1.62	2.92	2.27
Maxim XL + Apron XL + RhizoStart	1	1.45	2.65	2.05
	2	1.69	2.97	2.33
	3	1.80	3.10	2.45
	4	1.62	2.89	2.26
	5	1.75	3.06	2.40
Maxim XL + Apron XL + BioMAG Soya	1	1.48	2.68	2.08
	2	1.70	3.00	2.35
	3	1.82	3.13	2.48
	4	1.64	2.92	2.28
	5	1.76	3.10	2.43
RhizoStart + Ekostern Trichoderma, SC	1	1.43	2.61	2.02
	2	1.68	2.94	2.31
	3	1.77	3.02	2.40
	4	1.59	2.85	2.22
	5	1.72	3.00	2.36
BioMAG Soya + Ekostern Trichoderma, SC	1	1.44	2.64	2.04
	2	1.67	2.95	2.31
	3	1.78	3.06	2.42
	4	1.60	2.93	2.27
	5	1.72	3.07	2.40
$LSD_{0.05}$, t/ha, for	B	0.05	0.07	
	C	0.03	0.05	
	BC	**0.10**	**0.12**	

***Note:** 1. Control: no application. 2. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51–59). 3. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51–59) and at the flowering stage (BBCH 60-69). 4. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 5. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69)*

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

When the chemical product Kolosal Pro (0.5 L/ha) was replaced with the biofungicide Fitosporin-M Soya (1.5 L/ha), productivity was lower, amounting to 1.78 t/ha in 2024 and 3.06 t/ha in 2025, with no statistically significant difference between these variants ($\text{LSD}_{0.05}$ = 0.10 in 2024 and $\text{LSD}_{0.05}$ = 0.12 in 2025). Due to improved weather conditions in 2025, an increase in soybean grain yield was observed, with gains ranging from 0.5 to 1.2 t/ha. For the variety ‘RGT Saidina’, grain yield in 2025 was higher by 80.6-93.1% compared to 2024 (Table 2). On average over the two years, the application of pre-sowing seed treatment with fungicides and inoculants resulted in an increase in productivity of 0.18-0.30 t/ha compared to the control plots. In variants with the use of fungicides and micronutrient fertilisers during the growing season, the yield increase compared to the control ranged from 0.21 to 0.40 t/ha. The maximum yield values (1.84 t/ha in 2024 and 3.39 t/ha in 2025) were observed in the variant with pre-sowing seed treatment using Maxim XL + Apron XL + BioMAG Soya and double application during the growing season of the fungicide Kolosal Pro (0.5 L/ha) with micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) and Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69). The use of the biofungicide Fitosporin-M Soya (1.5 L/ha) in this scheme led to a slight decrease in soybean productivity, indicating the high effectiveness of biological protection systems.

***Table 2**. Grain yield of the soybean variety ‘RGT Saidina’ depending on the applied agrotechnological measures (average for 2024-2025), t/ha*

Pre-sowing seed treatment with fungicides and inoculants (B)	Fungicides and micronutrient fertilisers (C)	2024	2025	Average
Control	1	1.45	2.72	2.09
	2	1.63	3.04	2.34
	3	1.72	3.16	2.44
	4	1.59	2.99	2.29
	5	1.60	3.09	2.35
Maxim XL + Apron XL + RhizoStart	1	1.57	2.95	2.26
	2	1.79	3.30	2.54
	3	1.88	3.43	2.66
	4	1.74	3.26	2.50
	5	1.84	3.40	2.62
Maxim XL + Apron XL + BioMAG Soya	1	1.64	3.00	2.32
	2	1.82	3.33	2.57
	3	1.93	3.49	2.71
	4	1.77	3.30	2.53
	5	1.86	3.43	2.65
RhizoStart + Ekostern Trichoderma, SC	1	1.52	2.91	1.72
	2	1.76	3.27	2.51
	3	1.84	3.39	2.62
	4	1.71	3.22	2.47
	5	1.83	3.37	2.60
BioMAG Soya + Ekostern Trichoderma, SC	1	1.60	2.96	2.28
	2	1.78	3.29	2.53
	3	1.90	3.43	2.67
	4	1.72	3.27	2.49
	5	1.81	3.39	2.60
$\text{LSD}_{0.05}$, t/ha, for	B	0.05	0.07	
	C	0.03	0.05	
	BC	**0.10**	**0.12**	

