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Formation of soybean seed quality depending on plant protection in the forest-steppe of Ukraine

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Abstract. The aim of the study was to establish the patterns of formation of soybean seed productivity and quality depending on weather conditions and varietal characteristics in the Right-Bank Forest-Steppe of Ukraine. Field studies were conducted during 2023-2025 on experimental plots in the Uman district of the Cherkasy region. The object of the research was five soybean varieties of different genetic origin and morphobiological characteristics: Gallek, ES Mentor, OAC Brook, Sigalia, and Kobza. The soil and climatic conditions during the years of research differed significantly in terms of temperature and moisture supply, which made it possible to assess the adaptive potential of varieties under contrasting hydrothermal conditions. Methodologically, the research was based on a field experiment taking into account the main elements of the yield structure, the

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weight of 1,000 seeds, the fractional composition of the seeds and quality indicators. The protein and oil content in the seeds was determined by infrared spectroscopy, and the moisture content was determined by a standard laboratory method. The dynamics of above-ground biomass formation were analysed using the sum of effective temperatures and a logistic growth model. It was found that in 2024, under conditions of moisture deficiency and elevated temperatures, the rate of biomass growth, 1,000-seed weight, and yield decreased by 8-25% compared to 2023 and 2025. According to the average three-year data, the highest and most stable yields were formed by the ES Mentor and Kobza varieties, while the Gallek and Sigalia varieties were more sensitive to stressful conditions. Seed quality indicators were mainly determined by variety: the Gallek variety was distinguished by the highest weight of 1,000 seeds and a high proportion of large seeds, while the protein and oil content remained relatively stable throughout the years of research. The practical value of the work lies in substantiating the feasibility of selecting soybean varieties with high ecological plasticity and stable seed quality for the conditions of the Right-Bank Forest-Steppe of Ukraine in the context of increasing climate variability

Keywords: soybean productivity; varietal characteristics; seed quality; sugar content; economic efficiency; inoculation; cultivation technology

INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) is one of the strategically important leguminous crops in global agriculture due to its high nutritional value, significant protein and oil content, and wide range of uses in the food, feed and processing industries. Soybeans play an increasingly important role in the structure of agricultural production in Ukraine, as they combine high economic potential with the ability to adapt to different soil and climatic conditions. At the same time, modern challenges related to climate change, soil degradation and the need to improve resource efficiency necessitate the improvement of crop cultivation technologies and the optimisation of agrotechnical elements. An important component of stable soybean production is the selection of varieties capable of ensuring high yields and seed quality in changing agroecological conditions. According to the results of research by M. Alburaki *et al.* (2024), varietal characteristics significantly affect crop productivity, its adaptability to abiotic factors, and the realisation of yield potential. Similar conclusions were reached by Z.I. Hlupak (2020), who found that the varietal response of soybeans to moisture and temperature conditions is a determining factor in yield formation in different agroclimatic zones.

The problem of soybean variety adaptability to changing environmental conditions is also highlighted in the works of O. Laslo *et al.* (2024), which emphasise the significant variability of productivity indicators depending on the combination of genetic characteristics of the variety and growing conditions. The authors emphasise that the potential of modern varieties can only be realised with an optimal combination of agronomic factors. Similar conclusions were reached by L. Bilavska & A. Rybalchenko (2019), who point to significant differences between varieties in terms of protein content and other economically valuable traits, caused by both genetic and environmental factors. The mineral nutrition system has a significant impact on the formation of the yield and quality indicators of seeds. M. Ivasyk

& M. Bakhmat (2022) proved that balanced fertilisation contributes to increased yield and improved grain quality, but the effectiveness of such measures largely depends on soil and climatic conditions and the biological characteristics of the variety.

