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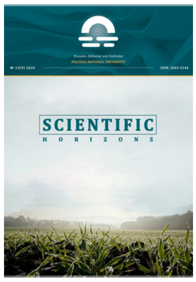

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Ecological plasticity, stability, and nitrogen-fixing capacity of edible bean cultivars in the Forest-Steppe of Ukraine

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Abstract. The purpose of this study was to investigate the influence of climatic conditions of the research years on changes in productivity and environmental plasticity and stability of edible bean cultivars. Furthermore, the study investigated the nitrogen-fixing potential of edible bean cultivars for the biologisation of agriculture. The study was conducted in the conditions of the educational and production department of the Uman National University of Horticulture during 2020-2022, using nine cultivars of edible beans. Standard methods of statistical analysis were used to

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study the parameters of adaptive variability. As a result of the comparative study, the characteristics of various parameters of the adaptive potential of edible bean cultivars were established by the following traits: the onset of the technical ripeness phase: Bianco and Extra Grano Violetto – 78 days. The cultivars Windsor Broad (16.42 t/ha), Bianco (13.73 t/ha), and Svitiaz (11.51 t/ha) stood out in terms of yield and adaptability in the technical ripeness phase, the cultivars Bacchus (1.92 t/ha) and Svitiaz (1.90 t/ha) – in terms of yield and adaptability in the biological ripeness phase; cultivars with high protein content in immature grain: Karmazin (12.77 g/100 g), Windsor Broad (13.51 g/100 g), Bianco (14.30 g/100 g), and Green lowland (14.43 g/100 g); cultivars with high nitrogen-fixing capacity: Ukrainian Sloboda (67.7 kg/ha), Windsor Broad (71.0 kg/ha), and Extra Grano Violetto (75.7 kg/ha). The results of the statistical analysis showed a significant influence of environmental conditions on the formation of productivity indicators of edible bean cultivars and a greater dependence on environmental conditions (CVA = 10.40-82.7%) than on the genetic component (CVG = 5.76-39.7%). The data suggest a tendency for yields to be inversely related to yield stability, with low-yielding cultivars showing stability and high-yielding cultivars showing instability. The presented findings suggest an idea of the change in the productivity parameters of edible beans under contrasting weather conditions, which makes it possible to identify cultivars with high productivity for food purposes and with a higher proportion of high-protein and energy-rich consumer products. Cultivars with increased nitrogen-fixing capacity were identified, which will help reduce the use of synthetic fertilisers

Keywords: yield; adaptability; seeds; nutritional value; protein content

INTRODUCTION

An analysis of the raw material base for food and feed production in Ukraine and variants for its development in the future shows the need to solve the problem of plant protein, primarily by expanding the area under legumes, increasing their protein content, and increasing yields through the selection and zoning of cultivars based on the above parameters. D. Cammarano *et al.* (2023) note that despite the improved functioning of agrocenoses and the benefits to human and livestock health, legumes are currently underutilised in most countries.

According to EUROSTAT (2022), among legume species, bean (*Vicia faba* L.) occupied 21% of the area under legumes in Europe in 2020 and was the main legume grown in, for instance, Denmark, Italy, and the UK. The findings of T. Aybegün (2021), inform that the small area of cereal legumes cultivation in Europe has been unchanged for many decades due to specialisation, market competitiveness, low yield stability, and lack of evidence of the benefits of legumes in the farming system. As a result, Europe imports 70% of its protein, primarily soy, from other regions to meet demand. Beans are a cold-tolerant crop and grow best in cool and moist conditions, making them a very attractive legume for cooler climates where soybeans do not always produce high yields (Duc *et al.,* 2015). Beans show good potential for use in the feed and processing industry due to their higher protein content than other common legumes such as peas (Animal Feed Resources Information System, n.d.).

Studies by W. Nelson *et al.* (2021) and C. Pankou *et al.* (2022) found that the selection and zoning of relevant cultivars substantially affect the productivity of the agrocenosis. According to H. Khazaei and A. Vandenberg (2020), A. Warsame *et al.* (2020) and J. Marshall *et al.* (2021), it is known that edible bean seeds are a rich source of protein, starch, dietary fibre, minerals, and vitamins and are widely grown for food, feed, and green manure worldwide.

H. Khazaei *et al.* (2021) notes that the use of legumes in conventional farming systems forms a symbiosis with nodule-forming bacteria that have nitrogen-fixing capacity, which increases yields and also contributes to agricultural sustainability through soil improvement. R.W. Neugschwandtner *et al.* (2023) point out that compared to other legumes, edible beans are considered an excellent protein crop because of their ability to provide nitrogen in temperate agricultural systems and because of their wide adaptability.

The conclusions drawn by V. Greveniotis *et al.* (2023) indicate that the yields of beans, like most legumes, are considered to be unstable. S.G. Tadesse *et al.* (2023) notes that this volatility is largely explained by the sensitivity of beans to drought and rainfall fluctuations. To make edible beans a more attractive crop for farmers, zoning for cultivars with high seed yields and the desired consistency of high yields is essential. The findings presented by D.N. Chiara *et al.* (2023) make it clear that yield stability can be investigated as the ability of some genotypes to perform consistently in a wide range of environments. S.G. Tadesse *et al.* (2023) report that there are different varieties of beans adapted to grow in a wide range of environments, including areas with cool climates and short growing seasons in the north and subtropical conditions in the south.

E. Sufar *et al.* (2024) noted that the grain yield of beans grown in long-term experiments in the UK, Sweden, and Germany ranged within 2.1-3.0 t/ha, which was on average 50% lower than that of cereals. However, when legume seeds were compared to spring cereals, the differences in performance were less pronounced in terms of yield stability. This should be considered when assessing the productivity of legumes, with the need to fill the existing knowledge gap on the effectiveness of legume productivity management and its impact on the ecosystem. J. Zhao *et al.* (2022) notes that it is necessary to include beans in crop rotations because of their biological nitrogen fixation. This reduces the need for nitrogen fertiliser and increases the overall efficiency of nitrogen fertiliser use in the farming system by potentially increasing the yield of subsequent crops.

The purpose of this study was to investigate the possibility of growing edible beans for green beans and seeds in the Forest-Steppe of Ukraine, the parameters of their adaptive capacity in terms of productivity and nitrogen-fixing capacity for biologisation of the agricultural sector. And replacing some of the soybean imports in European countries with locally produced beans will benefit not only the environment but also the national economy.

MATERIALS AND METHODS

The study was conducted in 2020-2022 at the experimental plots of the Department of Vegetable Growing and the Department of Plant Growing of the Uman National University of Horticulture. Geographical coordinates in Greenwich Mean Time: 48°46’ north latitude, 30°14’ east longitude and 245 m above sea level. The soil of the experimental plot was podzolised heavy loamy chernozem (World Reference Base, n.d.). The meteorological data base was the Uman weather station. An analysis of the climatic conditions during the study period showed a significantly higher precipitation rate in 2021 compared to long-term data for 2020 and 2022. The analysis of the temperature regime revealed an elevated temperature background in 2021, but there was no significant impact due to sufficient precipitation (Fig. 1).

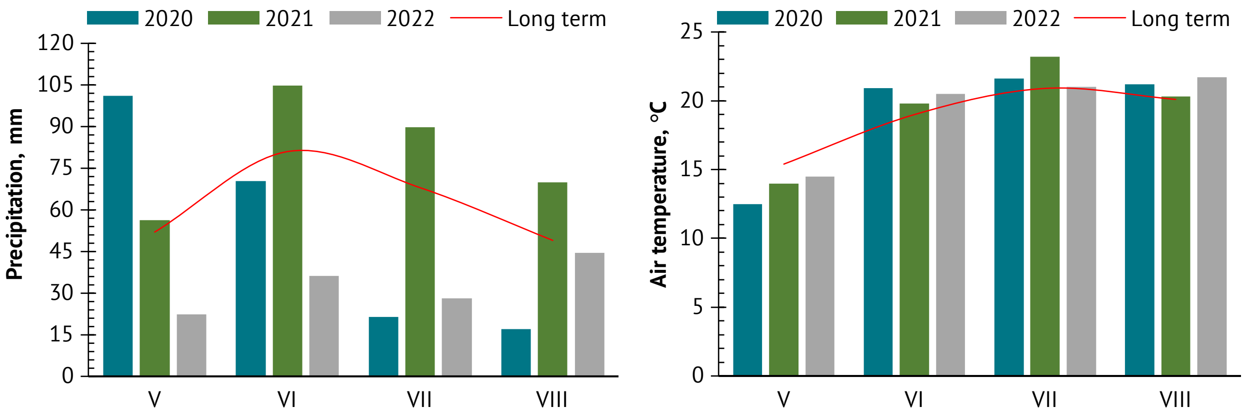

***Figure 1**. Climate map for the research period according to the data of the Uman weather station (2020-2022)*
***Source:** based on data from the Uman weather station*

Growth and development parameters of edible bean cultivars were determined on 100 typical plants. All measurements and studies were performed at the stage of technical maturity of the beans (BBCH 80), and seed yield was determined at the BBCH 99 stage. The study was conducted following the provisions of the Convention on Biological Diversity (1992).