***Note:** 1. Control: no application. 2. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 3. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69). 4. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 5. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69)*

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

It was established that the average grain yield of the variety 'RGT Saidina' was 2.47 t/ha, whereas for 'RGT Salsa' it was 2.27 t/ha, which is higher by 0.2 t/ha or 9.1% in relative terms. In both varieties, the highest yield indicators were obtained under conditions of combined use of chemical (Maxim XL (1.0 L/t) + Apron XL (0.5 L/t)) or biological fungicidal seed protection and inoculation (BioMAG Soya (3 kg/t)), together with double application during the growing season of the fungicides Kolosal Pro (0.5 L/ha) and Fitosporin-M Soya (1.5 L/ha), and micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha). It was determined that the greatest contribution to soybean yield formation is made by the genotype (variety) – 43.1% (Fig. 1). The second most influential factor is Factor C with a share of 17.6%, demonstrating the significant impact of fungicides and micronutrient fertilisers on yield. The influence of Factor B amounts to 15.0%, while the interaction between factors B × C accounts for 8.4%. This indicates that the combined application of seed treatment and foliar use of fungicides and micronutrient fertilisers provides an additional increase in yield. Weather conditions also have a considerable effect on soybean productivity – 8.2%. The growing seasons for soya in 2024 and 2025 differed significantly in terms of precipitation and temperature (Table 3).

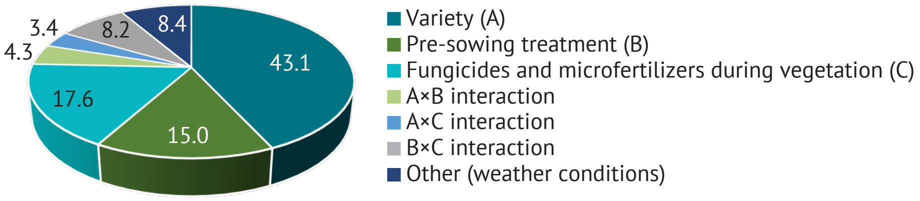

***Figure 1**. Contribution of the factors under study to soyabean yield, %*

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

***Table 3**. Weather conditions during the study years*

Month	Decade	2024		2025	
		Total precipitation, mm	Average temperature, °C	Total precipitation, mm	Average temperature, °C
May	I	0.8	14.8	20.9	12.6
	II	0.1	12.9	2.7	12.5
	III	14.8	19.5	71.5	15.8
	per month	15.7	15.8	95.1	13.6
June	I	21.8	21.3	11.5	21.6
	II	58.8	20	16.0	20.4
	III	0.7	21.2	10.2	21.7
	per month	81.4	20.8	37.7	21.2
July	I	0	22.5	7.8	22.1
	II	40.9	26.5	16.0	24.6
	III	1.2	21.4	31.9	22.0
	per month	42.1	23.5	55.7	22.9
August	I	7.8	20.7	15.9	20.4
	II	1.8	21.2	23.9	21.5
	III	0	23.5	12.5	24.1
	per month	9.6	21.8	52.3	22.0
September	I	3.9	20.8	4.1	19.7
	II	9.3	19.5	18.3	20.4
	III	0	18.2	8.6	16.5
	per month	13.2	19.5	31.0	18.9

***Note:** 1. Control: no application. 2. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 3. Fungicide Kolosal Pro (0.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69). 4. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59). 5. Biofungicide Fitosporin-M Soya (1.5 L/ha) + micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69)*

