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Assessing the yield potential of soybean maturity groups in different Ukrainian climatic zoness

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Abstract. In the context of global climate change, increasing demands for food security, and the need to expand sources of plant-based protein, soybean is gaining particular importance as a highly productive and valuable agricultural crop. Purpose. The study aimed to evaluate the yield potential of soybean cultivars from different maturity groups under various agro-climatic conditions of Ukraine by analysing their adaptability, productivity, and stability. The objective was to justify the selection of maturity groups best suited for specific regions to ensure sustainable soybean production. Methods. Field experiments were conducted in 2023–2024 across three agro-climatic zones: Odesa (Steppe), Cherkasy (Forest-Steppe), and Zhytomyr (Polissia). A total of 26 early- and mid-maturing soybean cultivars of Ukrainian and foreign origin were evaluated. Adaptive variability was assessed using standard statistical methods. Results. Among early-maturing cultivars, Taverna, Eri, and Calgary showed superior individual productivity, surpassing the standard by 9–13% in seed weight per plant and reaching yields up to 3.15 t ha^{-1} in Polissia. These cultivars demonstrated high plasticity and stability across environments. Among mid-maturing cultivars, ES Visitor and ES Collector delivered consistently high yields across all zones, exceeding the standard by 0.09–0.26 t ha^{-1}. Alicia also showed high productivity in the Forest-Steppe and Polissia, making it suitable for regions with moderate moisture. The highest average yield for early-maturing cultivars was recorded in Polissia (2.50 t ha^{-1}), and for mid-maturing ones - in the Forest-Steppe (2.68 t ha^{-1}). Regardless of the zone, Taverna, Eri, Calgary, ES Visitor, and ES Collector demonstrated stable and high productivity. Conclusions. The findings provide a basis for optimising cultivar selection and soybean production technologies, tailored to regional climatic conditions and challenges posed by climate change.

Key words: adaptability, cultivar, grain weight, soybean, yield.

INTRODUCTION

Soybean holds a leading position among oilseed crops worldwide, accounting for up to 44% of global oilseed production and approximately 35% of the total cultivated area under annual and perennial oil crops (Glauben & Svanidze, 2023). Due to its high protein content, soybean is a primary source of plant-based protein for human nutrition, livestock feed, and the processing industry (Voora et al., 2024). Global soybean production is largely concentrated in the United States, Brazil, Argentina, and China, which together account for up to 90% of the total output. At the same time, the growing demand for soybean in the feed and vegetable oil sectors opens up opportunities for further expansion of its cultivation.

The importance of soybean is increasing in the context of climate change, as the crop is highly sensitive to photoperiod and temperature regimes (Li et al., 2020; Abdala et al., 2025). High-temperature stress and droughts, particularly during the flowering (BBCH 60-69) and pod-filling (BBCH 70-79) stages, are increasingly causing significant yield reductions, as confirmed by studies conducted in the Forest-Steppe and Steppe zones of Ukraine (Liu et al., 2019; Biliavska et al., 2021).

Despite the high genetic potential of modern soybean varieties, only 50–60% of this potential is realised under production conditions (Shook et al., 2021). This is largely due to the use of standard cultivation technologies that often fail to account for varietal characteristics and regional environmental conditions. Addressing this issue requires the implementation of region-specific agronomic practices, scientifically justified crop rotation strategies, and the adaptation of technologies to evolving climate conditions (Tkachuk et al., 2022; Zabarna & Chereshniuk, 2024).

In Ukraine, interest in soybean cultivation is growing, as evidenced by an increase in the number of registered varieties from 125 to 279 over the past decade (Rybalchenko, 2022). However, the effective utilisation of this genetic resource requires a deeper understanding of varietal adaptability to local environmental conditions.

The need for this research stems from the necessity to develop scientifically grounded recommendations for the selection of suitable soybean varieties tailored to specific agro-climatic zones of Ukraine, aiming to enhance production efficiency, yield stability, and food security.

The scientific novelty of the study lies in the assessment of the yield potential of soybean varieties from different maturity groups under various soil and climatic conditions in Ukraine, considering their adaptability, ecological plasticity, and resistance to abiotic stress factors. The use of ecological data in analysing variety trials allows for a more accurate interpretation of genotype-environment interactions and enhances the ability to predict varietal performance under changing environmental conditions.

The aim of the research was to determine the yield potential of soybean cultivars of different maturity groups under the agro-climatic conditions of Ukraine by analysing their adaptability, productivity, and stability, with a subsequent justification for the feasibility of cultivating specific maturity groups in particular natural and climatic regions to ensure sustainable soybean production.

MATERIALS AND METHODS

To realise the yield potential of the cultivar, it is necessary to optimally interact with abiotic environmental factors (temperature, humidity, photoperiod), the dynamics of which during the growing season is complex and unpredictable. Humans have no direct control over these factors, and the possibility of partial regulation (in particular, through irrigation, mulching, covering, etc.) is accompanied by an increase in material costs. In this regard, an urgent task is to select and introduce adaptive, stress-resistant soybean cultivars capable of creating high efficiency of cultivation technology in different agroclimatic zones of Ukraine.

The study was conducted in three climatic zones of Ukraine - Steppe (Odesa region), Forest-Steppe (Cherkasy region) and Polissya (Zhytomyr region). The weather conditions during the study period differed significantly both by year and by climate zone. The distribution of precipitation was uneven throughout the study period (Table 1).

Table 1. Climatic conditions of the growing season of soybean plants (according to weather stations in Odesa, Uman and Zhytomyr)

Month	Steppe (Odesa)		Forest-steppe (Uman)		Polissya (Zhytomyr)	
	2023	2024	2023	2024	2023	2024
Precipitation, mm						
April	116.0	70.0	129.6	56.2	84	39.0
May	7.0	35.0	42.4	4.8	0.1	73.0
June	32.0	77.0	15.8	56.5	59.6	81.0
July	48.0	18.0	92.5	17.9	67.8	65.0
August	15.0	20.0	12.0	17.7	22.0	28.0
Σ	218.0	220.0	292.3	153.1	233.5	286.0
Air temperature, °C						
April	10.3	15.1	8.8	13.0	8.7	7.5
May	16.4	16.2	15.4	15.3	15.1	14.3
June	21.0	24.0	19.6	21.2	18.9	20.3
July	24.0	25.6	21.3	24.3	20.8	20.1
August	25.0	26.7	22.9	23.1	22.8	21.0
$\bar{X}$, t °C	19.3	21.5	17.6	19.4	17.3	16.6

Thus, although there was sufficient precipitation at the time of soybean sowing, the amount became inadequate after emergence and during the period of intensive growth in May. Rising temperatures further reduced productive moisture reserves, a trend that persisted across all zones until the end of the growing season, except in Polissya in 2024, where precipitation was relatively evenly distributed, ultimately impacting yield formation.

Soil conditions: Steppe - the soil of the experimental field is a low-humus heavy loamy chernozem with an average humus content of up to 2%. The thickness of the humus layer is 65–67 cm, and the humus horizon itself is 35–38 cm. The terrain of the area is predominantly flat with a gentle slope toward the Southwest.

In the Forest-Steppe zone, the soils are podzolized, low-humus, heavy loamy chernozems formed on carbonate loess, with a humus content of up to 2%, deep carbonates (115–120 cm), and a slightly acidic soil reaction.