The adaptive and productive potential of edible beans was studied according to a scheme that included nine cultivars of edible bean: Karadag, Ukrainian Sloboda, Bacchus (State register of plant cultivars suitable for dissemination in Ukraine, n.d.), Windsor Broad, Karmazin, Green lowland, Svitiaz, Bianco, Extra Grano Violetto. The Karadag cultivar was taken as the standard (st), as it was the most tested at the time of the study. The cultivation technology was generally accepted for the conditions of the Forest-Steppe. The cultivars were sown using the systemic method, and the repetition of the experiment was fourfold. The area of the experimental plot was 10 m^2. Seeds were sown in the second decade of April according to the scheme of 45×10 cm (222,000 pcs/ha). The predecessor was winter garlic.

Leaf area was determined according to the “notching” method using the formula:

$$S = \frac{K+Y}{P} \cdot B, \quad (1)$$

where S is the leaf surface area, cm^2; K is the number of notches, pcs; Y is the area of one notch, cm^2; P is the weight of notches, g; B is the weight of leaves, g.

Yield accounting was carried out following DSTU ECE LLC FFV-06:2007 (2008), a method of separate weighing during the period of technical ripeness with the division of products into standard and non-standard. The average weight of green beans was determined according to the weight method. The biochemical composition of green beans was determined in the laboratory of mass analysis of the Uman National University of Horticulture:

- dry residue in the beans – by drying at 105°C in a drying oven SNOL58/350A (Ukraine) according to DSTU 7804:2015 (2015);
- protein content – by the Kjeldahl method, according to DSTU ISO 5983-2003 (2004);

- the number and weight of rhizobia on plant roots and the content of legoglobin (leghaemoglobin) were determined according to the method of G.S. Posypanov (1991), the amount of fixed nitrogen – according to M. Unkovich *et al*. (2008). The parameters of total and active symbiotic potential (ASP) were used to determine the symbiotic productivity, which was calculated using the following formula:

$$ASP = M_1 + M_2 \cdot T, \quad (2)$$

where T is the period between two adjacent periods of analysis, days; $M_1 + M_2$ is the average mass of nodules with legoglobin for the period T, kg/ha.

The results were systematised using the rank classification of genotypes by using the ratio of plasticity (bi) and stability $\sigma^2 d$ parameters according to L. Biliavska *et al*. (2021) and S. Eberhart and W. Russell (1966).

Homeostaticity (Hom) was calculated according to the following formula:

$$H_{om} = \frac{\overline{x^2}}{\sigma}, \quad (3)$$

where $\bar{x}$ is the arithmetic mean of the grade; σ is the generalised standard deviation.

The selection value of a genotype was calculated using the following formula:

$$(S_C) = \bar{X} \cdot \frac{\bar{X}_{lim}}{\bar{X}_{opt}}, \quad (4)$$

where $\bar{X}$ is the arithmetic mean of the grade; $\bar{X}_{lim}$ is the limited arithmetic mean; $\bar{X}_{opt}$ – is the optimised arithmetic mean.

The multiplicative coefficient (MC) of the trait was calculated by the following formula:

$$MC = \frac{\bar{X}i + bi \cdot yi}{Xi}, \quad (5)$$

where $\bar{X}i$ is the average value of the studied trait in the i^{th} cultivar; bi is the linear regression coefficient of the i^{th} cultivar; yi is the average value for all averages for all cultivars yi for each j^{th} experiment point.

The environmental plasticity index (EPI) was calculated using the following formula:

$$EPI = \frac{\left(\frac{YV_1}{ATV_1} + \frac{YV_2}{ATV_2} + \dots + \frac{YV_n}{ATV_n}\right)}{n}, \quad (6)$$

where YV_1, YV_2, YV_n are the values of the trait in the cultivar in different years of testing; ATV_1, ATV_2, ATV_n are the average trait values of the cultivars in each of the experimental variants.

The annual adaptability coefficient (AC) was calculated using the following formula:

$$AC = \frac{(Xij) \cdot 100 \cdot X)}{100}, \quad (7)$$

where Xij is the yield of a particular cultivar in the year of testing; X is the average yield of the year.

The absolute average adaptability coefficient (AAC) was calculated for a cultivar using the following formula:

$$AAC = \frac{(XiC) \cdot 100 \cdot Xm)}{100}, \quad (8)$$

where Xic is the average yield of the cultivar over the years of testing; Xm is the multi-year average yield of the cultivar.

Stress resistance and compensatory capacity of cultivars were calculated according to A.A. Rossielle ***and*** J. Hemblin (1981):

$$SR = Y_{min} - Y_{max}; \quad (9)$$

$$CC = \frac{Y_{min} + Y_{max}}{2}, \quad (10)$$

where Y_{min} *and* Y_{max} is the minimum and maximum values of the cultivar trait.

The experiments were conducted to determine the phenotypic, genotypic, and ecological variability of cultivars using the following formulas:

- Genetic variance:

$$\sigma_G^2 = \frac{GM_t - GM_e}{r}, \quad (11)$$

- Environmental variance:

$$\sigma_A^2 = GM_e, \quad (12)$$

- Phenotypic variance:

$$\sigma_F^2 = \sigma_G^2 + \sigma_A^2, \quad (13)$$

- Genotypic variation coefficient:

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

- Phenotypic variation coefficient:

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

- Environmental variation coefficient:

$$\frac{\sqrt{\sigma_A^2 \cdot 100}}{\bar{X}}, \quad (16)$$

where is the generalised root mean square value of the population trait; is the generalised root mean square error; r is the number of repetitions.

Statistical processing of the data was performed using the arithmetic mean (x) and standard deviation (SD) calculated using Microsoft Excel 2019. Correlations were calculated using Statistica 12 software and analysed using the Chaddock scale.

RESULTS AND DISCUSSION

The introduction of high-quality, disease-resistant cultivars allows increasing yields and product quality at no additional cost. However, high productivity is not always possible when using valuable cultivars from other climatic zones. The principal difficulty in expanding the cultivation area of such cultivars is that those created in another zone and showing high productivity there are unsuitable for introduction, and therefore each cultivation region must have its varietal composition adapted to local soil and climatic conditions and resistant to major diseases.

Beans are a plant with a high environmental sensitivity to changes in soil and climatic conditions, which responds to climate, soil, water, and nutrient conditions. In cultivars, the duration of the flowering–technical maturity period is mainly controlled by the genotype, and therefore the duration of this period is considered during selection. In case of the Forest-Steppe zone, due to the climate, addressing the issue of early maturity of bean cultivars is also important. Studies have found that the period from germination to flowering is more constant and characteristic than the period from sowing to full maturity. The optimised length of day for vegetative and reproductive development does not coincide: for the former, the optimised length is 12 hours, for the latter – 18 hours. All forms of beans grown in Ukraine are long-day plants, and therefore their growing season is shortened moving north.

The cultivars under study, according to the classification of C. Francis *et al.* (2000), were divided into two maturity groups: mid-early and mid-ripening. The duration of the period from germination to the onset of technical ripeness in the experiments varied insignificantly depending on the agrometeorological conditions of the year and averaged 78 days for early-ripening forms, 93-94 days for mid-early forms, 97-105 days for mid-ripening forms; the duration of the growing season in the experiments also varied insignificantly and averaged: 93-98 days for early-ripening forms, 113-118 days for mid-early forms, 118-124 days for mid-ripening forms. The majority of the collection under study included samples from the mid-early group – 33% (Svitiaz, Karmazin, Windsor Broad) and from the mid-ripening group – 44% (Green lowland, Bacchus, Ukrainian Sloboda, and Karadag), while the early-ripening cultivars accounted for only 22%, or two cultivars – Bianco and Extra Grano Violetto (Fig. 2).

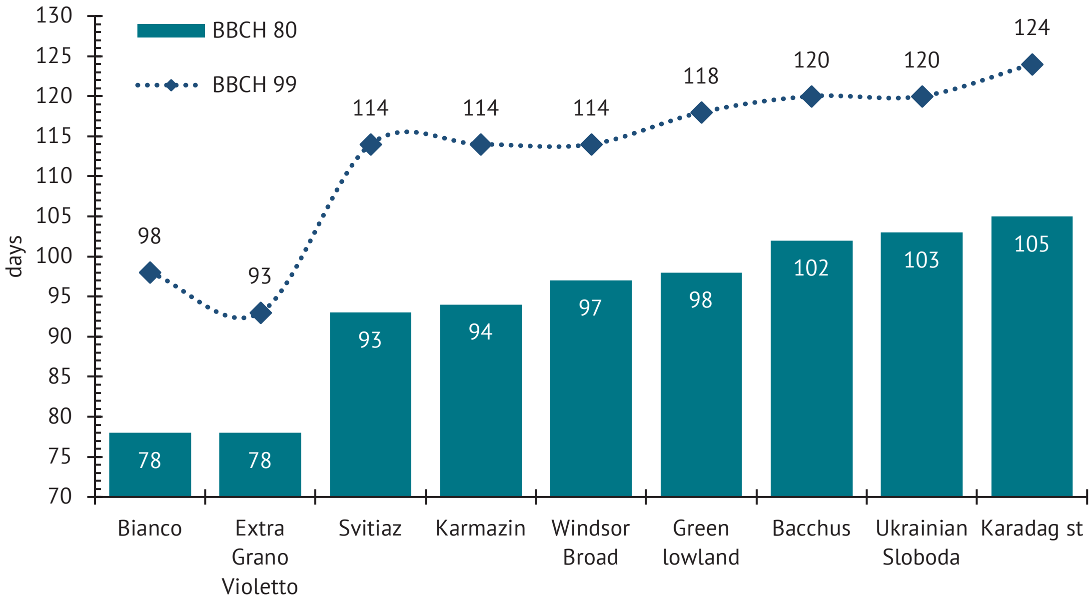

Figure 2*. Duration of periods from germination to technical/biological maturity of edible bean cultivars (2020-2022)*
Note: ** – st – standard*
Source: *obtained as a result of the present study*

Depending on the conditions of the year, most of the individual performance indicators varied greatly. The number of shoots varied from 34-56%, which is explained by the fact that in 2022 the minimum number of shoots was 1 pcs./plant, only in the Bacchus cultivar – 2 pcs./plant, while in 2020 and 2021 their number was at 3-6 pcs./plant. On average, the largest number of shoots was formed by plants of the cultivars Bacchus, Karmazin, Bianco, and Extra Grano Violetto – 3.67 pcs./plant, which is 22.2% more than the standard.