The impact of plant protection systems on crop formation and seed quality characteristics is of particular scientific interest. S.P. Hen *et al.* (2022) showed that the use of modern protection schemes can reduce crop losses from phytopathogens and stabilise productivity indicators, while the intensity of chemical load can affect the physiological state of plants. Climatic factors also make a significant contribution to the formation of soybean quality indicators. A. Riabultchenko & A. Serdiuk (2023) emphasised the complex nature of the relationship between yield, protein content and oil content of seeds depending on weather conditions during the growing season. A review of current scientific sources has shown that the formation of soybean seed quality indicators is a multifactorial process determined by a combination of genetically determined characteristics of the variety, agrotechnical features, plant protection systems, and specific soil and climatic conditions of cultivation. Despite the availability of a significant number of scientific works devoted to individual elements of soybean cultivation technology, there is a lack of systematic research in the scientific community aimed at a comprehensive assessment of the interaction between varietal characteristics and elements of the plant protection system in the formation of sowing and quality indicators of seeds. Generalised data on such interactions in the soil and climatic conditions of the Right-Bank Forest-Steppe of Ukraine, which are characterised by increased variability of weather factors and specific agro-ecological conditions, remain particularly limited. In this regard, there is a need for an in-depth scientific analysis of the role of varietal characteristics and technological elements in the formation of soybean seed quality, taking into account regional specifics, which

determines the relevance of conducting relevant research and determines its scientific and practical significance. That is why the aim of the study was to determine the influence of varietal characteristics and elements of the plant protection system on the formation of sowing and quality indicators of soybean seeds in the conditions of the Right-Bank Forest-Steppe of Ukraine.

MATERIALS AND METHODS

Research on the productivity and quality of soybean seeds depending on varietal characteristics, plant protection systems, and foliar fertilisation was conducted in 2023-2025 on the experimental field of the Department of Plant Growing of Uman National University (Cherkasy region), which belongs to the Right-Bank Forest-Steppe zone of Ukraine. The soil of the experimental site is podzolised medium loam chernozem with a humus content of 3.4-4.1% and a pH of 6.4-6.7. The climate of the region is temperate continental with an average annual precipitation of 520-580 mm. Weather conditions during the years of research differed significantly in terms of temperature and moisture supply, creating a contrasting background for assessing varietal responses. The meteorological conditions during the years of the study were characterised by significant variability in temperature and precipitation, which made it possible to evaluate the response of soybean plants to different levels of heat and moisture supply (Central Geophysical Observatory named after Borys Sreznevskiy, 2024). To quantitatively assess heat resources, was used the Growing Degree Days (GDD) index, which was calculated using the formula:

$$GDD = \Sigma(T_{ser} - T_o), \quad (1)$$

where T_{ser} – average daily air temperature, °C; T_o – base temperature for soybean growth, assumed to be 10°C.

To analyse the dynamics of above-ground biomass growth, a logistic growth model was used, which is described by the equation:

$$Y = Y_{asym} / (1 + e^{-k(GDD - t_m)}), \quad (2)$$

where Y – accumulated above-ground biomass; Y_{asym} – asymptotic (maximum) biomass value; k – growth intensity coefficient; t_m – GDD value at the inflection point of the growth curve.

The model parameters were estimated using non-linear regression. The quality of the approximation was checked using the coefficient of determination (R^2) and the root mean square error. Field experiments were conducted using a three-factor design (variety × protection system × foliar feeding) in four replicates: factor A – variety: ES Mentor, Gallek, OAC Brook, Sigalia, Kobza; factor B – plant protection system: control (without treatment), chemical, biological, integrated; factor C – foliar feeding: growth regulator Rizohumin-Plus in

concentrations of 0.5% and 0.75%. Sowing was carried out with a row spacing of 70 cm and a sowing rate of 450 thousand viable seeds/ha. Application phases and application rate: foliar feeding with chlormequat chloride Rizohumin-Plus was performed twice:

- in the phase of the 3rd-5th true leaf (V3-V5) and in the phase of budding (R1), working solution rate – 400 l/ha;

- for the plant protection system (chemical, biological, integrated), the preparations recommended for soybeans were used, according to the phases: weed control – before emergence; fungicide and insecticide – in the V4-V6 phase; working solution consumption rate – 300-400 l/ha, frequency – 1-2 times depending on the type of protection.

During the growing season, phenological observations, biometric measurements (plant height, number of nodes, pods, grains per pod, weight of 1,000 seeds), assessment of plant density and activity of symbiotic structures were carried out. Seed quality was assessed based on a set of indicators:

- fractional composition: calibration through 7.0, 6.0, and 5.0 mm sieves;

- weight of 1,000 seeds: triple weighing (DSTU 4138-2002, 2004);

- moisture content determined by standard method;

- protein and oil content: infrared spectroscopy (NIR, DSTU EN ISO 12099:2022, 2023);

- total sugars and sucrose: extraction-chromatographic method;

- symbiotic efficiency of soybeans was assessed by the weight of nodules in phases R3-R6 and calculated indicators of active symbiotic potential and biologically fixed nitrogen, averaged for 2023-2025. The mass of biologically fixed nitrogen was calculated based on the symbiotic potential value, converted per plant and per hectare.