Table 2. Origin of the studied soybean varieties

Ripeness group	Ripeness group	Cultivar	Originator	Yield, t ha^{-1}
Early maturing	Ukraine	Rhapsody st	Institute of Oilseeds of the National Academy of Agrarian Sciences of Ukraine	1.5–3.0
		Pallada	Institute of Feed and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine	1.5–3.5
		Perepilochka	National Scientific Center 'Institute of Agriculture of the NAAS of Ukraine'	1.6–2.5
		Taverna	Breeding and Genetic Institute - National Center for Seed Science and Variety Research	2.5–4.0
		Fortress	V.Ya. Yuryev Institute of Plant Growing of the National Academy of Agrarian Sciences of Ukraine	2.0–3.0
	Austria	Adelphia	SAATBAU PROBSTDORFER	3.8–5.2
		Adessa	SAATBAU PROBSTDORFER	1.5–3.5
	France	ES DECOR	Euralis Semences	1.8–3.0
		RGT SAKUZA	RAGT	1.6–3.4
	Canada	Eri	Semences Prograin INC.	1.8–3.2
		Calgary	Cerela Inc.	2.0–3.7
		Nunavik	Cerela Inc.	2.0–3.5
Mid-season	Ukraine	Titan st	Breeding and Genetic Institute - National Center for Seed Science and Variety Research, Institute of Feed and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine	2.0–3.3
		Ingus	LLC 'Institute of Organic Agriculture'	1.5–3.2
		Turizas	LLC 'Institute of Organic Agriculture'	1.5–2.5
	Austria	Acardia	Probstdorfer Zaatzucht Gez.m.b.H. and CoKG	2.0–3.5
		Alicia	SAATBAU PROBSTDORFER	4.0–4.5
	Canada	Dara	North American Plant Genetics	2.0–2.8
		Tersia	Semences Prograin INC.	2.5–3.3
		Neptune	Sevita Genetics	1.8–2.6
	France	ES VISITOR	Euralis Semences	2.0–3.5
		ES COLLECTOR	Euralis Semences	2.0–3.4
		ES COMPOSER	Euralis Semences	2.0–3.2
	Poland	Vitalina	Private enterprise 'Scientific breeding' and seed company 'Soybean Age'	2.0–2.5
		Zeus	Private enterprise 'Scientific breeding' and seed company 'Soybean Age'	2.0–2.5
		Carmelita	Monich Ruslan Vasylovych	2.0–3.2

In the Polissya region, the soils are sod-podzolized with a well-developed humus horizon, a humus content of up to 8%, and a neutral pH environment.

Sowing dates: Steppe – April 15–20; Forest-Steppe – April 28–May 5; Polissya - May 10–15. The sowing density was 450 thousand germinating seeds in all growing areas. The cultivation technology was typical and generally accepted for each zone.

In the experiment, new cultivars of cultivated soybeans of early maturing and mid-season groups recommended for the Steppe, Forest-Steppe and Polissya of Ukraine (Table 2).

The standard are the Rhapsody and Titan cultivars, which are the most tested in Ukraine (Methodology for testing cereal, groat, and legume crops for suitability to distribution in Ukraine, 2016). The area of the plot is 250 m^2, repeated four times. During the biometric measurements and formation of crop structure indicators, the generally accepted methods DSTU 4138-2002 (2004) and DSTU 4234:2003 (2004) were used; Methodical requirements in the field of seed production regarding the preservation of varietal and sowing qualities of soybean seeds (2023).

Proteins, oil content were determined by using standard methods described in the procedures of the American Organization of Analytical Chemists (International Organization of International, AOAC International) (Horwitz & Latimer, 2023). The crude oil (fat) was determined using a Soxhlet apparatus (Behr R 106 S, Germany) with petroleum ether, according to the AOAC 920.85 methodology (Horwitz & Latimer, 2023; Yatsenko et al., 2023).

Statistical processing of the results. A large number of methods are used to assess adaptability. Most of them are based on the method of regression analysis, the mathematical model of which for determining the stability and plasticity of cultivars was calculated according to Eberhart and Russell, and is also based on the principles of combining and transforming the effects of the environment and the interaction of the genotype with growing conditions.

$$bi = \Sigma\,(Xij \times Ij\,)\,/\,\Sigma\,Ij \qquad (1)$$

bi – the regression coefficient of the trait for the i-th cultivar under improving or deteriorating environmental conditions; Xij – the value of the trait for the i-th cultivar under the j-th set of conditions; Ij – the index of the j-th conditions, defined as the difference between the mean value of the trait for all cultivars under those conditions and the overall mean value of the trait across all trials.

The coefficient of linear regression of yield of a cultivar shows its reaction to changes in growing conditions. The higher the value of the coefficient ($bi > 1$), the better the response of the cultivar. In the case of $bi < 1$, the cultivar reacts weakly to changes in environmental conditions. Under the condition that $bi = 1$, there is a complete correspondence of the change in the yield of the cultivar in accordance with the change in growing conditions. The lower the stability coefficient, the more stable the cultivar (Eberhart & Russell, 1966).

The general homeostaticity of cultivars (H_{om}) was calculated according to the formula (Khangildin, 1984).

$$H_{om} = \frac{\overline{X^2}}{\sigma}, \qquad (2)$$

where $\overline{x}$ – arithmetic average by grade; σ – generalized root mean square deviation.

Breeding value of the cultivar:

$$(S_c) = \overline{X} \times \frac{\bar{X}_{lim}}{\bar{X}_{opt}}, \quad (3)$$

where $\overline{X}$ – arithmetic average by grade; $\bar{X}_{lim}$ – limited arithmetic mean; $\bar{X}_{opt}$ – optimal arithmetic mean.

Coefficient of multiplicity (CM). To avoid the linear artifact of the regression coefficient, - the coefficient of multiplicity, which allows comparing the variability of the trait. The higher the numerical value of this coefficient, the stronger the sign changes (Dragavtsev, 1984):

$$CM = \frac{\overline{X}i + bi \cdot yi}{Xi}, \quad (4)$$

where $\overline{X}i$ – average value of the studied characteristic in the *i* cultivar; *bi* – linear regression coefficient of *i* cultivar; *yi* –average value for all averages for all grades *yi* for each *j* point of the experiment.

The average index of ecological plasticity is calculated

$$IEP = \frac{\left(\frac{YC_1}{AYC_1} + \frac{YC_2}{AYC_2} + \dots + \frac{YC_n}{AYC_n}\right)}{n}, \quad (5)$$

where YC_1, YC_2, YC_n value of trait (yield) in the cultivar in different years of trials; AYC_1, AYC_2, AYC_n – average value of quality of the cultivars in each of variants of the experiment (Gryaznov, 2019).

The annual adaptability coefficient (CA). To determine the adaptive capacity, the coefficient of adaptability of the cultivar (CA) was used.

The absolute average coefficient of adaptability (CAA) is calculated for the cultivar according to the formula (Zhivotkov et al., 1994):

$$CAA = \frac{(XiA) \times 100 \times Xm)}{100}, \quad (6)$$

where XiA – average yield of the cultivar over years of testing; Xm – multi-year average cultivar yield.

Stress resistance and compensatory ability of cultivars were determined by Rossielle & Hemblin (1981):

$$SR = Y_{min} - Y_{max}, \quad (7)$$

$$CA = \frac{Y_{min} + Y_{max}}{2}, \quad (8)$$

where Y_{min} and Y_{max} – minimum and maximum value of the cultivar characteristic.

