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Adaptive potential and breeding value of daikon varieties (*Raphanus sativus* L. convar. *acanthiformis* Sazon.) under different sowing dates in the conditions of the Forest-Steppe of Ukraine

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Abstract. Global climate change and the shifting of agroclimatic zones in Ukraine necessitate a revision of traditional elements of vegetable crop cultivation technology to ensure stable food security. The aim of the study was to evaluate the adaptive potential of daikon varieties depending on sowing dates in order to achieve stable yields under modern agroclimatic transformations. Analysis of variance (Type III SS) showed that 92.5% of yield variation was determined by the studied factors. The greatest influence was exerted by sowing date (62.6%, $p < 0.001$), which significantly exceeded the effect of variety (15.4%, $p < 0.001$), while the influence of year was minor (4.1%, $p < 0.001$). Among interactions, only the “sowing date $\times$ year” combination was statistically significant (7.5%, $p < 0.001$). All varieties were characterised by high relative stability (S_g , 6.0-14.4%). According to ANOVA and Tukey's HSD test, significant differences between varieties were established for most sowing dates ($p < 0.05$). The variety 'Minowase' outperformed 'Gulliver' in the second ten-day period of July to the first ten-day period of August (50.8-58.9 vs 47.4-54.6 t/ha). The early sowing date (first ten-day period of July) did not provide significant differences between genotypes. All varieties showed high plasticity, except for 'Gulliver' in the early sowing period ($b_i = -0.39$). Reduced plasticity for 'Minowase' was observed in the first ten-day period of August ($b_i = 0.89$). The highest sensitivity to environmental conditions was recorded for the second ten-day period of July ($b_i = 1.43$ -2.20). The highest breeding value indices were obtained for sowing in the first ten-day period of August (34.8-40.9), which was associated with high yield (51.0-56.4 t/ha) and stability (2.9-3.1). The results substantiate the expediency of using the variety 'Minowase' and optimising sowing dates (late July – early August) as an effective agrotechnological tool for increasing productivity and stability of daikon cultivation under climate change conditions

Keywords: ecological plasticity; genotype stability; root yield; hydrothermal stress; adaptive capacity

Introduction

Climate change poses a threat to the stability of vegetable crop production. The use of ecologically adaptable genotypes, which are characterised by low sensitivity to adverse abiotic factors and ensure stable yields under various soil and climatic conditions, plays a key role in the adaptation process. At the same time, optimising sowing dates allows the negative impact of stress factors, pests and diseases to be minimised at critical stages of plant development.

According to X. Wang *et al.* (2025), global food security faces a dual challenge. Firstly, demographic expansion – with the population projected to reach 9.7 billion by 2050 and nearly 11 billion by the end of the century – requires a proportional increase in resources. Secondly, the agricultural sector generates around 33% of anthropogenic greenhouse gas emissions. As part of the transition to sustainable food systems, the intensive expansion of vegetable and fruit growing

is of critical importance: to provide for the diets of 10 billion people, global fruit and vegetable production must increase by 50-150% by the middle of the century.

Research by E.A. Dumitru *et al.* (2023) has shown that in the future, heat stress and droughts will render many areas that currently have an optimal climate unsuitable for growing vegetable crops in open fields. Research by A. Paul & R. Machavaram (2026) highlighted that the destabilisation of the Indian vegetable market is a direct consequence of weather anomalies. The unpredictability of monsoons and temperature fluctuations not only disrupt the production cycle but also trigger a chain reaction: from logistical disruptions to a sharp rise in product prices. Under such conditions, the adoption of climate-smart agriculture methods becomes a prerequisite for maintaining the sector's profitability. In Ukraine, the average annual temperature,

according to V. Vyshnevskiy (2025), has risen by more than 3°C. This has caused a shift in climatic zones of 500 km and, as highlighted by S. Klok *et al.* (2023), led to the expansion of “tropical nights” after 2000, exacerbating soil drought and temperature stress. Such changes have negatively affected traditional cold-tolerant brassica root crops due to impaired assimilation, premature bolting and the development of physiological disorders, in particular, softness, cracking and internal browning of tissues resulting from intensive lignification, disruption of Ca²⁺ transport and the activation of enzymatic oxidation of phenolic compounds. According to R.R. Babu *et al.* (2024), the stable development of the vegetable sector will depend directly on the adaptation of agronomic practices to these changes, in particular through crop diversification and the adjustment of traditional sowing dates.