***Source:** Crop-monitoring (n.d.)*

In May 2024, dry conditions were observed, with total precipitation of 15.7 mm, whereas in 2025 this indicator amounted to 95.1 mm, providing more favourable conditions for the initial development of soybean plants. June 2024 was better supplied with moisture (81.4 mm) compared to 2025 (37.7 mm). In July 2025, more favourable conditions were observed during the flowering and seed formation period of soybean (55.7 mm of precipitation), along with a more even distribution throughout the month. August 2024 was dry (9.6 mm), which negatively affected the yield potential of soybean, while in 2025 it was, on the contrary, sufficiently supplied with moisture (52.3 mm). The total precipitation in 2024 for the May-September period amounted to 162.0 mm, with an average air temperature of 20.3°C, whereas in 2025 it was 271.8 mm and 19.7°C, respectively. Overall, 2025 was characterised by more favourable conditions for the growth and development of soybean plants, while 2024 was characterised as a stressful year, particularly during critical periods – May and August. To quantitatively assess the influence of weather factors on soybean yield formation, predictive models were developed. Figure 2 presents a comparison of the actual soybean seed yield in 2024 and 2025 with the calculated values obtained based on models that take into account the weather conditions of July and August.

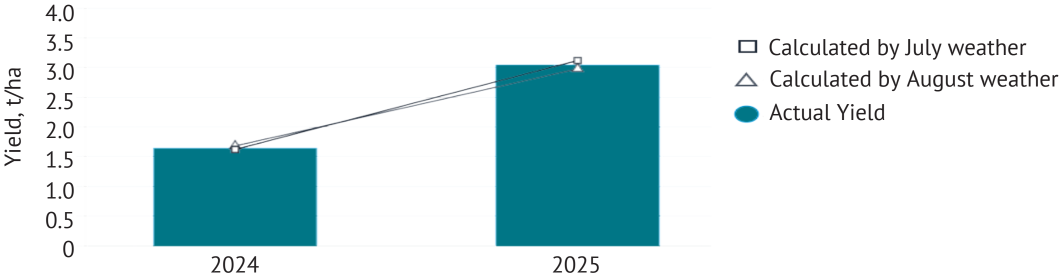

***Figure 2**. Actual and model-calculated soybean seed yield figures, tonnes per hectare*

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

The actual yield in 2024 amounted to 1.68 t/ha, and in 2025 – 3.06 t/ha, indicating a significant increase in productivity due to more favourable weather conditions. Models developed on the basis of weather factors of individual months demonstrated high forecasting accuracy. In 2024, the July model (1.62 t/ha) closely matched the actual data, confirming the decisive role of conditions during the soybean developmental stages (BBCH 51-69) in shaping future productivity. In 2025, the July model slightly overestimated the yield (3.12 t/ha). In 2024, the August model showed a higher value (1.75 t/ha) than the actual yield, indicating that the extreme drought in August (only 1.8 mm of precipitation in the second ten-day period) acted as a limiting factor that the model could not fully account for. In 2025, the August model (2.98 t/ha) was lower than the actual yield. The deviations between actual and calculated values were insignificant (up to 0.07 t/ha), which confirms the adequacy of the models and the strong dependence of soybean yield on climatic indicators in July and August. The July model is more stable for predicting the overall trend in soybean yield, as it is during this period that the structure of the future yield is formed.

In addition to analysing the influence of weather factors, cluster analysis was applied to generalise the obtained results and identify similarities between experimental variants. Figure 3, which presents the results of cluster analysis of the average soybean yield for 2024-2025, clearly shows several hierarchically formed clusters. Clustering was performed using the method of J.H. Ward (1963) with Euclidean distances, allowing the degree of similarity between variants to be assessed based on yield level. The first large cluster includes variants with the highest yield values: 13, 30, 45, 46, 49, and 50. This indicates that, regardless of the variety, certain agrotechnological measures (pre-sowing seed treatment and inoculation, as well as foliar application of fungicides and micronutrient fertilisers) contributed to consistently high yield results in both years of the study. The internal structure of this cluster is quite compact, indicating a high degree of similarity among the variants included in it. The second cluster consists of variants that demonstrated medium yield levels. Within this group, greater variability between variants is observed; however, they form a distinct branch separated from both high- and low-productivity combinations. Variants within this cluster are grouped at smaller Euclidean distances, indicating relatively similar, although not maximum, characteristics.