The coefficient of variation is a relative value used to characterize the dispersion (variability) of a feature. It is the ratio of SD mean square deviation to the arithmetic mean, expressed as a percentage:

$$CV = \frac{SD}{\bar{X}}, \quad (9)$$

Coefficient of variation on the following ratio scale:

CV < 10% – variation is weak; CV 11–25% – variation is average; CV > 25% – variation is significant.

In the experiments, phenotypic, genotypic and ecological variability of cultivars was determined according to the following formulas (Burton et al., 1953; Shing, et al., 1993):

Genetic variance:

$$\sigma_G^2 = \frac{CM_p - CM_e}{r}, \quad (10)$$

Environmental variance:

$$\sigma_A^2 = CM_e, \quad (11)$$

Phenotypic variance:

$$\sigma_F^2 = \sigma_G^2 + \sigma_A^2, \quad (12)$$

Coefficient of genotypic variation (CVG):

$$\frac{\sqrt{\sigma_G^2}}{\bar{X}} \times 100, \quad (13)$$

Coefficient of phenotypic variation (CVP):

$$\frac{\sqrt{\sigma_P^2}}{\bar{X}} \times 100, \quad (14)$$

Coefficient of ecological variation (CVE):

$$\frac{\sqrt{\sigma_E^2}}{\bar{X}} \times 100, \quad (15)$$

where CM_p – generalized root mean square value of the population trait; CM_e – generalized root mean square error, r – number of repetitions.

The results were statistically processed using the arithmetic mean (x) and standard deviation (SD) calculated using Microsoft Excel 2019. Correlations were calculated using Statistica 12 software. The Chaddock scale was used to qualitatively assess the correlation coefficients.

RESULTS

Experimental studies have shown that in terms of plant height, cultivars of the early-ripening group had an average variation (12%), and mid-ripening cultivars had a weak variation (9%). However, the difference in absolute values between the maturity groups was significant. Among the studied cultivars of the early ripening group, only the Pallada cultivar was found to be significantly taller than the standard (by 13 cm) and the Calgary cultivar (+4 cm to st), while all other cultivars were haracterized by a lower plant height of 2–19 cm. The absolute number of cultivars belongs to the medium-sized group, except for the Pallada cultivar, which is tall (Table 3).

Plant height. Mid-maturing cultivars had a higher average plant height (82 cm) compared to early-maturing ones (77 cm). This difference, supported by lower variability (CV = 9% vs. 12%), indicates greater morphological stability within the mid-maturing group. The tallest plants were observed in Pallada (97 cm), Neptune, Zeus, and Vitalina (93–94 cm), suggesting a genetic advantage in vegetative growth for these cultivars.

Total number of nodes. The number of nodes, which reflects morphophysiological activity, averaged 16 in mid-maturing cultivars and only 13 in early-maturing ones. This result is attributed to the longer vegetative period of mid-maturing genotypes and indicates greater generative organ biomass. The highest node count (18) was recorded in Neptune, Vitalina, and Zeus.

Table 3. Individual productivity of soybean cultivars of different maturity groups, pcs/plant. (BBCH 99), 2023–2024

Cultivar	Height of plants, cm	Total number of nodes, pcs/plant	Height of attachment of lower bean, cm	Number of pods, pcs/plant	Number of grains, pcs/plant
Early ripening					
Rhapsody st	84	14	12	42	44
Pallada	97	17	14	38	40
Perepilochka	69	12	10	29	26
Taverna	65	11	10	53	54
Fortress	69	12	10	33	30
Adelphia	76	13	11	39	36
Adessa	65	11	10	39	35
ES DÉCOR	75	13	11	40	36
RGT SAKUZA	78	14	12	39	36
Eri	79	14	12	49	67
Calgary	87	15	13	46	63
Nunavik	82	14	12	36	39
$\bar{X}$	77	13	12	40	42
SD	9.05	1.6	1.38	6.43	12.17
CV, %	12	12	12	16	29
Mid ripening					
Titan st	71	14	10	42	57
Ingus	76	15	10	33	30
Turizas	79	15	11	33	30
Acardia	74	14	10	38	47
Alicia	86	16	12	46	53
Dara	75	15	10	34	31
Tersia	78	15	11	38	39
Neptune	94	18	13	35	32
ES VISITOR	82	16	11	47	64
ES COLLECTOR	82	16	11	47	64
ES COMPOSER	79	16	11	36	33
Vitalina	93	18	13	32	29
Zeus	94	18	13	35	32
Carmelita	80	16	11	43	47
$\bar{X}$	82	16	11	38	42
SD	7.28	1.3	1	5.24	12.75
CV, %	9	8	9	14	30

Height of the first pod attachment. This trait is critical for efficient mechanised harvesting. Both maturity groups showed average first pod attachment at 11–12 cm; however, Pallada, Neptune, Vitalina, and Zeus had the highest values (13–14 cm), confirming their technological advantage in terms of harvestability.

Number of pods per plant. Early-maturing cultivars showed a broader range of pod numbers - 29 to 53 (CV = 16%), compared to 32 to 47 in mid-maturing cultivars (CV = 14%). Taverna had the highest pod count (53), while ES VISITOR and ES COLLECTOR led the mid-maturing group with 47 pods each. These results demonstrate strong genetic potential for forming numerous generative structures.

Number of seeds per plant. This productivity-defining trait was highest in early-maturing cultivars Eri (147), Calgary (139), and Taverna (120), significantly exceeding the group average (93 seeds). Similarly, mid-maturing ES VISITOR (141) and ES COLLECTOR (140) demonstrated high reproductive potential. In contrast, Perepilochka, Ingus, Turizas, and Vitalina produced the fewest seeds (57–66), far below average, indicating the need for further assessment before widespread adoption.

The analysis confirms that Taverna, Eri, and Calgary are the most productive early-maturing cultivars, combining high pod and seed numbers with favourable pod attachment height. These characteristics suggest strong adaptability, making them well-suited to areas with shorter growing seasons, such as Polissia and the northern Forest-Steppe.

In the mid-maturing group, ES VISITOR, ES COLLECTOR, and Alicia were the most productive, offering high generative output and compatibility with mechanised harvesting. These cultivars are recommended for the Forest-Steppe and northern Steppe zones, where moisture levels are sufficient to support their yield potential.

Cultivars with low pod and seed numbers (Perepilochka, Ingus, Turizas, Vitalina) may still possess breeding value for traits such as stability or specific morphotypes but require further evaluation.

In conclusion, the individual productivity potential of soybean is determined by both genetic factors and the cultivar’s adaptive response to environmental conditions. The integration of these factors is essential for optimising cultivar selection strategies under the pressures of climate change.