Analysing the characteristics of daikon cultivation, N. Khusanov *et al.* (2024) established a significant influence of sowing dates on field germination: when sown in July, germination was 97-98%, whereas in August it fell to 76% due to temperature stress, demonstrating the critical importance of adjusting sowing dates to maintain the necessary plant density. A. Kaur & N. Singh (2022) emphasised that the strategic combination of variety selection and sowing date is a critical factor for maximising radish yield under a changing climate. Incorrect variety selection can completely negate the benefits of optimal sowing dates, causing physiological disorders in the root crops. According to a study by I. Fedosiy *et al.* (2025), regulating sowing dates is a strategic method for adapting daikon to hydro-thermal challenges, as crop yield and quality depend directly on this. Sowing in the second half of summer not only promotes maximum root mass accumulation but also minimises the risks of pest damage and physiological disorders. S. Parajuli & P. Dhital (2023) argued that optimising plant spacing parameters is also critical for minimising competition for resources, as excessive density inhibits root morphogenesis. The key issue behind

low yields lies in the failure to adhere to sowing patterns, which limits vegetative development and the realisation of the crop's biological potential. Rational spatial geometry ensures better sunlight exposure and nutrient uptake, which is crucial for the formation of yield mass and quality.

At the same time, recent studies have confirmed that the limiting factors affecting daikon yield are largely due to soil degradation and an imbalance in mineral nutrition. In particular, Shilpa *et al.* (2023) demonstrated that the systematic application of mineral fertilisers alone, without integrated approaches, leads to a decline in soil fertility, whereas the synergy of organic and microbiological components results in a yield increase of over 10%. This confirmed the advisability of transitioning to sustainable fertilisation systems within the framework of adaptive technologies. An additional destabilising factor is the prolonged cultivation of a single crop in a monoculture. A. Nowak *et al.* (2024) found that the absence of crop rotation leads to a transformation of the soil microbiome structure and a reduction in enzymatic activity, which impairs the bioavailability of nutrients. This highlights the need to implement scientifically grounded crop rotations and strategies for the biologisation of agriculture.

Despite a significant number of studies on the influence of sowing dates and genotypic characteristics on the productivity of *Raphanus* crops, their combined effect on the formation of ecological plasticity and stability of daikon varieties under conditions of climate change remains insufficiently studied. Most existing studies have been conducted in other soil and climate zones and do not account for the specific characteristics of the Ukrainian Forest-Steppe, which limits the possibility of directly extrapolating the results. The lack of generalised data on “genotype × environment” interactions in combination with sowing dates complicates the scientifically grounded selection of varieties and the optimisation of cultivation techniques to ensure stable yields. Thus, the aim of this study was to

determine the parameters of ecological plasticity, stability and breeding value of daikon varieties depending on sowing dates under the conditions of the Ukrainian Forest-Steppe in order to optimise cultivation techniques.

Materials and Methods

Field experiments were conducted during 2022-2024 at the experimental fields (educational laboratory "Fruit and Vegetable Garden") of the Department of Vegetable Growing and Protected Cultivation at the National University of Life and Environmental Sciences of Ukraine. The coordinates of the experimental site were 50°22'42.21"N, 30°30'05.17"E, with an altitude of 158 m above sea level. The soils of the experimental plots were soddy-podzolic on loess. The granulometric composition of the soil was light loam. Agrochemical properties were as follows: pH of the salt extract 6.74, organic matter (humus) 2.71%, nitrate nitrogen 6.42 mg/kg, ammonium nitrogen 11.72 mg/kg,

available phosphorus 568.83 mg/kg, and available potassium 152.93 mg/kg.

Meteorological conditions during 2022-2024 were characterised by a general trend towards warming and increased moisture relative to long-term averages (LTA) (Fig. 1). On average over the study years, the annual temperature exceeded the norm by 1.6°C, and the annual precipitation total exceeded the LTA by 216.7 mm. Temperature conditions during the crop growing period (July-October) were characterised by an excess over long-term averages by 0.9-2.6°C, with the most pronounced warming observed in August (23°C). The moisture regime during this period was uneven: the average monthly precipitation ranged from 49.2 to 109.9 mm. In particular, July was characterised by anomalously high precipitation (deviation of +41.9 mm from LTA), whereas August and September showed a moisture deficit (-6.8 and -7.8 mm from LTA, respectively), followed by increased precipitation in October (35.5 mm above the norm).