The number of beans per plant is one of the indicators that is influenced by environmental factors and is only 45% determined by varietal characteristics. It is one of the main quantitative traits of pulses that is responsible for their seed yield. Plants of Bacchus and Karmazin cultivars produced a significantly higher number of beans – 10.33 and 9.33 pcs./plant, respectively, which is 34.8% and 21.7% more than the standard. The cultivars Ukrainian Sloboda, Windsor Broad, Green lowland, Bianco, and Extra Grano Violetto formed 6.0-7.3 pcs./plant, which is 4.3-21.7% less than the standard, or 0.33-1.67 pcs. The cultivars Bacchus and Karmazin, selected for this trait, are recommended as sources for breeding to increase the number of beans per plant (Table 1).

***Table 1**. Parameters of individual productivity of different cultivars of edible bean (BBCH 80), (2020-2022), (Lim ± SD)*

Cultivar	Shoots, pcs./plant		Beans, pcs./plant		Seeds, pcs./bean	
	Lim±SD	CV, %	Lim±SD	CV, %	Lim±SD	CV, %
Karadag st	1-5 ± 1.6	54	2-12 ± 4.2	55	2-3 ± 0.5	20
Ukrainian Sloboda	1-5 ± 1.6	54	2-12 ± 4.1	58	2-3 ± 0.5	20
Windsor Broad	1-5 ± 1.7	51	2-12 ± 4.1	56	2-4 ± 0.5	14
Bacchus	1-5 ± 1.2	34	4-15 ± 4.6	45	2-4 ± 0.8	27
Karmazin	1-6 ± 2.1	56	3-13 ± 4.5	48	2-3 ± 0.5	18
Green lowland	1-4 ± 1.2	47	2-10 ± 3.3	54	2-3 ± 0.5	18
Svitiaz	1-4 ± 1.4	47	2-15 ± 5.4	59	4 ± 0	0
Bianco	1-5 ± 1.9	51	2-12 ± 4.1	62	4 ± 0	0
Extra Grano Violetto	1-6 ± 2.1	56	3-10 ± 2.9	42	3-4 ± 0.5	13
$\overline{X}$	3		8		3	
σ^2_G	0.94		5.84		0.07	
σ^2_F	3.89		25.18		0.69	
σ^2_A	2.95		19.34		0.62	
CVG, %	29.39		30.93		8.75	
CVP, %	59.81		64.21		26.73	
CVA, %	52.10		56.27		25.25	
CVG/CVA	0.56		0.55		0.35	

Note: ** – st – standard*
Source: *obtained as a result of the present study*

Analysing the number of seeds in one bean, the Svitiaz and Bianco cultivars were distinguished, where this trait did not change over the years – 4 pcs./bean. Overall, the variation in this trait was 13-27%. The number of seeds per bean was significantly higher than the standard in Windsor Broad – 3.33 pcs., Bacchus – 3.0 pcs., Extra Grano Violetto – 3.67 pcs., and Svitiaz and Bianco – 4 pcs. each, respectively. The selected cultivars Svitiaz and Bianco are recommended as sources for breeding to increase the number of seeds per bean.

Statistical analysis of the formation of individual productivity indicators confirmed a strong dependence on environmental conditions with a significantly higher environmental variation coefficient (CVA) = 25.25-56.27% compared to the genetic variation coefficient (CVG) = 8.75-30.93%. According to the trait "weight of beans per plant", two cultivars were identified on average over three years – Windsor Broad and Bianco, which significantly outperformed the standard. The Karmazin, Svitiaz, and Extra Grano Violetto cultivars produced a less significant weight of beans. The cultivars Ukrainian Sloboda and Bacchus produced a slightly lower mass of beans per plant, while the cultivar Green lowland produced a significantly lower mass than all the cultivars under study.

The genetic-statistical analysis of this trait showed that the most stable (according to the set of indicators σ^2d and MC, Hom) was the Green lowland cultivar (σ^2d – 5.19; MC – 1.82; Hom – 50.1), but the cultivar was characterised by low breeding value (Sc = 79.9). According to the indicators of the ratio of plasticity (bi) and stability σ^2d parameters, all studied Windsor Broad, Svitiaz, and Bianco cultivars had indicators bi > 1, σ^2d > 0 – i.e., they have better results under favourable growing conditions. Cultivars Karadag st, Ukrainian Sloboda, Bacchus, Karmazin, Green lowland, and Extra Grano Violetto had indicators bi < 1, σ^2d > 0, i.e., they have better results under unfavourable conditions, and thus are unstable. According to the environmental plasticity coefficient (bi > 1), Windsor Broad, Svitiaz, and Bianco are highly plastic, and all other cultivars are relatively stable or low plastic (bi < 1).

High selection value (Sc) and compensatory ability (CC) were characterised by the cultivars Windsor Broad and Bianco, which outperformed all other cultivars in these parameters. The most stress-resistant cultivars were Green Lowland and Extra Grano Violetto. The least stress-resistant cultivars were Windsor Broad, Svitiaz, and Bianco. High adaptive capacity for this trait was characterised by cultivars Windsor Broad, Svitiaz, Bianco, in which AAC was greater than 1 (Table 2).

Table 2. *Parameters of adaptive capacity and breeding value of edible bean cultivars according to the trait "bean weight", g/plant, (BBCH 80), (2020-2022)*

Cultivar	Bean weight, g/plant	$\sigma^2 d$	bi	Hom	Sc	MC	EPI	SR	CC	AAC
Karadag st	75.12	6.13	0.76	83.3	103.0	1.87	0.90	-87	60	0.88
Ukrainian Sloboda	73.52	5.92	0.68	78.7	100.1	1.80	0.90	-78	56	0.86
Windsor Broad	123.65	9.67	1.94	241.8	175.5	2.29	1.28	-225	130	1.50
Bacchus	72.60	5.79	0.68	75.3	97.9	1.81	0.90	-78	58	0.84
Karmazin	84.40	6.10	0.75	100.1	112.9	1.77	1.06	-86	66	0.97
Green lowland	59.77	5.19	0.56	50.1	79.9	1.82	0.75	-64	49	0.68
Svitiaz	87.33	8.25	1.38	117.9	122.5	2.32	0.92	-160	95	1.05
Bianco	103.57	8.52	1.53	168.3	146.4	2.22	1.10	-177	104	1.25
Extra Grano Violetto	88.73	5.79	0.71	99.2	112.4	1.74	1.20	-45	95	0.96
$\bar{X}$	77.66									
σ_G^2	950.7									
σ_F^2	4126.1									
σ_A^2	3175.4									
CVG, %	39.7									
CVP, %	82.7									
CVA, %	72.6									
CVG/CVA	0.55									

Note: ** – st – standard*
Source: *obtained as a result of the present study*

Structural analysis of the ratio of green bean weight to total bean weight showed that only four cultivars produced green bean weight greater than the weight of bean valves: Windsor Broad (97.62 g/plant or 78.9% of the total bean weight); Bacchus (44.27 g/plant or 61.0% of the total bean weight); Bianco (57.88 g/plant or 55.9% of the total bean weight), and Svitiaz (47.76 g/plant or 54.7% of the total bean weight), all other cultivars under study formed grains weighing less than 50% of the total bean weight (Fig. 3).