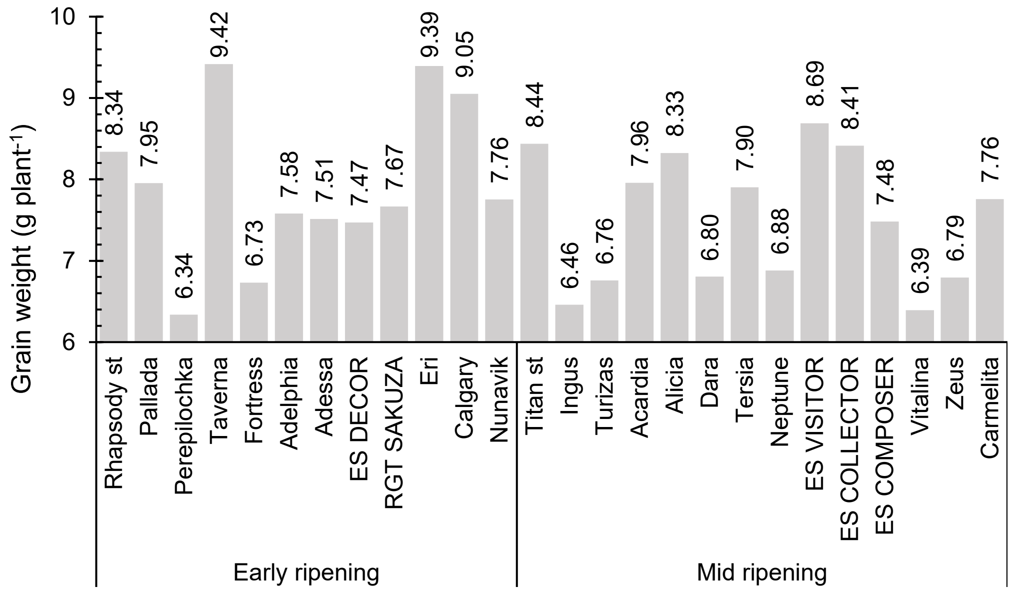
Among the early-maturing cultivars, the average seed weight per plant ranged from 6.34 to 9.42 g, with the lowest value recorded for Perepilochka, and the highest for Taverna (9.42 g), Eri (9.39 g), and Calgary (9.05 g). The overall trend indicates a relatively high level of variability in productivity within this group, which is likely attributed both to genetic differences among the cultivars and to their heightened sensitivity to fluctuations in agro-climatic conditions.

In the group of mid-maturing cultivars, the seed weight per plant varied from 6.39 to 8.69 g, with the lowest productivity observed in Vitalina, Ingus, Turizas, and Zeus, while the highest values were recorded for ES VISITOR (8.69 g), Titan st (8.44 g), ES COLLECTOR (8.41 g), and Alicia (8.33 g). Compared to the early-maturing group, this subgroup showed a narrower amplitude of variation, indicating a relatively higher level of trait stability and genetic uniformity.

Based on the distribution of seed weight per plant, three conditional categories were identified:

- Highly productive cultivars (> 8.3 g): Taverna, Eri, Calgary, ES VISITOR, ES COLLECTOR, Alicia, Titan st, and Rhapsody.
- Moderately productive cultivars (7.4–8.3 g): Pallada, Carmelita, Acardia, Tersia, RGT SAKUZA, Nunavik, Adelphia, Adessa, and ES COMPOSER.
- Low-productive cultivars (< 7.4 g): Fortress, Perepilochka, Vitalina, Ingus, Turizas, Zeus, Dara, and Neptune.

It is evident that the leading cultivars across both maturity groups include foreign selections (ES VISITOR, ES COLLECTOR, Alicia), as well as several Ukrainian or adapted cultivars (Taverna, Eri, Calgary) that consistently demonstrate high individual productivity under diverse agroecological conditions (see Fig. 1).



	$\bar{X}$	SD	CV, %	LSD_{05}
Early ripening	7.9	0.93	12	0.67
Mid ripening	7.5	0.78	10	0.4

Figure 1. Seed weight per plant of soybean cultivars of different maturity groups.

Only one foreign selection cultivar of the mid-ripening group was found, characterised by a slightly higher grain weight per plant – 'ES VISITOR' -8.7 g (+0.26 g or 3%). All other studied cultivars had lower productivity by 1–24%. The variation of this indicator was average (12%) in the early maturing group and weak (10%) in the mid-ripening group of cultivars.

Thousand Seed Weight. Early-maturing cultivars exhibited a significantly narrower range of thousand seed weight - from 139 to 158 g. The lowest values were recorded for Taverna (139 g), Eri (140 g), and Calgary (142 g), whereas the highest values were observed in Perepilochka and Adessa (both 158 g). It is worth noting that the seed weight within this maturity group generally corresponds to the medium- and large-seeded types, which is suitable for mechanised harvesting and ensures high seed vigour.

Mid-maturing cultivars were considerably heavier in terms of thousand seed weight - ranging from 151 to 195 g, which indicates a higher biomass potential and improved realisation of the generative function due to a longer vegetation period. Vitalina and Ingus reached the highest value of 195 g, exceeding the corresponding figures in the early-maturing group by 23–56 g.

Seed Bulk Density. The seed bulk density (test weight) reflects not only the thousand seed weight but also the internal structure and compactness of the seed.

In early-maturing cultivars, seed bulk density ranged from 557 to 633 g L^{-1}. The lowest values were found in Taverna (557 g L^{-1}), Eri (560 g L^{-1}), and Calgary (569 g L^{-1}), which correlates with their lower thousand seed weight. The highest values were recorded for Adessa (633 g L^{-1}) and Perepilochka (631 g L^{-1}).

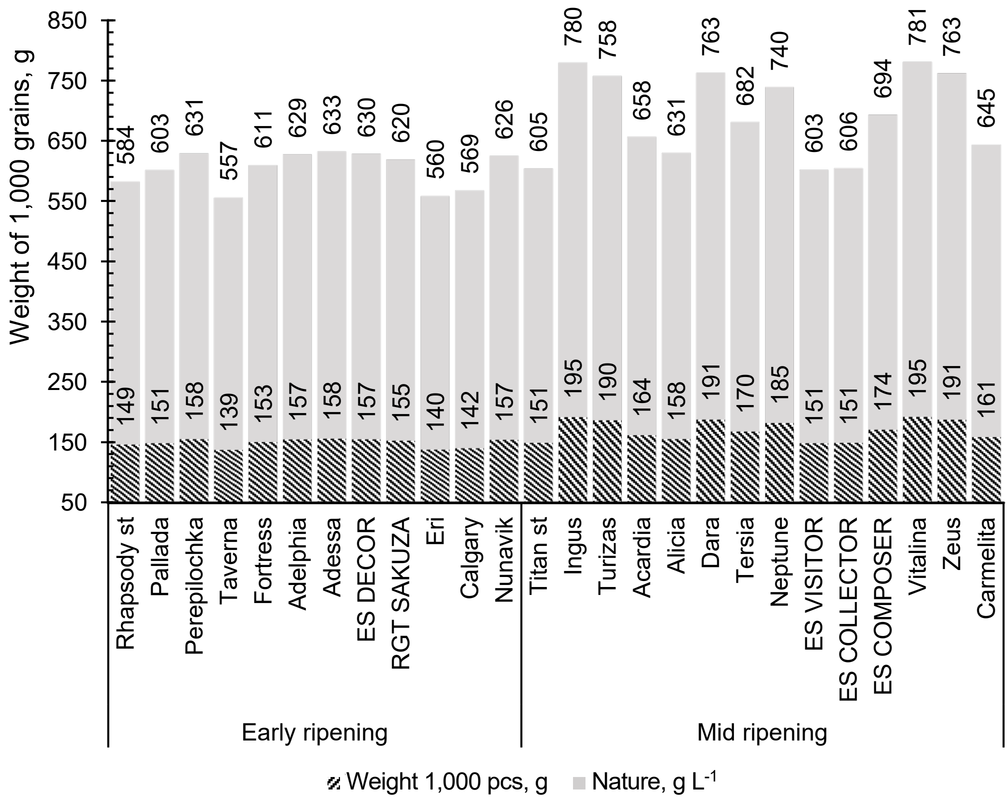
In mid-maturing cultivars, higher bulk density values were observed - ranging from 603 to 781 g L^{-1} indicating denser and more fully developed seeds. The absolute leaders in this trait were Vitalina (781 g L^{-1}), Ingus (780 g L^{-1}), Zeus, and Dara (763 g L^{-1}), reflecting the high commercial quality of their seeds, which is of considerable importance for seed production and food processing.

