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Compensatory and Yield Indicators of Oilseed Radish Depending on the Parameters of its Agrocenosis Design

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Effective pre-sowing design of crop agrocenoses involves the assessment of possible compensatory mechanisms of plants when changing the nutrition area against the background of corrective fertilization. In order to study such mechanisms and determine the influence of vegetative and reproductive architectonics of plants on the resulting indicators, a five-year cycle of research was conducted on oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.). The studies used a full range of options for pre-sowing design of oilseed radish agrocenoses from maximum thickening (4 million germinating seeds ha^{-1} for ordinary row sowing sowing, individual plant nutrition area 25 cm^2) to maximum thinning (0.5 million germinating seeds ha^{-1} for wide-row sowing, 200 cm^2). To evaluate the effectiveness of the regulating fertilizer, four variants of it were used: $N_0P_0K_0$, $N_{30}P_{30}K_{30}$, $N_{60}P_{60}K_{60}$, $N_{90}P_{90}K_{90}$. Based on the use of morphological features of the stem, indicators of the structure of individual seed productivity, correlation and regression analysis, the optimal parameters of formation of oilseed radish agrocenosis were determined. The adaptive compensatory mechanism in oilseed radish plants was established, which ensured the achievement of the maximum level of seed productivity of plants (more than 2.5 t ha^{-1}) in the range of nutrition area of 80–160 cm^2 (1.0–1.25 million germinating seeds ha^{-1} for row sowing on the background of $N_{30-60}P_{30-60}K_{30-60}$ and 0.80–1.0 million germinating seeds ha^{-1} for wide-row sowing on the background of $N_{60-90}P_{60-90}K_{60-90}$). The desired hydrothermal regime with these design parameters provided for an achievable level of precipitation of 260 mm and an average daily temperature for the period April-June in the range of 13–16.5 °C.

Keywords: *Raphanus sativus* L. var. *oleiformis* Pers., compensatory properties, plant architecture, nutrition area, seed yield

1 Introduction

The search for the optimal nutrition area in the agrotechnology of pre-sowing design of cruciferous crops cenosis remains an urgent task due to both global climate change and the transition of the breeding system to the creation of varieties with different adaptive tactics (Li et al., 2023). The dilemma of optimizing the nutrition area is a controversial issue, as it is determined by many factors, the main ones being soil and climatic conditions, the level of additional mineral nutrition, sowing dates and economic direction of cultivation, genetic characteristics of a variety or hybrid. It is noted (Zhang et al., 2020) that the main criterion for choosing this factor for the pre-sowing design of the agrocenosis of any crop is the achievable predictive level of individual plant productivity, in combination with the appropriate plant density, should ensure the productivity of one ha. In this regard, the achievability of the total yield of a genotype is realized by a parallel comparison of changes in individual plant productivity and in the level of cenotic stress due to the density of plants during the critical period of formation fruit elements (Rondanini et al., 2017; Yahbi et al., 2022). The plant organisms have evolved various mechanisms in terms of competition for nutritional space that allow maintaining the appropriate constancy of seed productivity both under changes in hydrothermal conditions during the period of active growth processes of the reproductive and generative apparatus formation and under changes in density in the range from maximum to minimum (Sokólski et al., 2023). One of these adaptations that geneticists and breeders have recently become interested in is the compensatory ability of a plant to compensate for the reduction in the number of individuals of its species per unit area in order to ensure the stability of seed reproduction intervals and maintain the stability of a particular species in the general phytocoenosis of the respective territories under the variability of the climate regime (Gan et al., 2016; Zhang et al., 2020; Wang et al., 2022). In the final task, the search for agrotechnological solutions in terms of choosing the optimal nutrition area is determined by the option where the maximum biomass or seed productivity is achieved at the lowest possible seed consumption (Tsytsiura, 2020). Plant compensation has a certain researched hierarchy that includes both a general increase in the number of fruit elements on a plant within a single pagenetic element and intensive tillering or stem branching, each is able to form own generative part and significantly increase the total seed yield (Rondanini et al., 2017). In natural populations, tillering and branching are the main mechanisms of plant adaptation to a significant change in individual nutrition area (Yang et al., 2022). From the point of view of plant architecture, compensatory branching is considered as intensive branching of the inflorescence on one shoot (in the absence of lateral branches in the lower part of the stem) or at the level of half its length (the so-called generative branching). An option is also possible intensive formation of additional stem shoots from the lower part of the stem (called bushy plant forms) (Qing et al., 2021). Each of these additional stem shoots is potentially capable of forming a generative part, which ensures a significant increase in the reproduction rate of this plant species (Yuan et al., 2023). The described mechanism of branching of both the first and second types was inherent in cruciferous plant species (Zhang et al., 2020; Wang et al., 2022; Ma et al., 2023). Over the past ten years, this trait has been used at the genetic level to create adaptive hybrids of winter and spring rape, and mustard species with a highly adapted compensatory mechanism that allowed cultivating these genotypes in a wide range of technological options for sowing densities (Sunagar & Pandey, 2024). This made it possible to form agrocenoses of these crops in a wide technological density range. The presence of a compensatory mechanism in plants is a requirement of the idiotype of highly plastic hybrids and varieties with the possibility of wide intervals of regulation of both sowing schemes and fertilization systems (Frieß et al., 2020; Abraha et al., 2024).