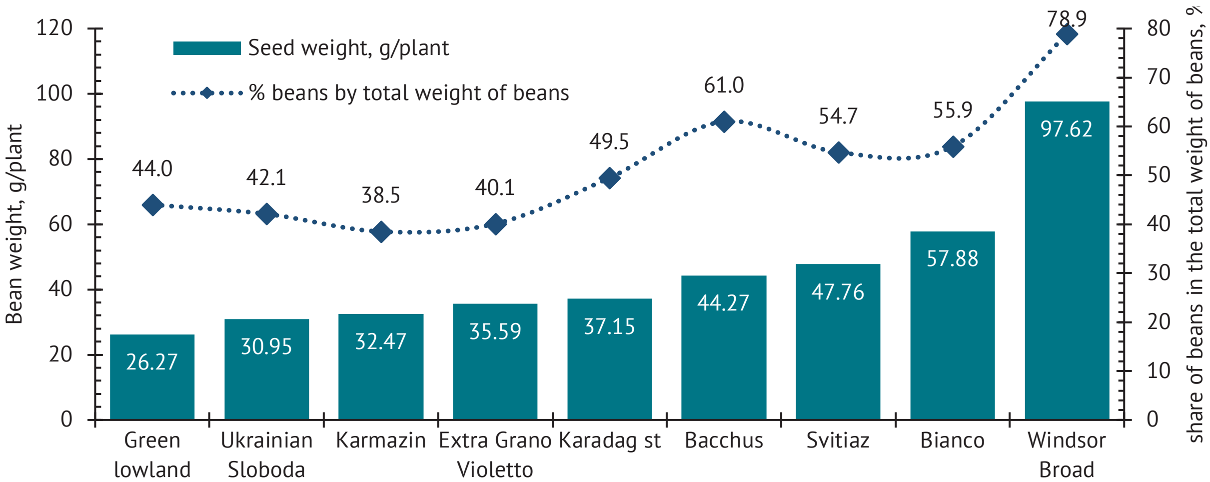

***Figure 3**. The ratio of green bean weight (g/plant) to the total weight of edible beans, %, (BBCH 80), (2020-2022)*
Note: ** – st – standard*
Source: *obtained as a result of the present study*

The Ukrainian Sloboda, Karmazin, Green lowland, and Extra Grano Violetto cultivars were characterised by a lower ratio of green bean weight to total bean weight compared to the standard. The generalised weight ratio of green seeds to bean shells showed a 52% advantage for seeds. That is, the so-called "kitchen waste" will account for 48% of the total weight of the edible bean crop on average. The distribution of green bean yields by year showed that the most productive year was 2021, where this indicator varied within 11.20-33.80 t/ha (CV = 42%). Windsor Broad, Svitiaz, and Bianco significantly outperformed the standard, while all other cultivars had yields slightly higher than the standard (Table 3).

***Table 3**. Yield of green beans of edible bean cultivars, t/ha, (BBCH 80), (2020-2022)*

Cultivar	2020	2021	2022	$\bar{X}$	SD	CV, %	K_{sfn}
Karadag st	10.20	12.00	4.37	8.86	3.26	37	2.75
Ukrainian Sloboda	10.46	11.50	4.48	8.81	3.09	35	2.57
Windsor Broad	10.91	33.80	4.56	16.42	12.56	76	7.41
Bacchus	9.62	13.50	4.92	9.35	3.51	38	2.74
Karmazin	11.16	14.70	6.14	10.67	3.51	33	2.39
Green lowland	7.48	11.20	4.37	7.68	2.79	36	2.56
Svitiaz	6.20	24.50	3.84	11.51	9.23	80	6.38
Bianco	10.30	26.80	4.08	13.73	9.59	70	6.57
Extra Grano Violetto	8.20	16.40	7.53	1=0.71	4.03	38	2.18
$\bar{X}$	9.39	18.27	4.92	10.86			
SD	1.61	7.65	1.11	2.59			
CV, %	17	42	23	24			
LSD_{05}	0.53	1.50	0.24				

Note: ** – st – standard*
Source: *obtained as a result of the present study*

Hydrothermal conditions in 2020 contributed to yields of 6.20-11.16 t/ha (CV = 17%). In the current year, the Windsor Broad and Karmazin cultivars yielded significantly higher yields of green beans. Weather conditions in 2022 were unfavourable for the bean harvest. This indicator varied greatly (CV = 23%), although the yield was very low – 3.84-7.53 t/ha. A statistically significant difference in yield increase was obtained in the cultivars Karmazin and Extra Grano Violetto. All other cultivars tested produced yields close to the standard and differed only slightly. On average, over the three years, bean yields ranged within 8.81-16.42 t/ha. Windsor Broad and Bianco were distinguished based on this trait. However, regardless of the growing conditions, the most productive cultivar was Windsor Broad, which gave a consistently high yield compared to other cultivars studied.

The analysis of the adaptive capacity parameters made it possible to distinguish Windsor, Svityaz, and Bianco varieties based on the ratio of plasticity (bi) and stability $\sigma^2 d$ parameters, which have better results under favourable growing conditions and have bi > 1, $\sigma^2 d > 0$, i.e., highly plastic. The cultivars Karadag st, Ukrainian Sloboda, Bacchus, Karmazin, Green lowland, and Extra Grano Violetto had bi < 1, $\sigma^2 d > 0$, i.e., they have better results under unfavourable conditions, are unstable and have low plasticity. High selection value (Sc) and compensatory ability (CC) were characterised by the cultivars Windsor Broad and Bianco, which outperformed all other cultivars in these parameters. The most stress-resistant cultivars were identified as Karadag st, Ukrainian Sloboda, and Green lowland. The least stress-resistant cultivars were Windsor Broad, Svitiaz, and Bianco. High adaptive capacity for this trait was characterised by cultivars Windsor Broad, Svitiaz, Bianco, with AAC greater than 1 (Table 4).

***Table 4**. Parameters of adaptive capacity and breeding value of edible bean cultivars for the trait "green bean yield", t/ha*

Cultivar	$\bar{X}$, t/ha	$\sigma^2 d$	bi	Hom	Sc	*MC*	EPI	SR	CC	AAC
Karadag st	8.86	1.80	0.52	10.9	13.4	1.64	0.88	-8	8	0.82
Ukrainian Sloboda	8.81	1.76	0.47	10.8	13.3	1.58	0.88	-7	8	0.81
Windsor Broad	16.42	3.54	2.25	37.6	24.8	2.48	1.31	-29	19	1.51
Bacchus	9.35	1.87	0.61	12.2	14.1	1.71	0.92	-9	9	0.86
Karmazin	10.67	1.87	0.61	15.9	16.1	1.62	1.08	-9	10	0.98
Green lowland	7.68	1.67	0.50	8.2	11.6	1.71	0.77	-7	8	0.71
Svitiaz	11.51	3.04	1.62	18.5	17.4	2.53	0.93	-21	14	1.06
Bianco	13.73	3.10	1.72	26.2	20.8	2.36	1.13	-23	15	1.26
Extra Grano Violetto	10.71	2.01	0.70	16.0	16.2	1.71	1.10	-9	12	0.99
$\bar{X}$	10.86									
σ^2_G	15.0									
σ^2_F	66.5									
σ^2_A	51.6									
CVG, %	35.6									

Table 4. Continued

Cultivar	$\bar{X}$, t/ha	σ^2d	bi	Hom	Sc	*MC*	EPI	SR	CC	AAC
CVP, %	75.1									
CVA, %	66.1									
CVG/CVA	0.54									

Note: ** – st – standard*
Source: *obtained as a result of the present study*

Seed productivity of plants is determined by a complex of morphological and physiological traits. The main ones include the number of seeds per plant, weight of seeds per plant, and thousand-kernel weight. The cultivars of edible bean under study were characterised by a strong variability of the trait "seed weight per plant", on average over the years CV ranged within 11-18%, while by cultivars over the years this indicator ranged within 27-47%. The most stable cultivars were Karmazin, Svitiaz, and Extra Grano Violetto – 27-29%, while the most volatile cultivars were Ukrainian Sloboda and Karadag – 41 and 47%, respectively. On average, over the years of the study, the most productive cultivars were Svitiaz and Bacchus – 8.33 g/plant and 8.17 g/plant, which is 20.8% and 18.4% more than the standard, respectively. Lower productivity than the standard was observed in the cultivars Ukrainian Sloboda, Green lowland, and Windsor Broad – 5.67-6.83 g/plant.

Statistical analysis of the obtained data on seed productivity of plants showed that the most stable in terms of the complex of indicators (σ^2d and MC, Hom) was the variety Green lowland (σ^2d = 1.30, MC = 1.84, Hom = 12.2) and Extra Grano Violetto (σ^2d = 1.39; MC = 1.76; Hom = 19.5). In terms of the ratio of plasticity (bi) and stability (σ^2d) parameters, the cultivars Karadag st, Ukrainian Sloboda, Bacchus, and Svitiaz had a ratio of bi > 1 and σ^2d > 0, i.e., they show better productivity under favourable growing conditions. Cultivars Karmazin, Green Lowlands, Bianco, and Extra Grano Violetto had a ratio of indicators bi < 1, σ^2d > 0, i.e., more productive under unfavourable conditions, unstable. The Windsor Broad cultivar had a ratio of bi = 1, σ^2d > 0 – responds well to improving conditions, unstable. According to the coefficient of environmental plasticity (bi), the Karadag, Bacchus, and Svitiaz cultivars are classified as highly plastic, or intensive, while the Karmazin, Green lowland, Bianco, and Extra Grano Violetto cultivars are classified as low plastic. The statistical data suggest a significant influence of growing conditions on the productivity of edible bean cultivars and a greater dependence on environmental conditions (CVA = 37.2%) than on the genetic component (CVG = 20.4) and a rather high CVG/CVA ratio of 0.55 (Table 5).