The mid-maturing group clearly outperformed the early-maturing one in both thousand seed weight and seed bulk density. This advantage is attributable to a longer vegetation period, more efficient utilisation of photosynthetic potential, and greater accumulation of assimilates. Despite lower values, early-maturing cultivars demonstrated greater uniformity and technological stability, making them well-suited for areas with a shorter growing season.

The analysis revealed that the highest values of thousand seed weight and bulk density were produced by mid-maturing cultivars such as Vitalina, Ingus, Dara, Zeus, and Turizas. Due to their large seed size and high density, they can be recommended as benchmark genotypes for seed production and export. Cultivars ES COMPOSER and Tersia also showed high performance in these traits, effectively combining yield potential with seed quality.

Among the early-maturing cultivars, Adessa, Perepilochka, ES DECOR, and Nunavik deserve special attention, as they delivered relatively high thousand seed weight values (157–158 g) and bulk density above 626 g L^{-1}, making them valuable sources of technological traits for regions with a shorter warm season.

In conclusion, thousand seed weight and seed bulk density should be regarded not only as indicators of seed quality but also as markers of a cultivar's adaptive strategy, influencing its efficiency across different climatic zones. The combination of large seed size and high bulk density is of particular importance for improving varietal composition in terms of productivity, stability, and commercial seed quality (Fig. 2).



		$\bar{X}$	SD	CV, %	*LSD*$_{05}$
Early ripening	Weight 1,000 pcs	151	6.89	5	9.06
	Nature	604	28.05	5	36.24
Mid ripening	Weight 1,000 pcs	173	16.70	10	10.38
	Nature	693	66.81	10	41.58

Figure 2. Weight of 1,000 grains (g) and natural content (g L^{-1}) of soybean cultivars of different maturity groups.

The data obtained showed that the highest yield of early ripe cultivars can be obtained in Polissya - 2.50 t ha^{-1}, which is 4% higher than in the Forest-Steppe (2.41 t ha^{-1}) and Steppe (1.69 t ha^{-1}) by 48% or 0.81 t ha^{-1}. To ensure high soybean yields, a ratio of coefficients of genetic (CVG) and environmental (CVE) variation close to one or greater than one is required. In our studies, the environmental variation was greater than the genetic variation in each climate zone, indicating a strong dependence of the crop on growing conditions. The results in Table 4 show that the greatest compliance of growing conditions with crop requirements was found in the Forest-Steppe - CVG/CVE = 0.89. In the Steppe, where crops had a better supply of the sum of positive and effective temperatures and a lower supply of moisture, CVG/CVE was 0.80. In Polissia, where moisture supply was sufficient, temperature conditions were less favourable, and yields were higher, CVG/CVE = 0.70, indicating that the biological potential of soybean cultivars in Polissia was not fully realised (Table 4).

Table 4. Yield of early-ripening cultivars of cultivated soybeans in different climatic zones of Ukraine

Cultivar	Steppe			Forest-steppe			Polissya		
	2023	2024	$\bar{X}$	2023	2024	$\bar{X}$	2023	2024	$\bar{X}$
Rhapsody st	1.78	1.38	1.58	2.77	1.98	2.38	3.03	3.20	3.12
Pallada	1.80	1.40	1.60	2.88	2.00	2.44	2.55	2.20	2.38
Perepilochka	1.74	1.24	1.49	1.90	1.31	1.61	2.12	1.62	1.87
Taverna	2.57	2.20	2.39	2.99	2.55	2.77	3.00	3.01	3.01
Fortress	1.98	1.46	1.72	2.29	1.55	1.92	1.85	1.70	1.78
Adelphia	1.66	1.33	1.50	2.95	2.10	2.53	2.28	2.40	2.34
Adessa	1.59	1.28	1.44	3.00	2.00	2.50	2.24	2.55	2.40
ES DECOR	1.67	1.35	1.51	2.77	2.00	2.39	2.35	2.64	2.50
RGT SAKUZA	1.71	1.38	1.55	2.91	2.06	2.49	2.35	2.40	2.38
Eri	2.40	1.79	2.10	3.14	2.51	2.83	3.00	2.92	2.96
Calgary	2.20	1.81	2.01	3.15	2.20	2.68	2.88	2.84	2.86
Nunavik	1.60	1.30	1.45	3.00	1.77	2.39	2.45	2.33	2.39
LSD_{05}	0.15	0.13	0.29	0.19	0.16	0.33	0.20	0.17	0.41
$\bar{X}$	1.89	1.49	1.69	2.81	2.00	2.41	2.51	2.48	2.50
SD	0.31	0.28	0.29	0.31	0.28	0.33	0.37	0.47	0.41
CV, %	17	19	17	12	17	14	15	19	16
CVG, %			17			20			12
CVE, %			21			22			17
CVP, %			27			29			21
CVG/CVE			0.80			0.89			0.70

The data analysis showed that regardless of the climatic zone of cultivation, high-yielding cultivars were Taverna (2.20–3.01 t ha^{-1} by zone), Eri (1.79–3.14 t ha^{-1}) and Calgary (1.81–3.15 t ha^{-1}).

Research has shown that the Perepilochka, Fortress and Nunavik cultivars were the least productive, with yields 12–30% lower than the standard. The cultivars Pallada, RGT SAKUZA, Adelphia, Adessa and ES DECOR were characterised by a yield lower than the standard by 9–10%, and the cultivars Taverna, Eri and Calgary were higher by 7–15%.

The genetic and statistical analysis of yields showed that the cultivars Perepilochka, Taverna, and Fortress were the most stable (σ^2 d = 0.53–0.56). The study found that the same cultivars had plasticity bi > 1 and stability σ^2d > 0, meaning they would be productive under favourable growing conditions. Other cultivars had bi < 1 and σ^2 d > 0, indicating their ability to produce better results under favourable conditions, but unstable yields.

The cultivars Rhapsody st, Pallada, Adelphia, Adessa, ES DECOR, RGT SAKUZA, Eri, Calgary, and Nunavik can be classified as intensive in terms of plasticity (bi), while the others are plastic. The cultivars differed significantly in homeostaticity from 2.31 to 6.25, which confirms the stability or vice versa - the plasticity of a particular cultivar. The cultivars Taverna and Eri were distinguished by high breeding value and compensatory ability. The Taverna, Eri, and Calgary cultivars were characterised by a higher coefficient of adaptability compared to the standard, where AAC was greater than 1 (Table 5).