The aim of our research was to study the peculiarities of compensatory properties due to stem branching on the background of changing the planting density and pre-sowing fertilizer rates in oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) as a cruciferous crop of multifunctional use. This crop has a number of adaptive mechanisms that qualitatively distinguish its prospects and potential use compared to other cruciferous crops in the zone of unstable moisture on gray forest soils. Despite this for oilseed radish the problem of compensatory mechanisms was poorly understood and required scientific analysis and generalization.

The research was based on the scientific hypothesis of the relationship between the density of oil radish agrocenosis and the compensatory ability of its plants against the background of variable variants of mineral nutrition and variability of hydrothermal conditions of vegetation and the presence of the optimum point of the ratio of the compensatory effect and the structure of individual seed productivity of oil radish plants in order to optimize the pre-sowing design of its cenosis.

2 Material and methods

2.1 Study area and data collection

The research was conducted during 2018–2023 at the experimental field of Vinnytsia National Agrarian University (N 49°11′31″, E 28°22′16″) on gray forest soils. The agrochemical potential of the field had the following average long-term indicators: humus content 2.68%, easily hydrolyzed nitrogen 81.5 mg kg^{-1} of soil, mobile phosphorus 176.1 mg kg^{-1} of soil, exchangeable potassium 110.8 mg kg^{-1} of soil, pH_{KCl} 5.8. The oilseed radish variety 'Zhuravka' was used in the research. The sowing time for all variants of the experiment was early spring (first or second decade of April) against the background of 20–22 cm autumn plowing and intermediate cultivation to a depth of 8–10 cm with leveling. The scheme of the experiment is presented in Table 1.

The experimental plots were formed in quadruplicate by the method of small plot randomization (total plot area 35 m^2, accounting area 25 m^2). Phenological periodization of oilseed radish plant development was determined in accordance with the international scale of BBCH (UPOV, 2017). Mineral fertilizers were applied in the pre-sowing periods.

The evaluation of stem morphological traits was carried out on 25 typical plants selected in 5 locations along the length of the row of the experimental plot stochastically with a 4-fold replication in the row horizontal for the phenological phase of the brown pod (BBCH 84–87). The following morphological traits were taken into account: plant height, height to the first branch of the stem, number of lateral branches of the stem, stem diameter (at the base of the stem), number of pods, seed weight per plant, 1000 seed weight).