Statistical data processing was performed with the determination of $LSD_{0.5}$. To assess the impact of factors, dispersion analysis was used, statistical significance was determined at $p < 0.05$, and the average values were compared using standard statistical methods. Correlation analysis was used to determine the relationship between seed weight, protein content and other quality indicators. The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

Weather conditions during the years of research differed significantly in terms of temperature and moisture supply, which created a contrasting background for assessing the response of soybean plants. The lowest amount of precipitation during the growing season was observed in 2024 (166.0 mm), while in 2025 it reached

359.8 mm. At the same time, 2024 was characterised by the highest number of days with air temperatures

above +35°C, which created stressful conditions for plant growth (Table 1).

Table 1. Weather conditions and soybean growth parameters in the Right-Bank Forest-Steppe of Ukraine (2023-2025)

Indicator	2023-2024	2024-2025	LSD _{0.5}
Precipitation during the growing season (May-October), mm (V-X)	166.0	359.8	18
Annual precipitation, mm	487.2	525.5	27
Average annual air temperature, °C	11.8	10.3	0.4
Average temperature during the growing season (V-VIII), °C	20.1	18.6	0.3
Number of days with temperatures > +35 °C	25	10	2
Biomass growth rate, k (GDD ⁻¹)	5.80×10^{-3}	6.72×10^{-3}	0.13×10^{-3}
Biomass asymptote, Y_{asym} (kg/ha)	6,345	7,015	145
Inflection point t_m (GDD)	845	905	22

Source: developed by the authors

The results of growth modelling show that in conditions of moisture deficiency and elevated temperatures, the rate of biomass accumulation decreased, as evidenced by lower values of the coefficient k and the asymptotic biomass level (Y_{asym}). In contrast, in years with better hydrothermal conditions, these indicators increased, indicating more active growth processes and more efficient use of thermal resources. Among the varieties studied, the highest average yield for 2023-2025 was provided by ES Mentor (3.30 t/ha) and Kobza (3.16 t/ha), confirming their high plasticity and ability to form a stable yield even under contrasting weather conditions. The years of research differed significantly in terms of hydrothermal conditions: during the growing season, precipitation ranged from 42.4-15.8 – -92.5 mm (2023) to 15.4-99.2-10.0 mm (2025), which caused fluctuations

in moisture availability at certain stages of plant growth. A particularly acute precipitation deficit was observed in 2024, while 2023 was characterised by a more even distribution. In addition to yield, an important indicator of the technological value of varieties is the fractional composition of seeds, as it determines the suitability of the crop for processing and seed production. The weight of 1,000 seeds, the proportion of large seeds, and seed uniformity are key criteria that are determined by a combination of factors, including the biology of the variety, moisture availability, and temperature conditions. According to the results of the research, the largest proportion of the large fraction was formed by the varieties Gallek, ES Mentor and OAC Brook, which confirms their better response to the moderate moisture conditions of 2023 and 2025 (Table 2).

Table 2. Fractional composition of soybean seed depending on the variety, average for 2023-2025, %

Variety	Large fraction (>5.0 mm)	Medium (4.0-5.0 mm)	Small (<4.0 mm)
Gallek	63.5	31.8	4.7
ES Mentor	59.2	36.1	4.7
OAC Brook	50.4	47.3	2.3
Sigalia	44.6	37.9	17.5
Kobza	47.2	44.4	8.4
LSD ($p < 0.05$)	4.55	4.10	3.35

Source: developed by the authors

During 2023-2025, it was established that the formation of quality indicators for soybean seeds and yields was largely determined by variable weather conditions. In 2023, with moderate rainfall and no prolonged droughts, most varieties produced a higher proportion of large seeds and yielded maximum harvests. In 2024, when there was a moisture deficit during the critical stages of branching and flowering, the yield of most varieties decreased, and the proportion of small seeds increased. The Kobza and ES Mentor varieties performed best under these conditions, maintaining a relatively even fraction composition. In 2025, a sharp contrast in precipitation (excess at the beginning and

deficit at the end of the growing season) contributed to an increase in the average fraction and a decrease in the small fraction in varieties with high adaptive potential. ES Mentor and Kobza provided the highest stability of indicators, forming a yield of 3.15-3.41 t/ha.