The third cluster comprises the variants with the lowest yield values: 1, 4, 15, 16, 35, 41. Variant 41 has one of the lowest average yields (1.66 t/ha) and forms its own isolated sub-cluster, showing the greatest distance from the other variants, which may indicate the influence of adverse weather conditions in this trial. Overall, the dendrogram confirms that soyabean yield depends to a significant extent not only on the variety but also on the combination of agronomic practices. Despite the differences between varieties, some experimental variants had similar productivity and are grouped into common clusters, indicating the possibility of optimising cultivation technologies for different genotypes.

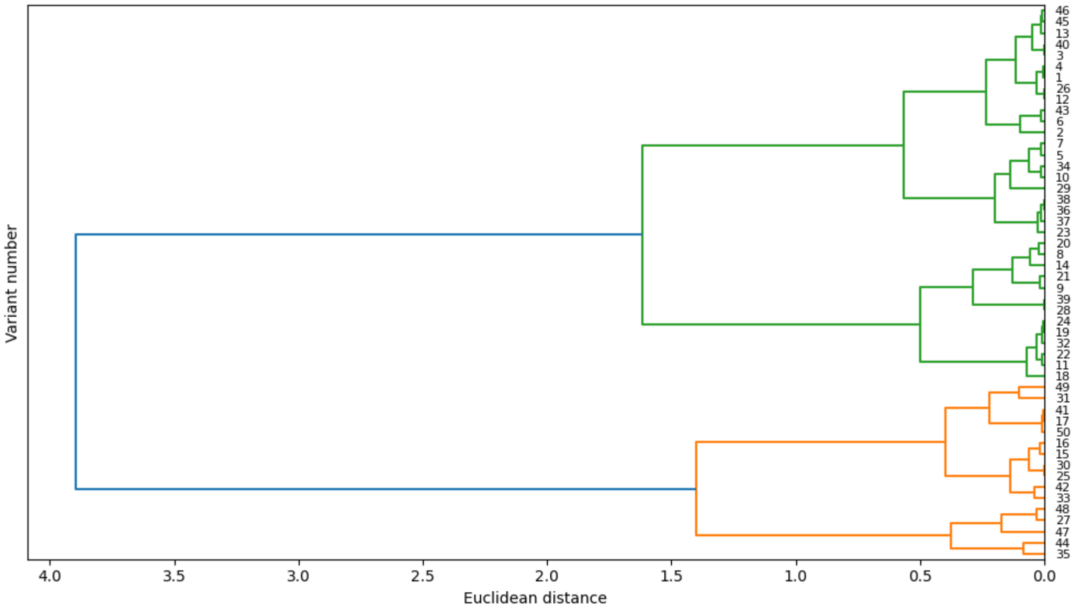

***Figure 3**. Dendrogram of cluster analysis of yield of soybean varieties 'RGT Salsa' and 'RGT Saidina' for 2024-2025*
***Source:** compiled by the authors*

DISCUSSION

The obtained research results are consistent with data from other authors regarding the influence of climatic factors on crop yields. According to E. Vogel *et al.* (2019), climate extremes increase yield variability of agricultural crops by 18-43%, accounting for more than half of the variance for maize, soybean, and rice. Temperature extremes have a stronger relationship with yield changes than precipitation-related variables such as drought or heavy rainfall. H. Zhang *et al.* (2019) indicated that for every 1°C increase in growing season temperature, soybean yield decreases by 3.1%. Soybean plants are particularly sensitive to elevated temperatures during the reproductive stage, especially during flowering and grain filling. According to H.A. Araji *et al.* (2018), water stress caused by reduced precipitation affects the physiological development of soybean plants and yield formation. As reported by K. Jumrani & V.S. Bhatia (2018), both temperature and water stress influence soybean growth and yield, but the effect is more pronounced when water deficit occurs under high air temperatures.

These findings fully correspond with the results of the present study. In the weather-stressful year of 2024, yields of the soybean varieties 'RGT Salsa' and 'RGT Saidina' ranged from 1.34-1.82 and 1.45-1.93 t/ha, respectively, whereas in the more climatically favourable 2025 (in terms of precipitation and temperature), they reached 2.51-3.13 and 2.72-3.49 t/ha, respectively, which is 70.6-93.1% higher. However, according to results obtained by R. Ramteke *et al.* (2015) in India during 2001-2013, a shift in precipitation from July to August was observed, while soybean yield in Indore district and Madhya Pradesh state increased by 21.6 and 13.9 kg, respectively.