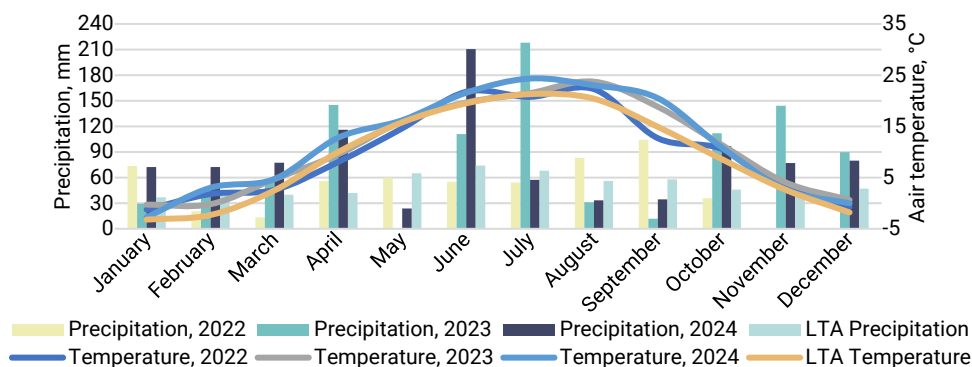


Figure 1. Monitoring of meteorological indicators in 2022-2024

Source: developed by the authors based on own research

The research programme was based on a two-factor design. Factor A comprised varietal characteristics of daikon: 'Gulliver' (control, bred in Ukraine) and 'Minowase' (the Netherlands). The variety 'Gulliver' served as the control as a widely distributed Ukrainian variety with high ecological plasticity under the agroclimatic conditions of Ukraine. Factor B included four sowing dates: the

first, second (control), and third ten-day periods of July, and the first ten-day period of August. Optimisation of daikon sowing dates was based on consideration of its photoperiodic response as a long-day crop. The selection of a sowing date that ensures active vegetation under shortening daylight conditions is critical for preventing premature bolting. A rationally determined sowing date

made it possible to synchronise plant development with periods of low activity of the cabbage root fly, thereby minimising entomological damage to crops. The hydrothermal regime – characterised by decreasing temperatures alongside increasing air and soil moisture – acted as a key factor in preventing physiological disorders such as bitterness accumulation and the development of pithiness in roots. At the same time, the temporal placement of sowing dates, in accordance with the duration of the growing period, limited the harvesting window, ensuring the attainment of marketable weight and high biochemical quality.

The experiment was established using a randomised block design with three replications. The area of the accounting plot was 5 m². Sowing was carried out manually to a depth of 4–5 cm, following a planting scheme of 45 × 10 cm. Harvesting was performed differentially, taking into account the duration of the growing period of the varieties: on the 50th day after mass emergence for ‘Gulliver’ and on the 60th day for ‘Minowase’. Records were taken at the onset of phenological stage BBCH 49 (Biologische Bundesanstalt, Bundessortenamt and Chemical Industry), when the root crop had reached the size and shape typical of the variety. This approach allowed the recording of maximum marketable productivity while preventing the risk of physiological overmaturity and tissue coarsening in the roots. The study adhered to the principles of the Convention on Biological Diversity (1992). For a comprehensive evaluation of daikon genotypes, the following traits were analysed: mean yield, coefficient of variation (CV), general (GAC_i) and specific (SAC_i) adaptive capacity, relative stability (Sg_i), ecological plasticity (regression coefficient b_i), and breeding value of the genotype (SVG_i). The adaptive response of the studied varieties to growing conditions was assessed through their general and specific adaptive capacity. According to the methodological approaches of A. Tyshchenko *et al.* (2023), GAC_i was defined as the mean value of a quantitative trait based on trials across different environmental gradients, whereas SAC_i was

considered as the amplitude of deviation from the mean value in a specific environment. The ability of a genotype to maintain stability of a given phenotype across a wide range of growing conditions due to internal regulatory mechanisms was identified as genetic stability. The parameter of ecological plasticity was calculated using the regression coefficient of the genotype against environmental conditions, allowing a quantitative assessment of the intensity of phenotypic variability in response to changes in external factors. The mathematical determination of the effects of general and specific adaptive capacity was based on the study of a population consisting of n genotypes tested in m environments with c replications. In this case, the number of replications equals c :

$$x_{ikr} = U + V_i + d_k + (Vd)_{ik} + e_{ikr}, \quad (1)$$

where x_{ikr} – phenotypic value of the i -th genotype grown in the k -th environment in the r -th replication; U – overall mean of the entire set of phenotypes; V_i – effect of the i -th genotype; d_k – effect of the k -th environment; $(Vd)_{ik}$ – effect of the interaction between the i -th genotype and the k -th environment; e_{ikr} – effect determined by random factors and attributed to the e_{ikr} phenotype.

The elements of the model are subject to the following constraints:

$$\begin{aligned} \sum_i v_i &= \sum_k d_k = \sum_k (vd)_{ik} = \\ &= \sum_k (vd)_{ik} = \sum e_{ik} = 0 \end{aligned} \quad (2)$$

The evaluation methodology consisted of a preliminary analysis of variance followed by the identification of parameters of adaptability and stability. The value V_i was taken as the effect of general adaptive capacity. Specific adaptive capacity was calculated as a deviation from the sum $U + V_i$ and included both the linear effect of the environment and the non-linear component of the interaction $(Vd)_{ik}$.