Table 5*. Parameters of adaptive capacity and breeding value of edible bean cultivars based on the trait "seed weight", g/plant*

Cultivar	$\bar{X}$, g/plant	σ^2d	bi	Hom	Sc	MC	EPI	SR	CC	AAC
Karadag st	6.90	1.81	1.35	18.1	6.7	2.39	0.92	-8	7	0.98
Ukrainian Sloboda	5.93	1.57	1.02	13.4	5.7	2.21	0.82	-6	6	0.84
Windsor Broad	6.83	1.57	1.01	17.7	6.6	2.05	0.96	-6	7	0.97
Bacchus	8.17	1.77	1.28	25.3	7.9	2.11	1.13	-8	8	1.15
Karmazin	7.33	1.45	0.86	20.4	7.1	1.83	1.06	-5	7	1.04
Green lowland	5.67	1.30	0.67	12.2	5.5	1.84	0.83	-4	6	0.80
Svitiaz	8.33	1.70	1.19	26.4	8.0	2.01	1.17	-3	8	1.18
Bianco	7.33	1.43	0.84	20.4	7.1	1.81	1.07	-5	8	1.04
Extra Grano Violetto	7.17	1.39	0.77	19.5	6.9	1.76	1.04	-5	7	1.01
$\bar{X}$	7.07									
σ^2_G	2.08									
σ^2_F	9.01									
σ^2_A	6.93									
CVG, %	20.4									
CVP, %	42.4									
CVA, %	37.2									
CVG/CVA	0.55									

Note: ** – st – standard*
Source: *obtained as a result of the present study*

The Svitiaz and Green lowland cultivars stood out in terms of stress resistance (SR), which suggests their high productivity under optimised growing conditions, as the cultivars with the highest and lowest productivity stood out. In terms of compensatory capacity (CC), the cultivars under study were characterised as quite stable, which allows them to be classified as plastic cultivars. According to the trait "seed weight", the most adaptive cultivars with an adaptation coefficient (AAC) greater than 1 were identified – Bacchus and Svitiaz, cultivars Karmazin, Bianco, and Extra Grano Violetto, which are medium adaptive, and cultivars Karadag, Ukrainian Sloboda, Windsor Broad, and Green lowland, which are classified as low adaptive.

In the conditions of the Right-Bank Forest-Steppe, beans are a rare crop, and there is no data on varietal characteristics of productivity formation. The findings of the study showed an average yield variation of 12%, although the cultivars varied by year within 21-34%. The optimised conditions for the formation of productivity of edible bean cultivars were characterised by 2021, where seed yields ranged within 1.60-2.56 t/ha. The most productive cultivars were Bacchus and Svitiaz, where this indicator was higher than the standard by 16.4% or 0.36 t/ha and 10.0% or 0.22 t/ha, respectively. In 2020, average data on vegetable bean yields were obtained, but the variation was the largest – CV = 16%. In the current year, the cultivars that significantly outperformed the standard were Bacchus and Svitiaz (+0.55 t/ha or 34.4%). Vegetable bean plants were the least productive in 2022, due to dry conditions during the growing season. IN the current year, the yield varied little, with a CV of 9%, but most cultivars were significantly more productive than the standard, with Karmazin (+0.21 t/ha or 23.3%), Svitiaz (+0.23 t/ha or 25.6%), and Extra Grano Violetto (+0.22 t/ha or 24.4%) standing out. The analysis of the average seed yields of edible bean cultivars showed that all cultivars had a comparable variation of data and significantly depended on the weather conditions of the growing season, but this contributed to the selection of more productive cultivars: Bacchus – 1.92 t/ha and Svitiaz – 1.90 t/ha. The Ukrainian Sloboda cultivar had a yield lower than the standard by 11.1%, while all other cultivars tested were slightly higher than the standard.

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***Table 6**. Seed yield of edible bean cultivars, t/ha, (BBCH 99), (2020-2022)*

Cultivar	Seed yield, g/plant			$\bar{X}$	SD	CV, %	K_{sfn}
	2020	2021	2022				
Karadag st	1.60	2.20	0.90	1.57	0.53	34	2.44
Ukrainian Sloboda	1.52	1.80	0.86	1.39	0.39	28	2.09
Windsor Broad	1.80	1.84	1.08	1.57	0.35	22	1.70
Bacchus	2.15	2.56	1.06	1.92	0.63	33	2.42
Karmazin	1.91	1.90	1.11	1.64	0.38	23	1.72
Green lowland	1.20	1.60	0.97	1.26	0.26	21	1.65
Svitiaz	2.15	2.42	1.13	1.90	0.56	29	2.14
Bianco	1.67	2.00	1.08	1.58	0.38	24	1.85
Extra Grano Violetto	1.91	1.80	1.12	1.61	0.35	22	1.71
	1.77	2.01	1.03	1.61			
SD	0.29	0.30	0.09	0.20			
CV, %	16	15	9	12			
LSD_{05}	0.09	0.12	0.06				

Note: ** – st – standard*

Source: *obtained as a result of the present study*

Statistical analysis of the obtained data on the yield of edible bean seeds showed that the most stable in terms of the complex of indicators (σ^2d and MC, Hom) was the variety Green lowland ($\sigma^2d = 0.51$; MC = 1.72; Hom = 3.3) and the variety Extra Grano Violetto ($\sigma^2d = 0.59$; MC = 1.78; Hom = 5.4). According to the indicators of the ratio of plasticity (bi) and stability σ^2d parameters, the cultivars Karadag st, Ukrainian Sloboda, Windsor Broad, Karmazin, Green lowland, and Bianco had a ratio of indicators bi > 1, $\sigma^2d > 0$ – i.e., they show better productivity under favourable growing conditions. Cultivars Karadag, Bacchus, and Svitiaz had a ratio of indicators bi < 1, $\sigma^2d > 0$, i.e., more productive under unfavourable conditions, unstable. According to the environmental plasticity coefficient (bi), the group of highly plastic or intensive cultivars includes Karadag, Bacchus, and Svitiaz, i.e., these cultivars respond well to improved growing conditions; the group of relatively low plastic cultivars includes Ukrainian Sloboda, Windsor Broad, Karmazin, Green lowland, Bianco, and Extra Grano Violetto. The statistical data suggest a significant influence of growing conditions on the yield of edible bean seed cultivars and a greater dependence on environmental conditions (CVA = 30.1%) than on the genetic component (CVG = 15.8) and a rather high CVG/CVA ratio of 0.53.

According to the stress resistance indicator (SR), the Green lowland cultivar stood out, as this cultivar had a minimum gap between the minimum and maximum yields, indicating a higher resistance to stress and a wider range of its adaptive capabilities. According to the compensatory capacity (CC), two cultivars were distinguished among the cultivars under study – Bacchus and Svitiaz, since the concept of "compensation" is close to "plasticity", this allows them to be classified as plastic cultivars (Table 7).

***Table 7**. Parameters of adaptive capacity and breeding value of edible bean cultivars based on the trait "seed yield", t/ha*

Cultivar	$\bar{X}$, t/ha	σ^2d	bi	Hom	Sc	MC	EPI	SR	CC	AAC
Karadag st	1.57	0.73	1.24	5.1	1.5	2.27	0.96	-1.3	1.6	0.98
Ukrainian Sloboda	1.39	0.63	0.95	4.0	1.4	2.09	0.86	-0.9	1.3	0.87
Windsor Broad	1.57	0.59	0.82	5.1	1.5	1.84	0.99	-0.8	1.5	0.98
Bacchus	1.92	0.80	1.52	7.7	1.9	2.27	1.17	-1.5	1.8	1.20
Karmazin	1.64	0.61	0.87	5.6	1.6	1.85	1.03	-0.8	1.5	1.02
Green lowland	1.26	0.51	0.57	3.3	1.2	1.72	0.80	-0.6	1.3	0.78
Svitiaz	1.90	0.75	1.33	7.5	1.9	2.13	1.17	-1.3	1.8	1.18
Bianco	1.58	0.62	0.91	5.2	1.6	1.92	0.99	-0.9	1.5	0.99
Extra Grano Violetto	1.61	0.59	0.78	5.4	1.6	1.78	1.02	-0.8	1.5	1.00
$\bar{X}$	1.61									
σ^2_G	0.06									
σ^2_F	0.30									
σ^2_A	0.23									
CVG, %	15.8									
CVP, %	34.0									
CVA, %	30.1									
CVG/CVA	0.53									

Note: ** – st – standard*
Source: *obtained as a result of the present study*

According to the trait "seed yield", the most adaptive cultivars with an absolute adaptation coefficient (AAC) greater than 1 were identified – Bacchus and Svitiaz, cultivars Karmazin, Extra Grano Violetto, and Bianco were medium adaptive, and cultivars Karadag, Ukrainian Sloboda, Karadag, Windsor Broad, and Green lowland were classified as low adaptive. For selection practice, seed size is significant. The thousand-kernel weight significantly depends on the varietal characteristics, climatic conditions of cultivation and agricultural practices, and the variability of this trait characterises the plasticity of the genotype.

The findings suggest the presence of a difference in yield and yield stability among the edible bean cultivars evaluated in this study. There is an inverse relationship between yield and yield stability (r = -0.061 at both bean maturity stages), with low yielding cultivars showing the highest stability and high yielding cultivars showing lower stability. This trend in different bean genotypes has been reported previously (Temesgen *et al.*, 2015). According to the thousand-kernel weight (TKW), the cultivars of edible beans under study were conditionally divided into three groups with a low TKW (up to 1,500 g), medium TKW (1,500-2,000 g), and large TKW (over 2,000 g). The first group includes cultivars Karmazin and Ukrainian Sloboda; the second – Karadag, Windsor Broad, Bacchus, and Green lowland; the third group includes Svitiaz, Bianco, and Extra Grano Violetto.