According to the average results for 2023-2025, the highest yields were provided by: ES Mentor – 3.30 t/ha; Kobza – 3.16 t/ha. The lowest average productivity was observed for Gallek (2.66 t/ha) and Sigalia (2.64 t/ha). Overall, the data demonstrate significant varietal differentiation and make it possible to recommend the most productive and stable varieties for the Forest-Steppe zone of Ukraine. In the dry year of 2024, against the

backdrop of high temperatures and moisture deficiency, there was an overall decrease in the weight of 1,000 seeds by 8-10% and a decrease in the large fraction by 5-7%. This directly affected the yield, as its decline ranged from 0.2 to 0.5 t/ha depending on the variety. The smallest decrease was observed in the OAC Brook variety, while Gallek and Sigalia proved to be more sensitive to stressful conditions. In 2025, with more optimal moisture and temperature conditions, most varieties restored their productivity to 2023 levels. ES Mentor and Kobza again showed the highest yield values – from 3.33 to 3.40 t/ha. The Sigalia variety showed

moderate but stable performance, ranging from 2.75 to 2.93 t/ha. According to the average results of three-year studies, the highest yields were provided by the ES Mentor (3.30 t/ha) and Kobza (3.16 t/ha) varieties. Slightly lower but more consistent results were obtained for the OAC Brook variety – 3.09 t/ha. The lowest average productivity was achieved by the varieties Gallek (2.66 t/ha) and Sigalia (2.64 t/ha). In general, the data obtained demonstrate significant varietal differentiation in terms of productivity and allow for the recommendation of the most productive and stable varieties for cultivation in the forest-steppe zone of Ukraine (Table 3).

Table 3. Weight of 1,000 seeds and protein content in soybean varieties in the Uman district of the Cherkasy region

Variety	Weight of 1,000 seeds, g ($\pm\sigma$)	CV% of weight	Protein content, % ($\pm\sigma$)	CV% of protein
Gallek	160 \pm 3.0	1.9	34.2 \pm 0.6	1.8
ES Mentor	156 \pm 3.0	1.9	33.5 \pm 0.6	1.8
OAC Brook	152 \pm 3.0	2.0	32.5 \pm 0.6	1.8
Sigalia	146 \pm 3.0	2.1	32.0 \pm 0.6	1.9
Kobza	151 \pm 3.0	2.0	33.8 \pm 0.6	1.8
LSD ($p<0.05$)	6.74	–	1.8	–

Source: developed by the authors

The graph shows the ratio of seed weight to protein content, allowing for a visual assessment of the

differences between varieties in terms of these indicators (Fig. 1).

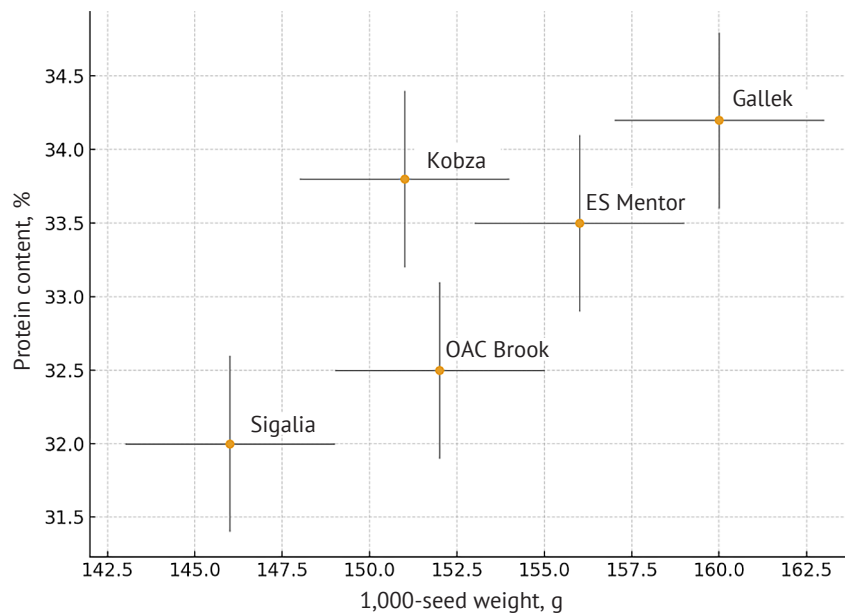


Figure 1. Ratio of the weight of 1,000 seeds and protein content in soybean varieties in the Uman district of the Cherkasy region