Table 5. Generalised parameters of adaptive and productive potential of early-ripening cultivars of cultivated soybean in different climatic zones of Ukraine (2023–2024)

Cultivar	$\bar{X}$	σ^2d	bi	Hom	Sc	CM	IEP	SR	CA	AAC
Rhapsody st	2.36	0.82	1.39	4.69	2.16	2.29	1.06	-1.82	2.29	1.07
Pallada	2.14	0.70	1.06	3.86	1.96	2.09	0.97	-1.48	2.14	0.97
Perepilochka	1.66	0.56	0.52	2.31	1.52	1.69	0.76	-0.88	1.68	0.75
Taverna	2.72	0.55	0.66	6.25	2.49	1.53	1.26	-0.81	2.61	1.24
Fortress	1.81	0.53	0.44	2.75	1.66	1.54	0.84	-0.83	1.88	0.82
Adelphia	2.12	0.72	1.13	3.79	1.94	2.17	0.96	-1.62	2.14	0.96
Adessa	2.11	0.76	1.25	3.76	1.93	2.30	0.95	-1.72	2.14	0.96
ES DECOR	2.13	0.71	1.12	3.83	1.95	2.15	0.96	-1.42	2.06	0.97
RGT SAKUZA	2.14	0.70	1.09	3.85	1.96	2.13	0.97	-1.53	2.15	0.97
Eri	2.63	0.68	1.01	5.83	2.41	1.85	1.20	-1.35	2.47	1.19
Calgary	2.51	0.69	1.06	5.33	2.30	1.92	1.15	-1.34	2.48	1.14
Nunavik	2.36	0.76	1.27	3.64	1.90	2.35	0.93	-1.70	2.15	0.94
LSD_{05}	0.13									
$\bar{X}$	2.20									
SD	0.30									
CV, %	14									
CVG, %	25									
CVE, %	26									
CVP, %	36									
CVG/CVE	0.97									

Note: σ^2d – stability; bi – coefficient of linear regression; Hom – homeostaticity; Sc – breeding value; cm – coefficient of multiplicity; IEP – index of ecological plasticity; SR – stress resistance; CA – compensatory ability; AAC – absolute average coefficient of adaptability.

Table 6 shows that the CVG/CVE ratio is 0.97, which confirms that the environmental conditions of the Steppe, Forest-Steppe and Polissya fully meet the requirements of the crop for the formation of a stable and high yield.

The study of the yield dynamics of cultivated soybean cultivars in the Steppe showed that only the Alicia cultivar was equal to the standard – the Titan cultivar with a yield of 1.63 t ha^{-1}. Two cultivars were significantly higher yielding than the standard - ES VISITOR (1.89 t ha^{-1}) and ES COLLECTOR (1.83 t ha^{-1}), which are 0.26 and 0.21 t ha^{-1} higher, respectively. All other tested cultivars in the Steppe zone had yields below the standard by 0.06–0.33 t ha^{-1}.

In the Forest-Steppe, the general trend was the same as in the Steppe, but the difference between cultivars was more significant. For example, the cultivars Alicia, ES VISITOR and ES COLLECTOR had yields that were slightly higher than or equal to the standard -2.63–2.68 t ha^{-1}. All other tested cultivars produced significantly lower yields - by 0.26–0.73 t ha^{-1}.

In Polissya, the general trend was the same: the Alicia cultivar significantly outperformed the standard at 2.96 t ha^{-1} (+0.28 t ha^{-1}), while the ES VISITOR and ES COLLECTOR cultivars were slightly better at 0.12 and 0.09 t ha^{-1}. The cultivar Carmelita was characterised by a slightly lower yield - 2.62 t ha^{-1} (-0.06 t ha^{-1}) and all other studied cultivars - significantly - 0.16–0.63 t ha^{-1} (Table 6).

Table 6. Yield of mid-season cultivars of cultivated soybeans in different climatic zones of Ukraine

Cultivar	Steppe			Forest-steppe			Polissya		
	2023	2024	$\bar{X}$	2023	2024	$\bar{X}$	2023	2024	$\bar{X}$
Titan st	1.83	1.42	1.63	3.07	2.20	2.64	2.70	2.66	2.68
Ingus	1.52	1.30	1.41	2.30	1.55	1.93	2.00	2.10	2.05
Turizas	1.57	1.20	1.39	2.40	1.60	2.00	2.12	2.20	2.16
Acardia	1.50	1.20	1.35	3.02	2.10	2.56	2.65	2.40	2.53
Alicia	1.85	1.40	1.63	2.89	2.40	2.65	2.76	3.16	2.96
Dara	1.59	1.27	1.43	2.44	1.63	2.04	2.10	2.14	2.12
Tersia	1.72	1.33	1.53	2.86	1.89	2.38	2.54	2.40	2.47
Neptune	1.59	1.30	1.45	2.41	1.55	1.98	2.20	2.44	2.32
ES VISITOR	1.97	1.80	1.89	2.96	2.40	2.68	2.90	2.70	2.80
ES COLLECTOR	1.85	1.81	1.83	2.93	2.33	2.63	2.80	2.75	2.78
ES COMPOSER	1.70	1.31	1.51	2.84	1.80	2.32	2.20	2.30	2.25
Vitalina	1.50	1.10	1.30	2.26	1.55	1.91	2.00	2.20	2.10
Zeus	1.56	1.12	1.34	2.46	1.80	2.13	2.10	2.37	2.24
Carmelita	1.74	1.40	1.57	2.94	2.20	2.57	2.31	2.92	2.62
LSD_{05}	0.12	0.08	0.17	0.22	0.15	0.29	0.16	0.22	0.29
$\bar{X}$	1.68	1.37	1.53	2.70	1.92	2.31	2.41	2.45	2.43
SD	0.15	0.21	0.17	0.29	0.32	0.29	0.31	0.30	0.29
CV, %	9	15	11	11	17	13	13	12	12
CVG, %			14			19			9
CVE, %			16			22			13
CVP, %			21			29			16
CVG/CVE			0.86			0.89			0.71

The analysis of the average grain yields of cultivated soybean cultivars showed that the yields in the Forest-Steppe (2.31 t ha^{-1}) and Polissya (2.43 t ha^{-1}) differed only slightly, within 5%. Whereas the productivity of cultivars in the Forest-Steppe and Polissya exceeded that in the Steppe (1.53 t ha^{-1}) by 51 and 59%, or 0.78 and 0.90 t ha^{-1}, respectively. At the same time, the analysis of compliance of growing conditions with crop requirements in the Polissya zone was the lowest -CVG/CVE = 0.71, and in the Steppe and Forest-Steppe, 0.86 and 0.89, respectively. In other words, the conditions of the Forest-Steppe and Steppe best meet the requirements of the crop for the formation of a stable and high yield.

Statistical analysis of the yield parameters showed that Vitalina, Inguz, Turizas, and Dara were the most stable ($\sigma^2 d$ = 0.60–0.65) but low-yielding cultivars. The cultivars ES VISITOR and ES COLLECTOR proved to be consistently high-yielding, regardless of the growing zone. The Alicia cultivar, which was characterised by high yields in the Forest-Steppe and Polissya, was found to be unstable. The research showed that the cultivars Titan, Arcadia, Alicia, Tersia, ES COMPOSITOR and Carmelita were characterised by a ratio of plasticity bi > 1 and stability σ^2d > 0, i.e. they will be productive under favourable growing conditions. Other cultivars had bi < 1 and σ^2d > 0, indicating their ability to produce better results under favourable conditions, but unstable yields (Table 7).