According to the authors' calculations, in 2024 the July model (1.62 t/ha) closely matched the actual soybean yield data, whereas in 2025 the July model slightly overestimated the yield (3.12 t/ha). In 2024, the August model showed a higher value (1.75 t/ha) than the actual yield, while in 2025 the August model (2.98 t/ha) was lower than the actual yield. At the same time, deviations between actual and calculated values were insignificant (up to 0.07 t/ha), indicating the adequacy of the models and the strong dependence of soybean yield on climatic indicators in July and August. These conclusions are also supported by findings of other researchers. According to O. Sobko *et al.* (2020), soybean yield showed a significant positive correlation with solar radiation ($r = 0.32$) and precipitation ($r = 0.33$), but a significant negative correlation with crop heat units (CHU) ($r = -0.42$). M. Tsekhmeistruk *et al.* (2021), based on correlation analysis of weather conditions and soybean yield during 2004-2020, identified a negative effect of average daily temperature in August (correlation coefficient $r = -0.428$). Ya.O. Yarovyi (2024) reported that July precipitation had a positive effect on the crop ($r = 0.501$-0.555). Soybean seed yield varies significantly depending on the weather conditions of the study year, as indicated by a low stability index of 0.36-0.40.

According to Kazakh researchers S. Didorenko *et al.* (2023), the yield of soybean varieties shows a positive correlation with maturity group ($r = 0.87$). Weather conditions had an inconsistent effect on the yield of varieties from different maturity groups. In the driest year, the yield of late-maturing soybean varieties Birlik KV and Zhansaya decreased the most. N.G. Buslaeva *et al.* (2024) established relationships between soybean seed yield and weather elements: a strong correlation with average monthly air temperature was observed for July ($r = -0.931$), while correlations with monthly precipitation were identified for May ($r = -0.875$), June ($r = 0.720$), and August ($r = -0.950$). The strongest combined influence of average daily air temperature and precipitation was found during the third ten-day period of June ($r = -0.938$ and 0.996) and August ($r = 0.976$ and -0.999). Ya.O. Yarovyi (2024) stated that soybean seed yield is most affected by weather conditions and fertilisation, and least by inoculation. Y. He & M.L. Matthews (2023) noted that solar radiation, temperature and relative humidity were the main climatic factors influencing yield improvement, and they showed an inverse correlation with yield improvement during the vegetative phase compared to the reproductive phase of soya.

In addition to the influence of climatic factors, agrotechnological measures, in particular pre-sowing seed treatment and the application of biological products, play an important role in determining soyabean yield. The results of this study showed that pre-sowing treatment of soya bean seeds with fungicides and inoculants contributed to an increase in grain yield of 0.09-0.30 t/ha or 5.1-12.8%, compared to the control. According to S. Hussain *et al.* (2009), soyabean yield in treatments involving seed treatment with the bacterium *B. japonicum* and the fungicide fludioxonil + *B. japonicum* was the highest and significantly exceeded the control treatment by 0.27-0.60 t/ha. Data from S. Kobak *et al.* (2025) indicated that inoculation of soyabean seeds with biological preparations increased yield: 40-45 days before sowing – by 7-10%, 19-21 days before sowing – by 10-16%, and on the day of sowing – by 13-19%. In experiments conducted by Ya.O. Yarovyi (2024), inoculating seeds before sowing yielded 0.54-0.60 t/ha of seeds, compared to plots without fertiliser. Pre-sowing inoculation of soyabeans with a cellular protector was effective 30 days before sowing, and grain yield was similar to that of standard inoculation even under unfavourable environmental conditions, indicating the potential for using this technology even under adverse conditions.

However, researchers A.S.F.D. Araújo & R.S. Araújo (2006) and E.J. Hartley *et al.* (2012) reported on the toxicity of plant protection products used for pre-sowing seed treatment to the bacteria present in inoculants and a possible reduction in yield due to this antagonistic effect. Thus, according to P.P. Pukhtaievych *et al.* (2023), the combined application of inoculants and the Benorad preparation resulted in a reduction in the above-ground biomass of soyabeans by 8.7-20.9% and root biomass by 4.8-16.8% during the growing season, compared with control plants (regardless of the rhizobium strain used for inoculation). A negative effect of seed treatment on the nitrogenase activity of symbiotic systems was noted following the application of Benorad at the three-true-leaf stage and during budding to early flowering.