Source: developed by the authors

The conducted research confirmed significant variability in the indicators. The highest weight of 1,000 seeds was recorded for Gallek (160 g) and ES Mentor (156 g), while the lowest was recorded for Sigalia (146 g), which was combined with the largest proportion of small fraction (<4 mm – 17.5%). The protein

content ranged from 32.0% (Sigalia) to 34.2% (Gallek), indicating the overall stability of this indicator. There was a tendency towards an inverse relationship between seed weight and protein content, confirmed by correlation analysis. The data can be used to select varieties for the conditions of the Central Forest-Steppe

of Ukraine. To assess the quality of soybean seeds, it is important to consider not only the yield, but also the chemical composition of the seeds, in particular the protein and oil content, which was determined by near-infrared spectroscopy (NIR), as well as the composition of protein fractions, amino acids and sugars. These indicators determine the food and feed value of

the crop, as well as its technological suitability for processing. During the 2023-2025 studies, the content of globulins, albumins, gliadins, lysine and methionine, fat and acid composition of oil, total sugars and sucrose, as well as active symbiotic potential were analysed. The calculation of $LSD_{0.5}$ allows to assess the reliability of differences between varieties (Table 4).

Table 4. Protein and oil content, chemical composition and quality of seeds of the studied soybean varieties (average for 2023-2025, determined by near-infrared spectroscopy)

Variety	Globulins, %	Albumins, %	Gliadins, %	Lysine, %	Methionine, %	Oil, %	Saturated acids, %	Unsaturated acids, %	Total sugars, %	Sucrose, %	Active symbiotic potential, thousand kg-day/ha	Moisture, %
Gallek	70	20	10	6.1	1.2	19.0	16	84	6.2	4.4	22.34	11.2
ES Mentor	68	22	10	6.0	1.2	18.5	16	84	7.8	5.6	16.46	11.5
OAC Brook	67	23	10	5.9	1.1	18.0	16	84	7.5	5.3	15.88	11.3
Sigalia	66	24	10	5.8	1.1	18.2	16	84	6.1	4.3	15.72	11.4
Kobza	69	21	10	6.0	1.2	18.7	16	84	7.6	5.4	15.97	11.3
LSD_{0.5}	1.6	1.5	0.3	0.25	0.12	0.6	0.4	0.4	0.7	0.6	2.3	0.5

Source: developed by the authors

Data analysis showed that protein content in seeds ranged from 36.0% (Sigalia) to 37.5% (Gallek). The highest level of globulins was also observed in the Gallek variety, while albumins and gliadins remained relatively stable in all varieties (20-24% and 10%, respectively), indicating a balanced protein composition of the seeds. The key amino acids lysine and methionine demonstrate high nutritional value, ranging from 5.8-6.1% and 1.1-1.2%, respectively. The fat content of the seeds was 18.0-19.0%, with saturated and unsaturated acids accounting for 16% and 84%, respectively, which ensures the high technological value of the oil. Total sugars and sucrose varied depending on the variety (6.1-7.8% and 4.3-5.6%), reflecting varietal differences in nutritional value. The active symbiotic potential index (thousand kg-day/ha) was used for evaluation. The moisture content of the seeds is within the range of 11-11.5%, which allows assessing their suitability for storage and use. The calculated $LSD_{0.5}$ indicates

statistically significant differences between varieties in all seed quality indicators. The data in the table show that the Gallek and ES Mentor varieties have an optimal combination of protein value, oil content and symbiotic potential, which makes them promising for cultivation in the forest-steppe zone of Ukraine. The near-infrared spectroscopy (NIR) method provided a fast, accurate and non-destructive determination of the protein, oil and amino acid composition of the seeds, which allowed for a comprehensive assessment of seed quality on an experimental scale without additional chemical analysis. The studies also demonstrated the high effectiveness of using improved plant protection systems in combination with optimised mineral nutrition. The use of biological and chemical protection agents together with foliar application of the growth regulator chlormequat chloride at concentrations of 0.5% and 0.75% had a positive effect on biometric indicators, plant resistance and productivity (Table 5).