The parameters of specific adaptive capacity were determined:

$$\sigma^2 SAC_i = \frac{\sum_{k=1}^m (SAC_{ik})^2}{m-1} - \frac{\sigma_e^2}{c}, \quad (3)$$

where $\sigma^2 SAC_i$ – variance of specific adaptive capacity of the i -th genotype (an indicator of its genetic stability); SAC_{ik} – effect of specific adaptive capacity of the i -th genotype in the k -th environment, calculated as a deviation from the sum $U + V_i$; m – number of environments in the study; σ_e^2 – random variance (mean square error) obtained from the analysis of variance; c – number of replications in each environment.

$$\sigma SAC_i = \sqrt{\sigma^2 SAC_i}, \quad (4)$$

where σSAC_i – the standard deviation of the specific adaptive capacity of the i -th genotype.

To assess the variability of traits comparatively, the relative stability coefficient was calculated (Sg_i):

$$Sg_i = \frac{\sigma_{SAC_i}}{U + GAC_i} * 100 \%. \quad (5)$$

The ecological stability of genotypes was assessed using the relative stability index (Sg_i) by classifying the obtained values into five categories: high stability ($0 \leq Sg_i \leq 25$), stability ($26 \leq Sg_i \leq 50$), moderate stability ($51 \leq Sg_i \leq 75$), instability ($76 \leq Sg_i \leq 100$) and high instability ($Sg_i > 100$).

Varietal plasticity was assessed using the regression coefficient b_i :

$$b_i = \frac{\sum X_{IR} * d_R}{\sum d_R^2}. \quad (6)$$

The regression coefficient b_i served as an indicator of the ecological plasticity of genotypes: values of $b_i > 1$ indicated high sensitivity of the variety to improved growing conditions (intensive type); $b_i < 1$ indicated a low response to agronomic practices and high adaptability to unfavourable factors; at $b_i = 1$, a complete correlation between changes in yield and environmental conditions was observed.

Comprehensive selection of genotypes based on productivity and stability was carried out using the breeding value index (SVG):

$$SVG_i = U + GAC_i - p \sigma_{SAC_i}. \quad (7)$$

The degree of variability of the studied traits was assessed using the coefficient of variation (CV, %), applying the following classification: low variability at $CV \leq 10\%$, moderate at $10\% < CV \leq 20\%$, and high at $CV > 20\%$.

Statistical analysis of the experimental data was performed using JASP software (Version 0.95.4, JASP Team, 2025). The calculations included a multifactor analysis of variance (ANOVA) to determine the significance of the effects of year, variety, sowing date, and their interactions. Comparison of mean values was carried out using Tukey's HSD post hoc test at a significance level of $p < 0.05$. To quantify the contribution of each factor to the overall variability of the traits, the partial eta-squared (η_p^2) index was calculated. The precision of mean yield values was assessed using the pooled standard error (SE). The applied statistical methods and mathematical models ensured the reliability of the obtained results, allowing conclusions to be drawn regarding the adaptive characteristics of daikon varieties under different sowing dates.

Results and Discussion

Assessment of daikon yield (2022-2024) indicated the dominant importance of cultivation technology elements. According to the results of the three-factor analysis of variance (Table 1), the main factor influencing variability of this trait was the sowing date, for which the effect size (η_p^2) was 0.894 at $p < 0.001$. The influence of the variety factor was also characterised by high statistical significance ($F = 99.2$; $p < 0.001$), although its share in the total variance ($\eta_p^2 = 0.674$) was lower compared with sowing dates. The influence of annual weather conditions was the smallest among the studied factors ($\eta_p^2 = 0.357$). The three-factor analysis of variance confirmed the high representativeness of the selected model, in which the predominant share of yield variation was determined by the influence of controlled factors with minimal contribution

from random error. The sowing date was identified as the key determinant of productivity, with its importance significantly exceeding the contribution of varietal characteristics and annual weather conditions. At the same time, the statistically significant interaction between the sowing date and seasonal meteorological

parameters indicates the need for an adaptive approach to cultivation technology in order to fully realise the genetic potential of the varieties. It was established that the total contribution of the studied factors to the variation in daikon yield amounted to 92.5%, whereas only 7.5% was attributable to random deviations (Fig. 2).

Table 1. Results of the analysis of variance examining the effect of the factors under study on daikon yield (2022-2024)

Cases	Sum of squares	df	Mean square	F	p	η^2	η_p^2
Variety	256.360	1	256.360	99.205	<0.001	0.154	0.674
Sowing date	1,040.821	3	346.940	134.258	<0.001	0.626	0.894
Year	69.003	2	34.501	13.351	<0.001	0.041	0.357
Variety * Sowing date	30.017	3	10.006	3.872	0.015	0.018	0.195
Variety * Year	1.496	2	0.748	0.289	0.750	8.991×10^{-4}	0.012
Sowing date * Year	123.978	6	20.663	7.996	<0.001	0.075	0.500
Variety * Sowing date * Year	17.825	6	2.971	1.150	0.349	0.011	0.126
Residuals	124.038	48	2.584				