Statistical analysis of the TKW of edible beans showed that the most stable according to the set of indicators (according to σ^2d, and MC, Hom) was the Karmazin cultivar (σ^2d = 3.29, MC = 1.19, Hom = 4,666.9). In terms of the ratio of plasticity (*bi*) and stability (σ^2d) parameters, all varieties Karadag st, Bacchus, Karmazin, Green lowland, Svitiaz, Extra Grano Violetto, and Bianco had a ratio of $bi > 1, \sigma^2d > 0$, i.e., they show better productivity under favourable growing conditions. Ukrainian Sloboda and Windsor Broad cultivars had a ratio of indicators $bi < 1, \sigma^2d > 0$, i.e., they have better results under unfavourable conditions, they are unstable. According to the environmental plasticity coefficient (*bi*), the group of highly plastic or intensive cultivars includes Ukrainian Sloboda, Bacchus, Green lowland, Svitiaz, Bianco, Extra Grano Violetto, i.e., these cultivars respond well to improved growing conditions; the group of relatively low plastic cultivars includes Karmazin, Karadag, and Windsor Broad. The statistical data suggest a strong influence of growing conditions on the TKW of edible bean cultivars and a greater dependence on environmental conditions (CVA = 20.88%) than on the genetic component (CVG = 5.76) and an average CVG/CVA ratio of 0.28.

The Karmazin cultivar stood out in terms of stress resistance (SR), as this cultivar had a minimum gap between the minimum and maximum TKW, indicating a higher resistance of the cultivar to stress and a wider range of its adaptive capabilities, but this cultivar was also characterised by the lowest TKW. According to the compensatory capacity (CC), two cultivars were distinguished among the cultivars under study – Bacchus, Svitiaz, Bianco, and Extra Grano Violetto, since the concept of "compensation" is close to "plasticity", which allows them to be classified as plastic cultivars (Table 8).

***Table 8**. Parameters of adaptive capacity and breeding value of edible bean cultivars by the trait "thousand-kernel weight", g*

Cultivar	$\bar{X}$, r	σ^2d	bi	Hom	Sc	MC	EPI	SR	CC	AAC
Karadag st	1,590	8.56	-0.91	6,723.2	1,602.1	-0.03	0.89	-163	1,561	0.88
Ukrainian Sloboda	1,453	11.92	1.81	5,612.2	1,463.8	3.25	0.80	-304	1,502	0.81
Windsor Broad	1,815	16.40	-3.41	8,760.2	1,828.8	-2.38	1.02	-576	1,723	1.01
Bacchus	1,979	13.84	2.44	10,411.0	1,993.6	3.22	1.10	-410	2,045	1.10
Karmazin	1,325	3.29	0.14	4,666.9	1,334.8	1.19	0.74	-25	1,328	0.74
Green lowland	1,517	10.07	1.30	6,114.8	1,527.9	2.54	0.84	-220	1,550	0.84
Svitiaz	2,059	17.69	3.97	11,266.1	2,073.9	4.47	1.14	-666	2,168	1.14
Bianco	2,126	12.88	2.12	12,011.3	2,141.4	2.80	1.18	-360	2,180	1.18
Extra Grano Violetto	2,354	11.96	1.54	14,734.6	2,371.8	2.18	1.31	-340	2,330	1.31
$\bar{X}$	1,802									
σ^2_G	10,772.44									
σ^2_F	152,285.85									
σ^2_A	141,513.41									
CVG, %	5.76									
CVP, %	21.66									
CVA, %	20.88									
CVG/CVA	0.28									

Note: ** – st – standard*
Source: *obtained as a result of the present study*

In terms of seed yield, the most adaptive cultivars with an absolute adaptability coefficient (AAC) greater than 1 were identified – Bacchus, Svitiaz, Bianco, and Extra Grano Violetto, while Karadag, Ukrainian Sloboda, Windsor Broad, and Green lowland cultivars are medium adaptive and Karmazin cultivar is classified as low adaptive. The main indicator of the nutritional value of beans, as well as other legumes, is the protein content. Studies showed that, on average, the protein concentration increased by 12.37% between the technical and biological ripeness phases. Thus, in the phase of technical ripeness, the maximum accumulation of protein in green grain was observed in the cultivars Windsor Broad (13.51 g/100 g), Bianco (14.30 g/100 g), and Green lowland (14.43 g/100 g), where this indicator is 22.5%, 15.7%, and 30.8% higher than the standard, respectively. Overall, only the Bacchus cultivar had a lower protein concentration than the standard – 10.57 g/100 g (-4.2%).

At the stage of biological ripeness, the dynamics of the cultivars changed slightly and became more even. Thus, the maximum protein concentration was obtained in the Green lowland cultivar – 30.57 g/100 g, which is 27.5% higher than the standard. The protein content of Bianco, Bacchus, and Karmazin cultivars was slightly lower than the standard. Significantly higher concentration was observed in the cultivar Windsor Broad, and slightly higher in the cultivars Svitiaz, Extra Grano Violetto, and Ukrainian Sloboda. Statistical analysis shows that in technical ripeness, varietal characteristics, and weather conditions have a greater impact (CVG 8.58%; CVA 18.39%; CVG/CVA 0.47%) on the protein concentration in grain than in biological ripeness (CVG 2.19%; CVA 10.11%; CVG/CVA 0.22%) (Fig. 4).

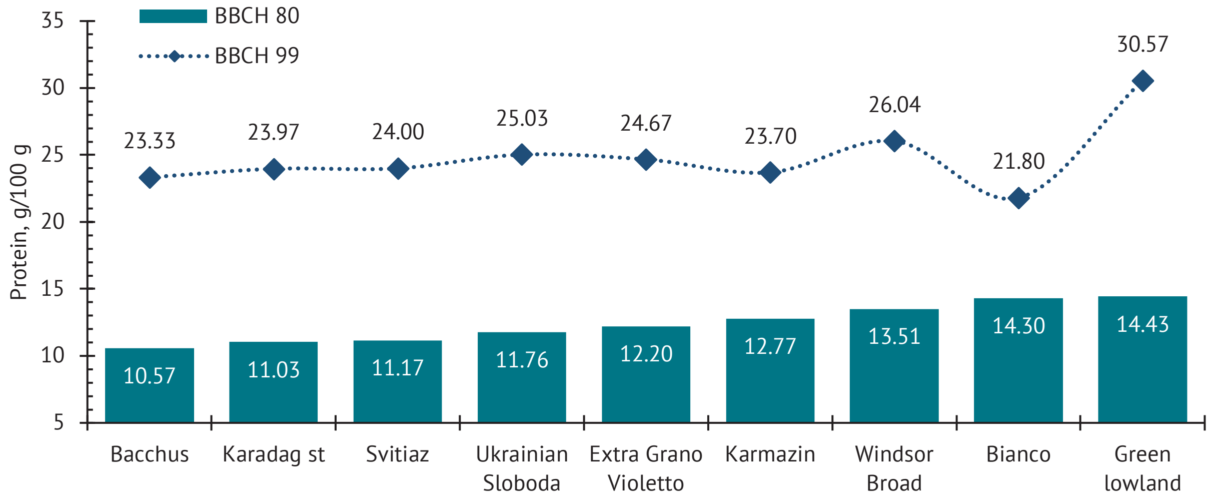


***Figure 4**. Crude protein content at different stages of bean ripeness depending on their cultivar (2020-2022), g/100 g*
***Note:** * – st – standard*
***Source:** obtained as a result of the present study*

No relationship was found between seed protein content and yield, which is in contrast to the findings of analogous phenotypic correlations in pea (Jha *et al.*, 2012) and chickpea (Frimpong *et al.*, 2009). In a study conducted in Finland by C. Lizarazo *et al.* (2015), the difference in protein content between bean cultivars was significantly dependent on the year (environment)×genotype interaction. According to the above researchers, these differences may be conditioned by genotypic differences in nitrogen metabolism in most cultivars.

Analysing the parameters of biochemical composition, it was found that the lowest yielding cultivar Green lowland had the highest dry matter content – 15.04%, which is 2.24% higher than the standard. Overall, only five cultivars outperformed the standard by this indicator (Green lowland, Ukrainian Sloboda, Windsor Broad, Bianco, and Extra Grano Violetto). The most productive and adaptive cultivars Bacchus and Svitiaz accumulated less dry matter than the standard. Over 50% of carbohydrates by weight of green seeds was recorded in the cultivars Windsor Broad (51%), Green lowland (60%), and Bianco (54%), which is 10.0-18.7% more than the standard. The dynamics of fat concentration in green seeds was comparable. Thus, the highest fat concentration was recorded in the Green lowland (0.84%), Bianco (0.82%), Windsor Broad (0.81%), and Extra Grano Violetto (0.80%) cultivars, which is 0.10-0.14% greater than the standard cultivar. All the above biochemical composition indicators contribute to a comprehensive assessment of edible bean cultivars by calculating the energy value of the products obtained. The results of determining the calorific value of 100 g of raw weight of green beans helped to identify the most valuable ones: Green Lowland (305 kcal), Bianco (242 kcal), and Windsor Broad (266 kcal), whose indicators are 23.6-41.5% or 50.81-89.42 kcal higher than the standard cultivar Karadag (Table 9).