T. Nyzhnyk *et al.* (2024) found that the application of the inoculant *Bradyrhizobium japonicum* (titre 10^9 cells per ml) and the fungicide fludioxonil (25 g/L) to seeds promoted the development of antioxidant protection in soybean plants under drought conditions through the activation of key enzymatic complexes and regulation of lipid peroxidation processes, which positively affect nitrogen fixation and soybean productivity. This increased the nitrogen-fixing activity of soybean at the pod formation stage by more than 71.7% and also increased soybean yield by 12.7%. Accordingly, in this study no negative effect of fungicides on the growth and development of soybean plants was observed either in the initial period of vegetation or in later stages.

An important element of cultivation technology is also the foliar application of fungicides and micronutrients, the effectiveness of which is confirmed by the obtained results. According to the data, the influence of foliar application of micronutrients and fungicides during soybean vegetation (17.6%) was more significant for yield formation. Thus, grain yield in these variants exceeded the control plots, depending on the variety, by 0.23-0.42 t/ha. This is confirmed by the findings of A.V. Melnyk *et al.* (2019), according to which the use of foliar fertilisation products contributed to an increase in soybean grain yield on average by 0.3-0.5 t/ha, or 12.5-15.5%. Studies by A.V. Holodna *et al.* (2024) showed that plant feeding at the flowering stage with an organo-mineral fertiliser ensured an increase in soybean yield of 0.64 t/ha; the application of the micronutrient YaraVita Mono Molytrac at the budding stage and additionally at the flowering stage with growth regulators increased yield by 0.21-0.44 t/ha. According to D.V. Kozyrsky *et al.* (2025), the fungicide protection system was effective and contributed to the formation of 0.23-0.45 t/ha more soybean grain compared with variants without their application.

Particular attention in modern soybean cultivation technologies is given to the use of biological products as an environmentally safe alternative to chemical plant protection agents. The use of biological products in crop production is highly relevant, and microbiological preparations are increasingly being applied. S.S. Nimenko & M.B. Grabovskyi (2023) and A. Korobko *et al.* (2024) noted that modern biological products contain various microorganisms that can enhance plant resistance to diseases and pests, promote growth and development, and improve the qualitative composition of soil microbiota. According to H. Panda (2017), they are an alternative to mineral fertilisers and pesticides that disrupt natural cycles and negatively affect biota and the environment. L.E. Fuentes-Ramírez & J. Caballero-Mellado (2006) pointed out that the widespread use of biological factors for the intensification of agriculture has not only environmental but, in most cases, economic priority. The positive effect of biofungicides is also confirmed by the data of Y. Prayogo *et al.* (2023) and T.P.C. Ezeorba *et al.* (2023). In this study, the use of the biofungicide Ecostern Trichoderma, SC (1.5 L/t) for pre-sowing seed treatment and the biofungicide Fitosporin-M Soya (1.5 L/ha) during vegetation resulted in lower grain yield than in variants where chemical products were used; however, the difference was not statistically significant, indicating the effectiveness of biological products in soybean cultivation technology.

CONCLUSIONS

According to the results of the two-year study, a significant influence of varietal characteristics, pre-sowing seed treatment and inoculation, as well as foliar application of fungicides and micronutrient fertilisers on soybean yield was established. The highest yield was obtained for the variety 'RGT Saidina' in the experimental variant with pre-sowing seed treatment using Maxim XL + Apron XL + BioMAG Soya and double application during the growing season of the fungicide Kolosal Pro (0.5 L/ha) with micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) and Quantum Bor Active (1.0 L/ha) at the budding stage (BBCH 51-59) and at the flowering stage (BBCH 60-69) – 2.71 t/ha. The use of the biofungicide Fitosporin-M Soya (1.5 L/ha) within this scheme resulted in a yield of 2.65 t/ha, indicating the high effectiveness of biological preparations. For the variety 'RGT Salsa', yield indicators under these variants were 2.48 and 2.43 t/ha. The variety 'RGT Saidina' provided an average yield of 2.47 t/ha over two years, whereas 'RGT Salsa' yielded 2.27 t/ha, which is higher by 0.2 t/ha or 9.1%.