Table 5. Soybean plant density before harvesting depending on variety and seed treatment, thousand plants/ha (average for 2023-2025)

Variety	Control (untreated)	Rhizohumin-Plus, 0.5%	Rhizohumin-Plus, 0.75%
Gallek	555.7	565.5	585.9
ES Mentor	550.6	555.4	569.8
OAC Brook	548.9	553.1	566.2
Sigalia	546.3	550.6	563.7
Kobza	552.4	558.3	571.5
LSD_{0.5}	4.7	7.5	11.1

Source: developed by the authors

Analysis of the data in Table 5 shows that the density of soybean plants before harvesting depended significantly on both varietal characteristics and the cultivation techniques used. In the control variant without seed treatment, plant density varied between 546.3 and 555.7 thousand plants/ha, reflecting the genetically determined difference between varieties in terms of initial growth intensity and plant survival during the growing season. The use of a biological preparation in combination with the growth regulator chlormequat chloride at a concentration of 0.5% provided a statistically significant increase in plant density in all studied varieties. The increase compared to the control averaged 4.0-6.2 thousand plants/ha, which indicates a positive effect of the technological method on germination energy and plant survival during vegetation.

The highest density indicators were formed when using a concentration of 0.75%, where the density of the Gallek, Kobza and ES Mentor varieties exceeded

569 thousand plants/ha. The increase compared to the control reached 14-17 thousand plants/ha, which indicates a significant positive effect of combining biological seed treatment with growth regulation. At the same time, varietal characteristics remained a determining factor in the formation of sowing density: the Gallek and Kobza varieties consistently formed a higher density regardless of the treatment option. The value of $LSD_{0.5}$ confirms the statistical significance of the differences between the variants. The results obtained indicate that the combination of biological preparations with growth regulators is an effective element of soybean cultivation technology, which contributes to the preservation of plants and creates the conditions for high yields under various soil and climatic conditions. For a comprehensive assessment of the impact of technological methods on the formation of plant production potential, it is also important to analyse symbiotic activity, the results of which are presented in Table 6.

Table 6. Symbiotic efficiency of soybeans depending on technological methods in the experimental field of the Department of Plant Growing of Uman National University (average for 2023-2025)

Variety	Seed treatment	Retardant concentration, %	Tuber weight, g/plant	Active symbiotic potential, thousand kg-days/ha	Biological nitrogen fixation weight, g/plant	Biological nitrogen fixation weight, kg/ha	$LSD_{0.5}^*$
ES Mentor	Control	-	221	15.72	77.38	77.38	0.91
	Rizohumin-Plus	0.5	226	15.88	77.87	77.87	
	Rizohumin-Plus	0.75	232	16.46	79.06	79.06	
Gallek	Control	-	453	19.76	117.54	117.54	0.91
	Rizohumin-Plus	0.5	470	20.32	119.87	119.87	
	Rizohumin-Plus	0.75	489	22.34	124.56	124.56	
OAC Brook	Control	-	420	15.88	92.00	92.00	0.85
	Rizohumin-Plus	0.5	435	16.30	94.50	94.50	
	Rizohumin-Plus	0.75	450	16.80	97.00	97.00	
Sigalia	Control	-	410	15.72	91.00	91.00	0.84
	Rizohumin-Plus	0.5	425	16.20	93.50	93.50	
	Rizohumin-Plus	0.75	440	16.65	96.00	96.00	
Kobza	Control	-	430	15.97	92.50	92.50	0.85
	Rizohumin-Plus	0.5	445	16.40	95.00	95.00	
	Rizohumin-Plus	0.75	460	16.90	97.50	97.50	