***Table 9**. Nutritional value of green beans of edible bean (BBCH 80), (2020-2022), (X ± SD)*

Cultivar	Dry matter, %	Carbohydrates (g/100 g of wet weight)	Fats (g/100 g of wet weight)	Energy, kcal 100 g of wet weight
Karadag st	12.81±1.80	41±5.3	0.71±0.12	216±26
Ukrainian Sloboda	13.51±1.35	46±2.9	0.79±0.14	239±15
Windsor Broad	14.30±1.20	51±7.4	0.81±0.14	266±34
Bacchus	10.95±1.04	38±4.9	0.71±0.11	202±25
Karmazin	12.75±2.96	49±6.6	0.79±0.14	253±41
Green lowland	15.04±1.50	60±7.8	0.84±0.14	305±39
Svitiaz	11.93±2.91	43±4.6	0.76±0.12	225±29
Bianco	15.02±1.64	54±8.0	0.82±0.14	280±40
Extra Grano Violetto	13.47±1.54	47±6.2	0.80±0.14	242±32
$\bar{X}$	13.31	48	0.78	246
σ_G^2	1.19	12.72	0.004	

Table 9. Continued

Cultivar	Dry matter, %	Carbohydrates	Fats	Energy, kcal 100 g of wet weight
		g/100 g of wet weight		
σ_F^2	6.43	90.38	0.018	
σ_A^2	5.24	77.6	0.014	
CVG, %	8.20	7.47	8.13	
CVP, %	19.05	19.90	17.18	
CVA, %	17.19	18.44	15.13	
CVG/CVA	0.48	0.40	0.54	

Note: ** – st – standard*
Source: *obtained as a result of the present study*

The symbiotic potential of edible beans is significantly greater than that of other legumes. The intensive nitrogen fixation lasts from the budding phase to the full filling of the beans in the upper tiers. On average, during the study period, the total number of nodules varied greatly, ranging within 11-51 pcs./plant (CV = 49%), while the number of active nodules varied significantly less – 6.63-12.76 pcs./plant (CV = 21%). The efficiency of the symbiotic apparatus depends on the number of active nodules. Active nodules are much larger and contain legoglobin. The total mass and mass of active nodules varied greatly (CV = 28% and 37%, respectively). The formation of these indicators was significantly influenced by both varietal characteristics (CVG = 22.62% and 21.90%) and, to an even greater extent, growing conditions (CVA = 48.36% and 53.15%), which is confirmed by the moderate strength of the CVG/CVA ratio, especially when studying active nodules.

The analysis of the data obtained contributed to the selection of cultivars with the best development of the nodulation apparatus, where the highest weight and number of nodules were noted – these are the cultivars Ukrainian Sloboda and Bianco, where the number of nodules was 51 pcs./plant and 39 pcs./plant, while their weight was 0.70 g/plant and 0.80 g/plant. The maximum number of active nodules was observed in the cultivars Svitiaz (12.76 pcs./plant), Ukrainian Sloboda (10.70 pcs./plant), and Bianco (10.40 pcs./plant). The highest percentage of active nodules of the total number was obtained in the cultivar Green lowland – 78.7%, which accounted for 80.6% of their total weight. A large number of nodules, but with a low weight, was obtained in the Extra Grano Violetto cultivar (Table 10).

Table 10*. Development of the nodulation apparatus of edible bean cultivars (BBCH 80), (2020-2022) (X ± SD)*

Collection sample	Nodules, pcs/plant		Bulb weight, g/plant	
	general	active	general	active
Karadag st	23 ± 9.5	6.6 ± 3.6	0.56 ± 0.25	0.28 ± 0.11
Ukrainian Sloboda	51 ± 7.1	10.7 ± 3.3	0.70 ± 0.36	0.41 ± 0.20
Windsor Broad	14 ± 4.5	9.7 ± 3.7	0.71 ± 0.34	0.47 ± 0.21
Bacchus	17 ± 5.3	9.4 ± 3.5	0.58 ± 0.15	0.24 ± 0.05
Karmazin	21 ± 5.7	9.8 ± 3.6	0.51 ± 0.23	0.23 ± 0.10
Green lowland	11 ± 2.5	8.6 ± 2.3	0.33 ± 0.18	0.26 ± 0.14
Svitiaz	18 ± 3.1	12.8 ± 3.2	0.33 ± 0.06	0.22 ± 0.03
Bianco	39 ± 12.3	10.4 ± 4.6	0.80 ± 0.16	0.46 ± 0.10
Extra Grano Violetto	28 ± 4.6	6.1 ± 1.8	0.78 ± 0.18	0.61 ± 0.14
$\bar{X}$	25	9.34	0.59	0.35
σ_G^2	15.16	3.77	0.02	0.01
σ_F^2	204.96	18.76	0.10	0.04
σ_A^2	189.80	14.99	0.08	0.04
CVG, %	15.81	20.78	22.61	21.90
CVP, %	58.13	46.37	53.38	57.49
CVA, %	55.94	41.45	48.36	53.15
CVG/CVA	0.28	0.50	0.47	0.41

Note: ** – st – standard*
Source: *obtained as a result of the present study*

The best development of the nodulation apparatus was found in the cultivars Ukrainian Sloboda, Windsor Broad, Bianco, and Extra Grano Violetto, which had the highest concentration of legoglobin, the highest activity of symbiotic potential and, accordingly, the highest amount of fixed nitrogen. Thus, plants of the Extra

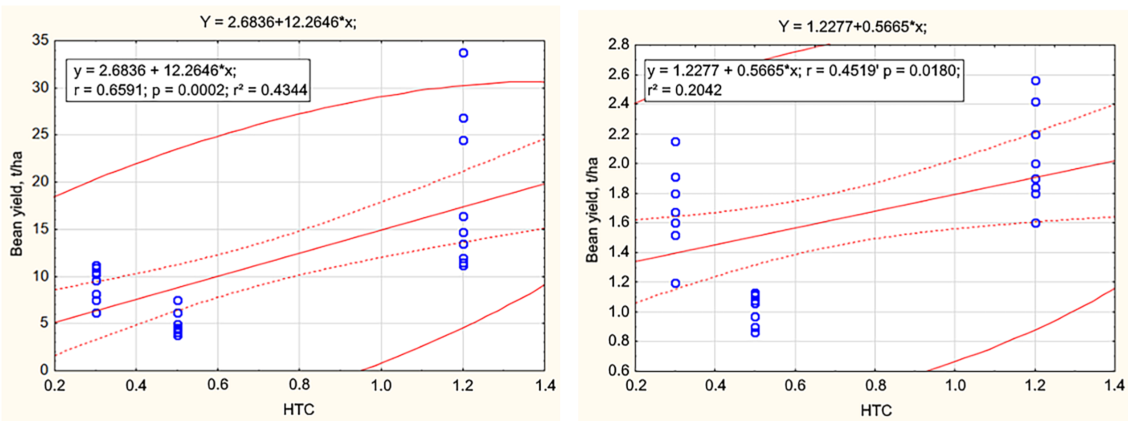
Grano Violetto cultivar had the highest nitrogen fixation among others – 75.7 kg/ha, which is 25.5 kg or 54.0% greater than the standard cultivar. The Ukrainian Sloboda and Windsor Broad cultivars fixed significantly more nitrogen than the standard – 67.7 kg/ha (+37.7% to st) and 71.0 kg/ha (+44.5% to st), respectively, compared to the standard cultivar. Bacchus, Karmazin, and Green lowland cultivars fixed slightly less nitrogen than the standard. Statistical analysis confirmed the noticeable influence of growing conditions on the formation of symbiotic potential productivity. Overall, the influence of environmental conditions was almost twice as strong as the genetic component: CVA = 41.28-53.44%; CVG = 19.26-27.35%, which is confirmed by the CVG/CVA ratio of 0.47-0.53 (Table 11).

***Table 11**. Activity of the symbiotic apparatus of edible bean cultivars (BBCH 80), (2020-2022) (X ± SD)*

Collection sample	Legoglobin content, mg/g	Active symbiotic potential, thsd kg×day/ha	Fixed nitrogen, kg/ha
Karadag st	4.52 ± 1.29	15.7 ± 8.2	49.1 ± 26.7
Ukrainian Sloboda	5.82 ± 1.73	19.3 ± 8.3	67.7 ± 25.2
Windsor Broad	6.45 ± 2.15	22.0 ± 7.9	71.0 ± 27.0
Bacchus	3.34 ± 1.24	11.3 ± 5.6	45.0 ± 20.6
Karmazin	4.16 ± 1.06	13.7 ± 7.4	47.0 ± 20.3
Green lowland	4.46 ± 1.17	12.0 ± 6.5	46.3 ± 22.6
Svitiaz	4.34±1.41	15.7 ± 9.0	50.0 ± 23.0
Bianco	5.15±2.03	17.7 ± 9.7	50.0 ± 30.6
Extra Grano Violetto	7.58±2.56	24.3 ± 8.5	75.7 ± 28.7
$\overline{X}$	16.85	5.09	55.8
σ_G^2	21.24	0.96	211.71
σ_F^2	102.33	5.38	975.96
σ_A^2	81.09	4.42	764.25
CVG, %	27.35	19.26	26.10
CVP, %	60.03	45.55	56.03
CVA, %	53.44	41.28	49.58
CVG/CVA	0.51	0.47	0.53

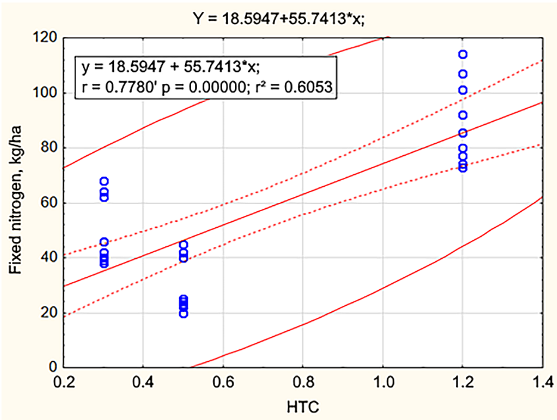
Note: ** – st – standard*
Source: *obtained as a result of the present study*

The statistical analysis revealed a significant relationship on the Chaddock scale – r = 0.6591 between the yield of beans in the phase of technical ripeness and the hydrothermal coefficient (HTC): y = 2.6836 + 12.2646 - x, where x is HTC, g, y is yield, t/ha. A moderate relationship (r = 0.4519) was found between the yield at the stage of biological maturity of seeds and the HTC, which is explained by the regression equation y = 1.2277 - 0.5665 - x, where x is the HTC, y is the yield at biological maturity. Considering the statistical reliability of the equations, the corresponding dependence is presented graphically in Figures 5, 6.