In 2024, the average soybean yield across the experiment was 1.68 t/ha, while in 2025, under favourable moisture conditions, it increased to 3.06 t/ha. The developed mathematical models confirmed that July data have higher predictive value. Deviations between actual and calculated values were insignificant (up to 0.07 t/ha), indicating the adequacy of the models and the strong dependence of soybean yield on climatic indicators in July and August. Cluster analysis of 50 experimental variants based on soybean grain yield identified three main groups according to productivity level. The first cluster included variants with yields above 2.5 t/ha, most of which combined the use of the inoculant BioMAG Soya with the fungicides Maxim XL (1.0 L/t) + Apron XL (0.5 L/t), as well as the fungicide Kolosal Pro and micronutrient fertilisers Intermag Molybdenum (1.0 L/ha) + Quantum Bor Active. Further research should be aimed at expanding environmental testing of the experimental variants to assess the stability of the identified relationships under different soil and climatic conditions, as well as at studying the long-term effects of biological preparations on soil microbiota and the efficiency of symbiotic nitrogen fixation in soybean plants. A promising direction is yield modelling using long-term weather datasets to develop adaptive management systems for soybean cultivation under varying climatic conditions.

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CONFLICT OF INTEREST

None.

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Формування врожайності сої залежно від сортових особливостей і агротехнологічних прийомів на основі прогностичного моделювання

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Анотація. У статті висвітлено результати дворічного польового досліду щодо вивчення впливу сортових особливостей, агротехнологічних прийомів та погодних умов на врожайність сої з використанням прогностичного моделювання. Актуальність дослідження обумовлена необхідністю підвищення стабільності врожаю сої в умовах кліматичних змін і важливістю застосування біологічних засобів захисту рослин (біофунгіцидів). Метою було встановлення ефективності різних схем передпосівної обробки насіння та позакореневого застосування фунгіцидів і мікродобрив, а також розроблення математичних моделей прогнозування врожайності сої залежно від погодних умов. Польові дослідження проводилися в 2024-2025 роках на базі Навчально-виробничого центру Білоцерківського національного аграрного університету з сортами сої ‘РЖТ Сальса’ і ‘РЖТ Сайдіна’. Дослід включав 50 варіантів. Встановлено, що найбільшу врожайність (2,71 т/га) отримано у сорту ‘РЖТ Сайдіна’ за комбінованого використання фунгіцидів Максім XL, Апрон XL, інокулянта БіоМАГ Соя і дворазового внесення фунгіциду Колосаль Про з мікродобривами Інтермаг Молібден і Квантум Бор Актив у фазу бутонізації (BBCH 51-59) і фазу цвітіння (BBCH 60-69). За цієї схеми, варіанти з біофунгіцидом Фітоспорин-М Соя забезпечили врожайність 2,65 т/га, що підтверджує високу ефективність біологічного захисту. Математичне моделювання виявило високий рівень відповідності між фактичними і розрахованими даними (похибка до 0,07 т/га). Кластерний аналіз 50 досліджених варіантів за врожайністю зерна сої виявив три основні групи за ступенем продуктивності. До першого кластеру увійшли варіанти з врожайністю понад 2,5 т/га, більшість з яких поєднували застосування інокулянта БіоМАГ Соя з фунгіцидами Максім XL (1,0 л/т) + Апрон XL (0,5 л/т) та фунгіцидом Колосаль Про і мікродобривами Інтермаг Молібден (1,0 л/га) + Квантум Бор Актив. Практична цінність результатів полягає у виділенні оптимальних комбінацій застування біологічних і хімічних фунгіцидів, інокулянтів та мікродобрив для підвищення продуктивності сої, а також у можливості прогнозування врожайності на основі кліматичних показників

Ключові слова: інокуляція; фунгіциди; сорт; мікродобрива; кліматичні умови; кластеризація