Source: developed by the authors

Data analysis showed that the use of "Rizohumin-Plus" in combination with foliar application of the retardant contributed to an increase in nodule mass, active symbiotic potential, and biological nitrogen fixation in all studied varieties. The highest indicators for all parameters were observed at a retarder concentration of 0.75%, which indicates the stimulating effect of the technological technique on the symbiotic activity of soybeans. Among the varieties, Gallek showed the highest symbiotic efficiency, while the lowest indicators of active symbiotic potential were observed in the Sigalia variety. The calculated $LSD_{0.5}$ for the treatments demonstrates the reliability of the differences between

the variants and confirms the effectiveness of the technological measures used in increasing plant productivity and adaptability. In general, the results of three years of research have shown a significant influence of the combination of varietal characteristics, weather conditions and technological methods on the formation of productivity and quality indicators of soybean seeds in the conditions of the Right-Bank Forest-Steppe of Ukraine. It was established that the most productive and stable varieties were ES Mentor and Kobza, while the highest symbiotic activity was demonstrated by the Gallek variety, especially when inoculated and treated with a 0.75% concentration of retardant. The data

obtained indicate the feasibility of using integrated technological approaches that include inoculation, nutrition optimisation, and selection of varieties with high adaptive potential, which ensures stable yields even in contrasting agroclimatic conditions. The presented results can serve as a scientific basis for improving soybean cultivation technologies and formulating recommendations for production practice.

The results obtained indicate the significant role of varietal characteristics and technological techniques in the formation of soybean symbiotic efficiency, which is consistent with modern ideas about biological nitrogen fixation as a complex physiological and biochemical process. Similar patterns regarding the significant role of varietal characteristics in the formation of the symbiotic apparatus of soybeans are noted in the work of A. Korobka (2021), where it was found that modern varieties differ significantly in their response to elements of cultivation technology in organic systems. The authors emphasise that the genetically determined ability to symbiosis determines the efficiency of biological nitrogen use, which is confirmed by the results of current research, where the highest values of active symbiotic potential were recorded in the Gallek and OAC Brook varieties.

The results of studies by O. Grygor'eva *et al.* (2019) and K. Cartier (2025), conducted under irrigation conditions, also indicate a close relationship between varietal characteristics and plant response to technological techniques. The authors found that intensification of technology promotes the growth of root system biomass and nodule activity, which correlates with the observed increase in nodule mass and biologically fixed nitrogen following seed inoculation. O. Milenko *et al.* (2021), O. Revtio & O. Zolin (2023) note that the adaptive potential of modern soybean varieties is determined not only by the level of yield, but also by the efficiency of physiological processes, in particular nitrogen fixation. Their studies showed that varieties with higher ecological plasticity demonstrate more stable performance under variable growing conditions. A similar trend was observed in current study, where varieties with a higher nodule mass provided higher symbiotic potential values regardless of the treatment option.

Data from L. Bilavska & A. Rybalchenko (2020), A. Parfenuk *et al.* (2021) and B. Siamabele (2021) confirm that the variability of economically valuable traits in soybeans is largely determined by growing conditions and the biological characteristics of the variety. Although the study focused primarily on productivity, the authors note that effective nitrogen nutrition is one of the key factors in yield formation, which is consistent with the observed increase in biologically fixed nitrogen mass. The work of Y.M. Hadzalo *et al.* (2023) emphasises the importance of optimising mineral nutrition and biological factors to increase soybean productivity. The authors point out that the combination of biological and agronomic measures contributes to a

more complete utilisation of the symbiotic potential of the crop. The present findings complement these findings, demonstrating that seed inoculation can effectively enhance symbiotic activity even without excessive application of mineral fertilisers. In general, the results of the studies are consistent with current scientific data and, at the same time, refine them, showing the variety-specific nature of soybean response to technological techniques. The differences identified between varieties indicate the need for a differentiated approach to the development of cultivation technology, taking into account their biological characteristics and symbiotic nitrogen fixation potential.

CONCLUSIONS

According to the results of three-year studies (2023-2025) conducted in the Right-Bank Forest-Steppe zone of Ukraine, a significant influence of hydrothermal conditions during the growing season on the growth, development, productivity and quality of soybean seeds has been established. The contrasting weather conditions during the years of research, in particular the lack of rainfall and higher temperatures in 2024 and more favourable moisture conditions in 2023 and 2025, made it possible to objectively assess the adaptive potential of the varieties studied. Among the five soybean varieties (Gallek, ES Mentor, OAC Brook, Sigalia, Kobza), ES Mentor (3.30 t/ha) and Kobza (3.16 t/ha) provided the highest average yield for 2023-2025, which indicates their high ecological plasticity and ability to form a stable yield under changing weather conditions. The OAC Brook variety (3.09 t/ha) had slightly lower but more consistent yield indicators. The lowest average productivity over the three-year period was recorded for the Gallek (2.66 t/ha) and Sigalia (2.64 t/ha) varieties, indicating their higher sensitivity to drought and temperature stress conditions.