BBCH 80 BBCH 99

***Figure 5**. Correlations between edible bean yields in the phase of technical maturity and HTC and the amount of fixed nitrogen by plants and HTC*
Source: obtained as a result of the present study



BBCH 80

Figure 6*. Correlations between the volume of fixed nitrogen in plants and the HTC index*

Note: ** – st – standard*

Source: *obtained as a result of the present study*

Statistical studies of the relationship between the volume of fixed nitrogen and the hydrothermal coefficient revealed a strong relationship (r = 0.7780) in edible beans, which is explained by the regression equation y = 18.5947 + 55.7413 - x, where x is the HTC, y is the amount of fixed nitrogen.

Statistical analysis showed significant differences in the interaction of genotypes with the environment in terms of growth and productivity parameters, which affects the difference in yield (both immature grain and seeds) of genotypes; sufficient differences between the environment by years of research to distinguish genotypes. Thus, genotypes did not show analogous development for all years, which is a consequence of unstable climatic conditions (precipitation and temperature). L. Barroso *et al.* (2016) and A. Santos *et al.* (2017) found comparable results for grain yields of cowpea genotypes in multi-environmental analyses in Mato Grosso, Sul, Brazil, showing that edaphoclimatic factors had a significant impact on genotype adaptability and stability, and that additional analyses are needed to identify genotypes that are adapted to multiple environments. The findings of the study conducted in 2020-2023 by S. Barvinchenko *et al.* (2023) showed the variability of quantitative traits of bean plants that are comparable to the ones presented in this study.

C. Grasshoff (1990), F.J. López-Bellido *et al.* (2005) and E. Rezaei *et al.* (2023), with a substantial gap between the years of their studies, note that climatic variables also explain the high variation in cultivar performance, as it was based on three years of data during which the bean cultivars were grown. It is clear that air temperature and precipitation are the limiting factors for the formation of bean productivity, which is confirmed by the data presented in Figure 5. The findings are in line with previous reports that high temperatures and insufficient rainfall are the main factors limiting yields in temperate regions of Europe.

In the current study, the average amount of atmospheric nitrogen fixed by beans was 55.8 kg/ha. This level of biological nitrogen fixation is average, confirming previous reports by G. Ntatsi *et al.* (2018) on the high efficiency of biological nitrogen fixation by beans. In a field study conducted in the British Isles over several consecutive years, M. Maluk *et al.* (2022) observed that pulses can cover almost all of their own nitrogen requirements through biological fixation in a relatively wet and cool climate. E. Jensen *et al.* (2010) reported nitrogen fixation by beans within 73-211 kg/ha. In another study by M. Oliveira *et al.* (2019), it was reported that the average nitrogen fixation for beans was 41 kg, and the findings of S. Klippenstein *et al.* (2021) suggest a significant inter-varietal variance in terms of nitrogen fixation volume, which is analogous to the findings obtained in this study. The values of biological nitrogen fixation estimated in the current study appear to be the result of sufficient soil nitrogen levels.

Thus, the findings of other researchers' studies are largely comparable to the findings presented in this study. However, it was noted that productivity and nitrogen fixation rates vary significantly depending on the genotype, technology, and region of cultivation.

CONCLUSIONS

As a result of the study, the promising cultivars Bianco and Extra Grano Violetto with the shortest period of technical ripeness – 78 days – were identified. Overall, a rather extended period of technical maturity of edible bean cultivars from 78 to 105 days contributes to the production of fresh bean products within 27 days without additional operations. Only one cultivar was identified – Karmazin – which had a significantly higher attachment of the first (lower) bean (which facilitates mechanised harvesting), depending on the year of research, this indicator varied at 11-16 cm. Evaluation of edible bean cultivars by individual productivity parameters showed a significant variation in the number of shoots per plant and the number of beans depending on the year, while the number of seeds per bean varied less significantly. The Svitiaz and Bianco cultivars were stable for this trait – 4.0 pcs./plant, compared to 2-3 and 2-4 pcs./plant for other cultivars. The analysis of the trait "weight of beans per plant" contributed to the selection of two cultivars with a significantly higher value – 123.65 g in the Windsor Broad cultivar and 103.57 g in the Bianco cultivar. The study helped to determine the proportion of immature seeds in the beans – an average of 52%. According to this trait, the cultivars Bacchus, Svitiaz, Bianco, and Windsor Broad were identified, with the share of immature seeds ranging within 54.7-78.9%. These findings will help forecast the conditional harvest of the consumer portion of the crop.

The study of the ecological plasticity and stability of the bean contributed to the selection of the Windsor

Broad, Svitiaz, and Bianco cultivars with a ratio of indicators $bi > 1$, $\sigma^2 d > 0$ – i.e., these cultivars give better results under favourable growing conditions and were characterised by a wide agro-ecological adaptability and belong to the cultivars of intensive type according to the characteristic "yield of green beans". In terms of seed yield, the cultivars under study slightly exceeded the standard, but the Bacchus and Svitiaz cultivars stood out with a maximum of 1.92 t/ha and 1.90 t/ha, which can provide high seed yields, are characterised by high plasticity and respond well to improved growing conditions. Statistical analysis revealed a significant correlation between bean yield at the stage of technical maturity and the HTC index and a moderate correlation between seed yield and HTC. Varieties with high energy value were identified: Green lowland (305 kcal), Bianco (280 kcal), and Windsor Broad (266 kcal). The best development of the nodulation apparatus and increased nitrogen fixation were found in the cultivars Extra Grano Violetto (75.7 kg/ha), Ukrainian Sloboda, and Windsor Broad – 67.7 kg/ha and 71.0 kg/ha, respectively. A strong dependence of the nitrogen-fixing capacity on the hydrothermal coefficient ($r = 0.7780$) was found.

The environmental testing of edible bean cultivars revealed that the conditions of the Ukrainian Forest-Steppe are suitable for growing edible beans for both food and seed purposes. Further research prospects include zoning of the cultivars under study in other zones of Ukraine, investigating changes in nutritional value depending on the methods of storage and processing of immature bean seeds.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Екологічна пластичність, стабільність та азотфіксуюча здатність сортів бобу овочевого у Лісостепу України

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Анотація. Метою досліджень передбачалося дослідження впливу кліматичних умов років досліджень на зміну показників продуктивності й екологічної пластичності й стабільності сортів бобів овочевих. Крім цього, досліджено азотфіксуючий потенціал сортів бобів овочевих для біологізації галузі землеробства. Дослідження проведені в умовах навчально-виробничого відділу Уманського національного університету садівництва впродовж 2020-2022 рр., використано дев'ять сортів бобів овочевих. Для вивчення параметрів адаптивної мінливості використано стандартні методи статистичного аналізу. У результаті порівняльного вивчення дано характеристику різних параметрів адаптивного потенціалу сортів бобів овочевих за ознаками: настання фази технічної стиглості: Б'янко і Екстра Грано Віолетто – 78 діб. За врожайністю й адаптивністю у фазу технічної стиглості виділилися сорти Віндзорські (16,42 т/га), Б'янко (13,73 т/га) і Свитязь (11,51 т/га), за врожайністю й адаптивністю у фазу біологічної стиглості сорти Бахус (1,92 т/га) і Свитязь (1,90 т/га); з підвищеним вмістом протеїну у незрілому зерні сорти Кармазін (12,77 г/100 г), Віндзорські (13,51 г/100 г), Б'янко (14,30 г/100 г), Зелені низинні (14,43 г/100 г); з високою азотфіксуючою здатністю сорти Українські слобідські (67,7 кг/га), Віндзорські (71,0 кг/га) і Екстра Грано Віолетто (75,7 кг/га). Результати статистичного аналізу показали істотний вплив екологічних умов на формування показників продуктивності сортів бобу овочевого і більшу залежність від екологічних умов (CVA = 10,40-82,7 %) аніж від генетичної складової (CVG = 5,76-39,7 %). Отримані дані вказують, що є тенденція зворотного зв'язку між врожайністю і стабільністю врожаю, причому низьковрожайні сорти демонструють стабільність, а високоврожайні сорти – нестабільні. Представлені результати дають уявлення про зміну параметрів продуктивності бобів овочевих за контрастних погодних умов, що дає змогу виділити сорти з високою продуктивністю на продовольчі цілі та з більшою часткою високобілкової й енергетично цінної споживчої продукції. Виділено сорти з підвищеною азотфіксуючою здатністю, що сприятиме зменшенню використання синтетичних добрив

Ключові слова: урожайність; адаптивність; насіння; харчова цінність; вміст протеїну