Note: the Type III sum-of-squares method was used. Statistical significance was set at $p < 0.05$. The symbol η_p^2 denotes the partial eta-squared (a measure of the strength of the effect)

Source: developed by the authors based on own research

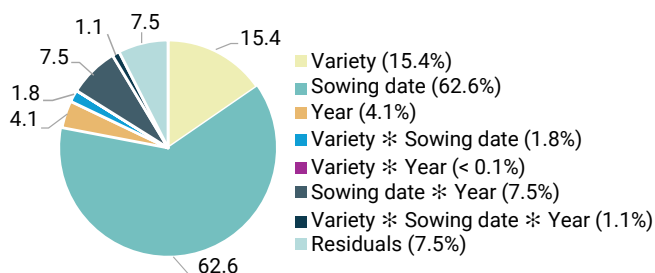


Figure 2. Structure of the influence of the studied factors on the variability of daikon yield (based on the η^2 coefficient), % (2022-2024)

Source: developed by the authors based on own research

Graphical visualisation of the data (Fig. 3) made it possible to identify a clear pattern in yield variation. In particular, regardless of variety and year of study, an increase in yield was observed from the first to the third ten-day period of July, followed by a decline in yield in the first ten-day period of August. The high precision of the experiments is confirmed by the small length of the error bars (95% confidence intervals) relative

to the mean values, indicating data stability and reliability of the measurements. According to the results of the statistical significance assessment using Tukey's HSD test, the variety 'Minowase', when sown in the third ten-day period of July and the first ten-day period of August, demonstrated significantly higher yields compared with the control variety (Table 2). The increase amounted to 4.3-5.4 t/ha (7.9-10.6%), corresponding to yields

of 56.4–58.9 t/ha. Analysis of sowing dates for the variety 'Gulliver' indicates that sowing in the third ten-day period of July and the first ten-day period of August ensured a significant increase in yield to 51.0–54.6 t/ha, which is 3.6–7.2 t/ha (7.6–15.2%) higher than the control (second ten-day period of July). At the same time, when sown in the

first ten-day period of July, yield indicators were statistically similar to the control variant. A similar trend was observed for the variety 'Minowase': the maximum yield relative to the control was recorded for sowing in the third ten-day period of July and the first ten-day period of August, with an increase of 5.6–8.1 t/ha (11.0–15.9%).

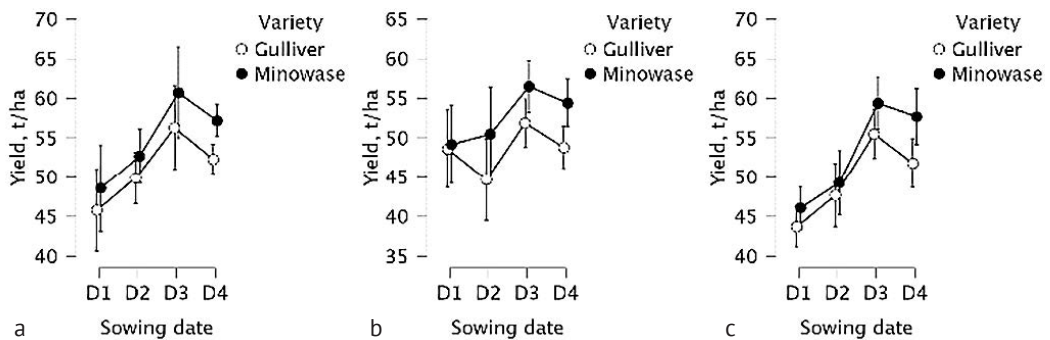


Figure 3. Comparative characteristics of the yield of daikon varieties depending on sowing dates (2022–2024)

Note: a – 2022, b – 2023, c – 2024; each point represents the mean value based on three replications ($n = 3$). Vertical error bars indicate the 95% confidence interval (95% CI). Sowing dates: D1 – first ten-day period of July, D2 – second ten-day period of July, D3 – third ten-day period of July, D4 – first ten-day period of August

Source: developed by the authors based on own research

Table 2. Parameters of adaptive capacity and stability of daikon varieties under different sowing dates (2022–2024)

Variety	'Gulliver'*				'Minowase'			
Sowing date	D1	D2*	D3	D4	D1	D2*	D3	D4
Mean, t/ha	46.0 ^a	47.4 ^a	54.6 ^c	51.0 ^b	48.0 ^a	50.8 ^b	58.9 ^d	56.4 ^c
CV, %	5.7	5.7	4.5	3.7	4.5	4.3	4.0	3.3
GAC _i	-5.6	-4.2	2.9	-0.7	-3.7	-0.8	7.2	4.8
SAC _i	6.4	6.8	5.6	3.1	4.1	4.3	5.2	2.9
Sg _i , %	14.0	14.4	10.2	6.0	8.6	8.5	8.9	5.2
b_i	-0.39	2.20	1.23	1.15	0.30	1.43	1.19	0.89
SVG _i	12.1	11.4	25.2	34.8	26.2	27.9	31.3	40.9