The fractional composition of seeds significantly depended on both varietal characteristics and weather conditions of the year. The largest share of the large fraction (>5.0 mm) according to the average indicators for 2023-2025 was formed by the varieties Gallek, ES Mentor and OAC Brook, while the variety Sigalia consistently showed an increased share of the small fraction, especially in conditions of moisture deficiency in 2024. The ES Mentor and Kobza varieties were distinguished by the highest stability of fraction composition regardless of the year of cultivation. The weight of 1,000 seeds and protein content were characterised by moderate varietal variability and relative stability over the years of research. The highest weight of 1,000 seeds was formed by the Gallek variety, while the Sigalia variety had the lowest values of this indicator, which is consistent with the high proportion of small seeds. The protein content in soybean seeds ranged from 32.0 to 34.2%, without sharp interannual changes, which indicates the genetically determined stability of this

indicator. A tendency towards an inverse relationship between seed weight and protein content was established.

A comprehensive assessment of the chemical composition of seeds using near-infrared spectroscopy (NIR) showed that the Gallek and ES Mentor varieties combined high protein content, optimal amino acid composition and sufficient fat content in the seeds, which determines their high nutritional and technological value. The ES Mentor and Kobza varieties were also characterised by stable indicators of active symbiotic potential. The use of the biological preparation Rizohumin-Plus in combination with the growth regulator chlormequat chloride at concentrations of 0.5 and 0.75% contributed to an increase in plant density, symbiotic activity and crop preservation in all studied varieties. The most pronounced positive effect was observed in the varieties Gallek, ES Mentor and Kobza, which creates the

conditions for increasing their production potential. In general, the results of three years of research confirm the feasibility of growing the ES Mentor and Kobza varieties as the most productive and stable in the conditions of the Right-Bank Forest-Steppe of Ukraine, while the OAC Brook variety can be recommended as plastic with balanced seed quality indicators.

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CONFLICT OF INTEREST

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Формування якості насіння сої залежно від захисту рослин у лісостепу України

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Анотація. Метою дослідження було встановлення закономірностей формування продуктивності та якості насіння сої залежно від погодних умов і сортових особливостей у Правобережному Лісостепу України. Польові дослідження проводили упродовж 2023–2025 рр. на дослідних ділянках Уманського району Черкаської області. Об'єктом досліджень були п'ять сортів сої різного генетичного походження та морфобіологічних особливостей: Галлек, ЕС Ментор, ОАЦ Брук, Сигалія та Кобза. Ґрунтово-кліматичні умови років досліджень суттєво відрізнялися за температурним режимом і вологозабезпеченням, що дало змогу оцінити адаптивний потенціал сортів за контрастних гідротермічних умов. Методично дослідження базувалися на польовому експерименті з обліком основних елементів структури врожаю, маси 1 000 насінин, фракційного складу насіння та показників якості. Вміст білка й олії в насінні визначали методом інфрачервоної спектроскопії, а вологість – за стандартною лабораторною методикою. Динаміку формування надземної біомаси аналізували з використанням суми ефективних температур та логістичної моделі росту. Встановлено, що у 2024 році за умов дефіциту вологи та підвищених температур темпи наростання біомаси, маса 1 000 насінин і врожайність знижувалися на 8-25 % порівняно з 2023 та 2025 роками. За середніми трирічними даними найвищу та найстабільнішу врожайність сформували сорти ЕС Ментор і Кобза, тоді як сорти Галлек і Сигалія виявилися більш чутливими до стресових умов. Якісні показники насіння мали переважно сортову детермінацію: сорт Галлек вирізнявся найбільшою масою 1 000 насінин і високою часткою крупної фракції, тоді як вміст білка та олії залишався відносно стабільним упродовж років досліджень. Практична цінність роботи полягає в обґрунтуванні доцільності добору сортів сої з високою екологічною пластичністю та стабільною якістю насіння для умов Правобережного Лісостепу України в умовах зростаючої кліматичної мінливості

Ключові слова: продуктивність сої; сортові особливості; якість насіння; цукристість; економічна ефективність; інокуляція; технологія вирощування