Table 7. Generalised parameters of adaptive and productive potential of mid-season cultivars of cultivated soybean in different climatic zones of Ukraine (2023–2024)

Cultivar	$\bar{X}$	σ^2d	bi	Hom	Sc	CM	IEP	SR	CA	AAC
Titan st	2.31	0.75	1.19	4.05	1.67	2.07	1.10	-1.65	2.25	1.11
Ingus	1.80	0.60	0.75	2.44	1.29	1.88	0.87	-1.00	1.80	0.86
Turizas	1.85	0.65	0.89	2.58	1.33	2.00	0.88	-1.20	1.80	0.88
Acardia	2.15	0.80	1.32	3.48	1.55	2.28	1.01	-1.82	2.11	1.03
Alicia	2.41	0.78	1.24	4.39	1.74	2.07	1.15	-1.76	2.28	1.15
Dara	1.86	0.63	0.84	2.62	1.34	1.94	0.89	-1.17	1.86	0.89
Tersia	2.12	0.72	1.10	3.41	1.53	2.09	1.01	-1.53	2.10	1.02
Neptune	1.92	0.67	0.93	2.77	1.38	2.01	0.92	-1.14	1.87	0.92
ES VISITOR	2.46	0.67	0.92	4.56	1.77	1.78	1.19	-1.16	2.38	1.18
ES COLLECTOR	2.41	0.67	0.94	4.40	1.74	1.81	1.17	-1.12	2.37	1.15
ES COMPOSER	2.03	0.70	1.01	3.10	1.46	2.04	0.97	-1.53	2.08	0.97
Vitalina	1.77	0.65	0.88	2.36	1.27	2.04	0.84	-1.16	1.68	0.85
Zeus	1.90	0.68	0.98	2.73	1.37	2.08	0.91	-1.34	1.79	0.91
Carmelita	2.25	0.75	1.14	3.83	1.62	2.06	1.07	-1.54	2.17	1.08
LSD_{05}	0.14									
$\bar{X}$	2.09									
SD	0.25									
CV, %	12									
CVG, %	26									
CVE, %	26									
CVP, %	37									
CVG/CVE	0.98									

Note: σ^2d – stability; bi – coefficient of linear regression; Hom – homeostaticity; Sc – breeding value; cm – coefficient of multiplicity; IEP – index of ecological plasticity; SR – stress resistance; CA – compensatory ability; AAC – absolute average coefficient of adaptability.

The cultivars differed significantly in homeostaticity from 2.36 to 4.56, which confirms the stability or vice versa - the plasticity of a particular cultivar. 'Titan', Alicia, ES VISITOR, ES COLLECTOR and Carmelita cultivars were distinguished by high breeding value (Sc). The high-yielding cultivars Alicia, ES VISITOR and ES COLLECTOR were characterised by a higher adaptability coefficient compared to the standard, where the AAC was more than 1, although the standard cultivars 'Titan' and 'Carmelita' also had AAC above 1. Table 5 shows that the CVG/CVA ratio is 0.98, which confirms that the environmental conditions of the Steppe, Forest-Steppe and Polissya fully meet the requirements of the crop for a stable and high yield.

As a result of statistical calculations, a strong inverse correlation was found on the Chaddock scale between soybean yield and air temperature during the growing season: for early-ripening cultivars, r = -0.7120 and and r = -0.8031 for mid-ripening cultivars. A noticeable relationship was found between yield and precipitation: in early-ripening cultivars, r = 0.5077 and – r = 0.5597 in mid-ripening cultivars (data not shown).

The content of crude protein and oil in soybean seeds is among the key biochemical indicators that determine its intended use - either as a source of plant protein for the food and feed industries or as an oil-rich raw material. Analysis of the variation in these parameters among cultivars of different origins and maturity groups, grown in three agro-climatic zones of Ukraine (Steppe, Forest-Steppe, and Polissia), allows identification of the most promising cultivars for specific utilization purposes (Table 8).

According to the results, the protein content in early-maturing soybean cultivars ranged from 34.32% to 41.46%. The highest average protein content was recorded in Canadian cultivars Nunavik (41.46%), Eri (40.42%), and Calgary (40.23%), indicating the high genetic potential of these lines for protein productivity. Ukrainian cultivars (Titan st, Turizas, Ingus) also showed worthy results, with mean protein contents ranging from 36.61% to 38.56%, which is acceptable for food and feed applications.

The variation analysis revealed that the lowest standard deviation in protein content was observed under Forest-Steppe conditions (SD = 1.91; CV = 5%), indicating high stability of trait expression in this agro-climatic zone. In contrast, the Steppe region showed the highest average value (X = 39%) due to the presence of high-protein cultivars, albeit with slightly higher variability (CV = 6%).

Table 8. Protein content in soybean grain of different maturity groups in different climatic zones of Ukraine (2023–2024)

Cultivar	Protein content, %			
	Steppe	Forest-steppe	Polissya	$\bar{X}$
Early ripening				
Rhapsody st	37.25	37.27	36.00	36.84
Pallada	36.81	35.51	34.95	35.76
Perepilochka	36.79	36.81	36.98	36.86
Taverna	37.57	36.99	36.33	36.97
Fortress	36.41	35.65	35.09	35.71
Adelphia	41.20	40.34	39.70	40.41
Adessa	37.53	36.90	36.32	36.91
ES DECOR	39.47	38.65	38.04	38.72
RGT SAKUZA	41.20	40.34	39.70	40.41
Eri	42.18	39.57	39.52	40.42
Calgary	41.04	40.04	39.61	40.23
Nunavik	42.16	41.28	40.96	41.46
X	39	38	38	38
SD	2.19	1.91	1.98	2.01
CV, %	6	5	5	5
Mid ripening				
Titan st	39.47	38.86	37.35	38.56
Ingus	36.58	37.38	35.89	36.61
Turizas	37.00	37.76	36.26	37.01
Acardia	36.29	34.68	32.01	34.32
Alicia	41.61	39.62	37.31	39.52
Dara	36.28	36.87	35.40	36.18
Tersia	34.46	35.02	33.63	34.37
Neptune	40.20	40.85	39.23	40.10
ES VISITOR	38.14	36.10	33.19	35.81
ES COLLECTOR	37.19	36.65	33.72	35.85
ES COMPOSER	38.29	38.91	37.36	38.19
Vitalina	36.66	37.26	35.78	36.56
Zeus	38.38	39.01	37.46	38.28
Carmelita	38.95	39.29	37.73	38.66
X	38	38	36	37
SD	1.79	1.73	2.00	1.81
CV, %	5	5	6	5

The average oil content in early-maturing cultivars ranged from 17.33% to 24.07%, while in medium-maturing cultivars it ranged from 18.58% to 24.01%. The highest oil content was observed in the Ukrainian cultivars Pallada (24.07%) and Fortress (24.00%), as well as in the Austrian cultivar Akardia (24.01%). Conversely, Canadian cultivars such as Nunavik (17.33%) and Eri (18.01%) had significantly lower oil content, which is typical for protein-oriented genotypes.

The Polissia region exhibited the lowest variability in oil content (CV = 6%) with fairly high average values, making it suitable for the cultivation of oilseed-type cultivars with stable traits. In contrast, the Steppe region demonstrated the highest variability (CV = 14%), necessitating a careful selection of cultivars based on their adaptability to stress conditions (Table 9).