Note: the table presents mean values for 2022–2024, $n = 9$ (where n is the total number of observations: 3 years $\times$ 3 replications for each treatment). The pooled standard error (SE) for all treatments is 0.54. Values marked with different letters (a, b, c, d) differ significantly at $p < 0.05$ according to Tukey's HSD test. Mean – average yield (t/ha); CV – coefficient of variation (%); GAC_i and SAC_i – general and specific adaptive capacity; Sg_i – relative stability (%); b_i – plasticity (regression coefficient); SVG_i – breeding value. Sowing dates: D1 – first ten-day period of July, D2 – second ten-day period of July, D3 – third ten-day period of July, D4 – first ten-day period of August. The symbol (*) indicates the control

Source: developed by the authors based on own research

The coefficient of variation in the experiment ranged from 3.3 to 4.5%, indicating low variability of the studied trait ($CV < 10\%$). For a comparative assessment of yield stability, the Sg_i index was also used. As the obtained values ranged from 6.0 to 14.4%, this fully corresponds to the criterion of high genotype stability ($Sg_i < 25\%$).

The ability of genotypes to maximise the expression of economically valuable traits is directly correlated with the magnitude of GAC_i ; therefore, the most valuable variants are those with the highest values of this parameter. In particular, sowing in the third ten-day period of July and the first ten-day period of August provided the highest GAC_i effects, while the lowest values of this parameter were observed for sowing in the first ten-day period of July. When assessing variety stability using the SAC_i parameter, it was taken into account that higher values indicate lower stability of the trait under fluctuating environmental conditions. The lowest SAC_i values were recorded for sowing in the third ten-day period of July and the first ten-day period of August, allowing these variants to be characterised as the most stable within the experiment.

When the variety 'Gulliver' was sown in the first ten-day period of July, the linear regression coefficient was $b_i < 1$, indicating a weaker response of the variety to environmental changes compared with the average across all studied variants. This justifies its use under resource-saving conditions, where the genotype ensures high return on inputs at a moderate level of agronomic practice. Conversely, values of $b_i > 1$ for subsequent sowing dates indicate a transition to an intensive type of response. In particular, sowing in the second ten-day period of July proved to be the most sensitive: with an increase in the environmental index by 1 t/ha, productivity increased by 2.20 t/ha. Slightly lower responsiveness was observed for sowing in the third ten-day period of July and the first ten-day period of August (1.1–1.23 t/ha per unit improvement in conditions). According to the calculations, all experimental variants of the variety 'Minowase' exhibited characteristics of an

intensive type ($b_i > 1.0$), indicating high sensitivity to improved growing conditions. The minimum b_i value (0.30) was recorded for sowing in the first ten-day period of July, while the maximum was observed in the second ten-day period of July ($b_i = 1.43$), after which the indicator gradually decreased with later sowing dates.

Thus, the optimal genotype for the experimental zone is one that combines high general adaptive capacity with maximum productivity and stability. For this reason, an integrated index, SVG_i , was used for comprehensive evaluation, allowing the risks of low productivity in unstable varieties under unfavourable conditions to be minimised. The SVG_i index was highest for the varieties 'Gulliver' and 'Minowase' when sown in the first ten-day period of August (34.8–40.9). In contrast, a decrease in this indicator was observed at earlier sowing dates.

As noted by S. Ali *et al.* (2023), ensuring food security requires careful consideration of the dynamics of environmental factors and an understanding of their impact on specific crops. In recent years, species distribution models have been widely used to assess the effects of climate change on geographical ranges. In particular, the study by Q. Han *et al.* (2023), based on a maximum entropy model, demonstrated that the geographical distribution of wild radish in East Asia is determined by hydrothermal conditions by 93.9%, primarily by precipitation in the driest month and its seasonality. The results of the analysis of variance obtained in this study are fully consistent with this model: the three-factor ANOVA showed that the dominant factor influencing yield variability was the sowing date ($\eta^2_p = 0.894$), which determines the moisture and thermal conditions for crop development.

The high significance of the varietal effect ($F = 99.2$; $p < 0.001$) is consistent with the findings of S.N. Mari *et al.* (2025), where genotype was also identified as a key determinant of radish productivity. In particular, the variety Medium Roasted produced the highest root mass (122.90 g). At the same time, the high coefficient of variation

reported in that study indicates considerable intra-varietal variability in root weight, which may be due to the specific agroclimatic conditions of the study region. However, according to the results obtained in the present study, high stability and uniformity of the trait were recorded (coefficient of variation CV only 3.3-4.5%), indicating a high adaptive capacity of the varieties 'Gulliver' and 'Minowase'. In the study by A. Manzoor *et al.* (2024) involving 20 radish genotypes, it was also established that heredity, rather than the environment, plays a decisive role in the development of economically valuable traits (>20%).

A strong dependence of crop productivity on agroclimatic conditions and sowing dates is evident. It was established that for the varieties 'Gulliver' and 'Minowase', the optimal sowing period is from the third ten-day period of July to the first ten-day period of August, which ensured yields of 51.0-58.9 t/ha. These values significantly exceed the results of S. Parajuli & P. Dhital (2023), where under lowland conditions in Rupandehi (120 m above sea level, Nepal), early sowing (12 April) resulted in only 24.5 t/ha and late sowing (27 April) in 20.4 t/ha. In comparison with the data of B. Luitel *et al.* (2024) for the mid-hills of Dailekh (1,255 m above sea level), it was found that even the highest result of May sowing in Nepal (24.0 t/ha) remains twice as low as the values obtained in the present study. Such a substantial difference in yield is explained not only by varietal characteristics but also by the conditions under which the experiments were conducted. This supports the scientific assumption that high yields in the third ten-day period of July to the first ten-day period of August due to an optimal combination of daylight hours and temperature conditions, which promotes the intensive growth of root crops and vegetative mass.

At the same time, the results of N. Kamal & H. Kaur (2023) in Punjab (India), where October sowing ensured yields of 41 t/ha, are the closest to the recorded values. High productivity in both cases confirms the expediency of shifting sowing dates to late summer and autumn periods. It

also indicates the high effectiveness of the selected sowing window (late July – early August) for the full realisation of the genetic potential of daikon varieties under the conditions of the Forest-Steppe of Ukraine. Moreover, the risks of premature bolting and morphological branching of roots – identified by E. Kim *et al.* (2025) as key factors reducing yield and quality under high-altitude conditions in Bolivia – were minimised in the present experiments through optimisation of sowing dates (third ten-day period of July – first ten-day period of August), which ensured maximum yields for the variety 'Minowase' at the level of 56.4-58.9 t/ha.

In a study of 30 Asian radish genotypes under different sowing dates in Bathinda (India), A. Dhand & N. Garg (2023) found that the contribution of the environment to total variance was highest for root weight, followed by plant weight and rosette weight – 60.2%, 59.6%, and 43.6%, respectively. Although the study's results also confirm the primacy of external factors, it was clarified that the influence of the year's weather conditions is significantly lower ($\eta^2_p = 0.357$) than the effect of sowing dates. This complements the conclusions of L. Mbambalala *et al.* (2025), who showed that sowing date is a decisive factor in determining the forage value of radish: December sowing resulted in maximum protein accumulation due to optimal hydrothermal conditions, whereas March sowing ensured the highest carbohydrate and metabolisable energy content. At the same time, later sowing in May under drought conditions led to a deterioration in biomass quality.

L.N. Dongarwar *et al.* (2024) noted that understanding the relationship between yield and its components is of considerable importance, as this indicator results from the complex interaction of numerous plant morphological traits. Significant progress can be achieved through targeted selection for traits that exhibit strong positive correlations with productivity, including plant height, leaf area, chlorophyll content, root diameter and weight, total biomass, root-to-leaf

ratio, and the content of moisture, ascorbic acid, and soluble solids. Analysis of ecological plasticity ($b_i > 1.0$) demonstrated that the studied genotypes belong to an intensive type, capable of fully realising their potential only under improved agronomic conditions. At the same time, the results of H. Hong *et al.* (2023) complement this strategy, indicating that genetic differentiation of radish varieties is closely linked to their adaptability to seasonal growing conditions. Cluster analysis using molecular markers enabled clear differentiation between autumn, spring, and summer/winter varieties, which is an important factor in planning sowing dates. The application of an integrated breeding value index made it possible to establish that August sowing dates provide the best alignment between genotype and environmental conditions of the growing region. In the study by L.M. Dang *et al.* (2023), it was noted that the use of an automated phenotyping system based on the Mask-RCNN algorithm ensures high accuracy in measuring morphological traits of radish (82-100%), which is critically important for evaluating the breeding value of samples under different growing conditions.

The results of the present study demonstrated that the use of classical parameters of stability and adaptive capacity remains a highly reliable method for identifying promising daikon varieties under field conditions. The findings clearly highlight the importance of sowing dates for daikon yield, particularly under the conditions of the Forest-Steppe of Ukraine. Increased yields at the identified sowing dates confirmed the adaptability of the studied varieties to changing climatic conditions, which is essential for ensuring the stability of production.

Conclusions

The conducted research demonstrated that optimising sowing dates is an important element in adapting daikon to current climatic challenges in the Forest-Steppe of Ukraine. The studied factors accounted for 92.5% of yield variation, with sowing dates being dominant (62.6%, $p < 0.001$).