A clearly defined negative correlation between protein and oil content (data not shown) was established, which reflects the competitive allocation of resources within the seed. Therefore, cultivars with elevated protein levels (particularly Canadian ones) tend to exhibit lower oil content. This trade-off should be considered when defining the technological purpose of cultivar use.

Table 9. Oil content in soybean grain of different maturity groups in different climatic zones of Ukraine (2023–2024)

Cultivar	Oil content, %			
	Steppe	Forest-steppe	Polissya	$\bar{X}$
Early ripening				
Rhapsody st	23.81	22.81	21.19	22.60
Pallada	24.78	24.66	22.78	24.07
Perepilochka	24.76	23.13	20.35	22.74
Taverna	22.70	23.25	21.63	22.52
Fortress	24.92	24.31	22.76	24.00
Adelphia	19.00	18.70	18.06	18.58
Adessa	23.50	23.78	21.45	22.91
ES DECOR	19.89	20.09	18.86	19.61
RGT SAKUZA	18.40	18.14	17.66	18.07
Eri	17.55	18.39	18.11	18.01
Calgary	19.15	18.29	17.67	18.37
Nunavik	17.08	17.16	17.77	17.33
X	21	21	20	21
SD	2.92	2.71	1.96	2.50
CV, %	14	13	10	12
Mid ripening				
Titan st	20.28	21.07	21.05	20.80
Ingus	24.05	22.12	21.13	22.43
Turizas	22.61	21.56	21.73	21.96
Acardia	23.80	24.05	24.18	24.01
Alicia	18.90	18.36	20.85	19.37
Dara	23.80	22.73	22.91	23.15
Tersia	23.75	23.77	23.57	23.70
Neptune	19.95	18.50	20.31	19.59
ES VISITOR	21.82	23.52	23.84	23.06
ES COLLECTOR	22.22	22.60	23.46	22.76
ES COMPOSER	21.82	21.56	21.48	21.62
Vitalina	23.01	22.34	22.52	22.62
Zeus	21.82	21.56	21.08	21.48
Carmelita	21.32	20.58	20.60	20.83
X	22	22	22	22
SD	1.52	1.66	1.28	1.44
CV, %	7	8	6	7

DISCUSSION

The results of the conducted research fully confirm the key statements outlined in the introduction, particularly regarding the importance of varietal composition and agroecological adaptation of soybean cultivars to specific soil and climatic growing conditions. As noted in the introduction (Glauben & Svanidze, 2023, modern soybean production is characterised by a high degree of intensification and requires new cultivars capable of ensuring stable yields under changing climatic conditions. In this context, the observed variability in morphobiometric traits and yield structure elements between early- and mid-maturing soybean cultivars indicates significant differences in responses to environmental factors, which is fully consistent with the findings of Voora et al. (2024) and Zabarna & Chereshniuk (2024).

The research confirmed the conclusions of Liu et al. (2019) and Abdala et al. (2025) regarding soybean sensitivity to abiotic stresses, particularly high temperatures during the flowering–pod-filling phase. The identified strong negative correlation between air temperature during the growing season and yield (r = -0.7120 for early-maturing and r = -0.8031 for mid-maturing cultivars) confirms the critical impact of temperature stress on the formation of generative organs. Simultaneously, the established positive correlation between yield and precipitation (r = 0.5077–0.5597) aligns with the findings of Tkachuk et al. (2022), highlighting the need to adapt technologies to new moisture and temperature regimes.

The observed wide variation in plant height, number of nodes, pods and seeds, as well as thousand-seed weight and bulk density, indicates substantial genetic differences among the cultivars, which, according to Melnyk et al. (2020), points to differing levels of ecological plasticity. For instance, the cultivars Taverna, Eri, and Calgary demonstrated high individual productivity and adaptability across all climatic zones, confirming the hypothesis regarding their broad ecological suitability and supporting their recommendation for the Polissia, Forest-Steppe, and even Steppe zones.

The presence of significant inter-varietal differences in homeostatic index, breeding value, and compensatory ability makes it possible to identify cultivars with high breeding potential. Thus, the cultivars Taverna, Eri, Calgary, Alicia, ES VISITOR and ES COLLECTOR not only exceeded the standard in terms of yield but also had a high adaptability index, indicating their suitability for wide geographical testing, as noted by Hrabovskyi et al. (2024). At the same time, the observed trend of decreasing yields in the Steppe zone due to rising temperatures and water shortages confirms the need for the development of cultivars specialised for extreme conditions, as emphasised in the introduction.

Of particular note is the difference in yield potential realisation between zones: although the highest average yields were recorded in the Polissia zone, the the ratio of genetic and environmental variation (CVG/CVE) = 0.70 indicates lower efficiency of genetic potential realisation compared to the Forest-Steppe (0.89) and Steppe (0.80). This is entirely consistent with the statement regarding soybean's high dependence on growing conditions and the need to improve varietal agronomy (Shook et al., 2021).

Overall, the obtained results confirm the importance of long-term variety trials across different agroclimatic conditions using multifactorial analysis. They also demonstrate that breeding efforts aimed at increasing varietal adaptability should be based not only on yield potential but also on a comprehensive assessment of homeostatic stability, performance consistency, and responsiveness to changing climatic factors. Such approaches will enable the development of a scientifically grounded varietal policy in the context of agro-landscape transformations and climate instability, as required by modern agricultural science.

The results of this study are consistent with international research, emphasising the importance of taking into account climatic factors, cultivar adaptability, and the use of models to predict yields, which demonstrates the relevance of the study in the context of global climate change and the need to adapt agricultural practices.

CONCLUSIONS

Thus, based on the state results of experimental studies on agrobiological evaluation of soybean cultivars of different maturity groups, it can be stated that in different climatic zones (Steppe, Forest-Steppe and Polissya) of Ukraine, the structure of soybean grain yields largely depended on the biological characteristics of the cultivar and maturity group. The obtained results confirm considerable diversity in protein and oil content among soybean cultivars, which is driven by both genetic characteristics and environmental growing conditions. A differentiated approach to cultivar selection based on their intended processing direction enables effective adaptation of agronomic technologies to specific goals while maintaining production stability and profitability.

Recommendations for Soybean Cultivar Use

- **For protein processing and feed production**, it is advisable to grow cultivars with high protein content:
  - ✓ Nunavik, Eri, Calgary (Canada),
  - ✓ Titan st, Karmelita, Zeus (Ukraine – medium-maturing group).
- **For the oil-processing industry**, cultivars with oil content above 23% are recommended:
  - ✓ Pallada, Fortress, Ingus (Ukraine),
  - ✓ Akardia, Tersia (Austria).
- **For the Polissia and Forest-Steppe zones**, preference should be given to cultivars ensuring trait stability due to lower coefficients of variation (e.g., ES COMPOSER, Turizas, Dara).
- **For the Steppe region**, cultivars with enhanced tolerance to environmental fluctuations should be used – those demonstrating good plasticity and high potential for either protein (Calgary, Nunavik) or oil content (Pallada, Dara).

Prospects for further research include a detailed analysis of the influence of environmental factors on the formation of qualifying grain parameters in terms of sowing suitability and biochemical complex, and the widespread introduction of selected cultivars in the technological direction.

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