The influence of variety and year amounted to 15.4% and 4.1%, respectively. Across all experimental variants, high relative yield stability was observed (Sg_i 6.0-14.4%). According to Tukey's test, the variety 'Minowase' significantly outperformed 'Gulliver' when sown in the second and third ten-day periods of July and the first ten-day period of August, with yields of 50.8-58.9 t/ha. A high coefficient value ($b_i > 1$) in most variants indicates considerable plasticity of the varieties. Such genotypes realise their potential only under intensive cultivation technologies. In contrast, the variety 'Gulliver', when sown in the first ten-day period of July with $b_i < 1$, exhibited lower-than-average sensitivity to environmental changes, characterising this variant as suitable for extensive farming systems, where achieving results with limited resources is essential. The latest sowing dates showed the lowest response to improvements in agronomic conditions within the experiment. With an increase in the overall yield level by 1 t/ha, the yield of genotypes sown in the first ten-day period of August increased by only 0.89-1.15 t/ha. At the same time, sowing in the second ten-day period of July proved to be the most intensive: its response to changes in environmental conditions was the highest, amounting to 1.43-2.20 t/ha for each unit increase in the group mean. The highest breeding value (34.8-40.9) and stability (2.9-3.1) for the studied varieties were ensured by sowing in the first ten-day period of August, with yields of 51.0-56.4 t/ha.

The obtained results provide a scientific basis for integrating breeding and agronomic approaches to enhance crop adaptability. The identification of genotypes with high ecological plasticity and stability enables the optimisation of breeding programmes aimed at developing varieties capable of effectively realising their productive potential under variable hydrothermal conditions. At the same time, the decisive role of sowing dates as a key agronomic factor has been established, as it allows the alignment of critical growth and development stages of plants with

optimal environmental conditions. This creates favourable conditions for stabilising production by reducing interannual yield fluctuations and improving resource-use efficiency. Further research will focus on studying the effect of sowing and harvesting dates on the storability of root crops in order to extend the consumption period of fresh daikon produce throughout the autumn–spring period. This will contribute to strengthening food security and the development of sustainable agroecosystems capable of adapting to future climate change.

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Conflict of Interest

None.

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Адаптивний потенціал та селекційна цінність сортів дайкону (*Raphanus sativus* L. *convar. acanthiformis* Sazon.) за різних термінів сівби в умовах Лісостепу України

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Анотація. Глобальні кліматичні зміни та зміщення агрокліматичних зон в Україні зумовлюють необхідність перегляду традиційних елементів технології вирощування овочевих культур для забезпечення стабільної продовольчої безпеки. Метою дослідження було оцінити адаптивний потенціал сортів дайкону залежно від термінів сівби для формування сталої врожайності в умовах сучасних агрокліматичних трансформацій. Дисперсійний аналіз (Type III SS) показав, що 92,5 % варіації врожайності зумовлено досліджуваними факторами. Найбільший вплив мав термін сівби (62,6 %, $p < 0,001$), що суттєво перевищував вплив сорту (15,4 %, $p < 0,001$), тоді як вплив року був незначним (4,1 %, $p < 0,001$). Серед взаємодій статистично значущою виявилася лише комбінація «термін сівби $\times$ рік» (7,5 %, $p < 0,001$). Усі сорти характеризувалися високою відносною стабільністю (S_g , 6,0-14,4 %). За результатами ANOVA та критерію Тьюкі (HSD) у більшості термінів сівби встановлено достовірні відмінності між сортами ($p < 0,05$). Сорт 'Міновасі' перевищував 'Гулівер' у II декаді липня – I декаді серпня (50,8-58,9 проти 47,4-54,6 т/га). Ранній термін (I декада липня) не забезпечив істотних відмінностей між генотипами. Високою пластичністю характеризувалися всі сорти, за винятком 'Гулівер' у ранній термін ($b_i = -0,39$). Для 'Міновасі' у I декаді серпня відмічено знижену пластичність ($b_i = 0,89$). Найбільшу чутливість до умов середовища зафіксовано для II декади липня ($b_i = 1,43$ -2,20). Найвищі показники селекційної

цінності отримано за сівби у I декаді серпня (34,8-40,9), що поєднувалося з високою врожайністю (51,0-56,4 т/га) та стабільністю (2,9-3,1). Отримані результати обґрунтовують доцільність використання сорту 'Міновасі' та оптимізації термінів сівби (кінець липня – початок серпня) як ефективного агротехнологічного інструменту підвищення продуктивності й стабільності вирощування дайкону в умовах кліматичних змін

Ключові слова: екологічна пластичність; стабільність генотипу; врожайність коренеплодів; гідротермічний стрес; адаптивна здатність