Table 1 General scheme of the experiment on the peculiarities of morphogenesis of oilseed radish plants under different design of its agrophytocenosis

Plant placement due to the ratio of the seeding rate (factor B – million germinating seeds ha^{-1}) to the sowing method (factor C – conventional row method (15 cm), wide-row method (30 cm))		Fertilizer rates (factor D)***, kg ha^{-1}
4.0 (*1.67 × 15), ****25 cm^2	2.0 (1.67 × 30), 50 cm^2	$N_0P_0K_0$ (D_1)
3.0 (2.22 × 15), 33.3 cm^2	1.5 (2.22 × 30), 66.6 cm^2	$N_{30}P_{30}K_{30}$ (D_2)
2.0 (3.33 × 15), 50 cm^2	1.0 (3.33 × 30), 100 cm^2	$N_{60}P_{60}K_{60}$ (D_3)
1.0 (6.67 × **15), 100 cm^2	0.5 (6.67 × 30), 200 cm^2	$N_{90}P_{90}K_{90}$ (D_4)
Conditions of the year: 2018 – A_1, 2019 – A_2, 2020 – A_3, 2021 – A_4, 2022 – A_5, 2023 – A_6		
Scheme of combinations of variants	$A_{1–6}$ × $B_{1–4}$ × $D_{1–4}$	The total number of combinations (*N = 192*)

Note: * distance in the row, cm: ** row spacing, cm; *** pre-sowing application; **** nutrition area of the plant

Plant height was measured from the root collar to the highest bud on the central branch, and the height of the first side branch from the root collar to the first branch (Rondanini et al., 2017) using a Bosch GR 240 measuring rail (Bosch, Stuttgart, Germany).

The number of lateral branches of the stem were calculated by direct counting on selected 25 plants in each replicate according to the recommendations of Rondanini et al. (2017).

The morphological index of the stem was calculated as the ratio of the stem height to its diameter (Gan et al., 2016). The diameter of the main stem was measured with an electronic caliper Didital Caliper (Microtech. Ukraine) (measurement accuracy 0.01 mm).

The number of pods, seed weight per plant and seed yield was recorded in the format of its biological level by direct manual threshing and subsequent calculation after separation and drying of seeds of the average seed yield (g $plant^{-1}$) from the general population of plants (in accordance with Cai et al. (2016)).

The weight of 1000 seeds was determined according to the standard protocol (ISTA, 2018).

The characteristics of the mass of plant parts and seeds were determined using laboratory scales RADWAG PS 1000.R1 (Radwag, Poland) with a discreteness of 0.001 g.

The plant survival rate was calculated as the ratio of the recorded plant density (on 1 m^2) on the date of recording the seed yield to the plant density at the time of full germination according to the seeding rate for the corresponding experimental variant (according to McDowell et al., 2008).

For accounting, additionally used: the method of processing scanned and photographic images (using the CanoScan LIDE 700F scanner (Canon, Japan) with the appropriate software), field and laboratory photography using Canon EOS 750D Kit (Canon, Japan) with the objective lenses Canon EF 100mm f/2.8L USM (Canon, Japan) and Canon MP-E 65mm f/2.8 1-5x Macro (Canon, Japan).

2.2 Analysis of weather conditions

The hydrothermal regimes of the vegetation of oilseed radish of different sowing dates for the period 2014–2023 were assessed the following indicators and coefficients (according Latief et al. (2017)): the hydrothermal coefficient (HTC) (Formula 1), De Marton aridity index (I_{DM}) (Formula 2), Vysotsky-Ivanov moisture coefficient (K_h) (Formula 3).)

$$HTC = \frac{\sum P}{0.1 \times \sum t_{>10}} \quad (1)$$

Where: ΣP – the sum of precipitation (mm) for the period with temperatures above 10 °C, Σt>10 – the sum of effective temperatures for the same period. Ranking of HTC values: > 1.6 – excessive humidity, 1.3–1.6 – wet conditions, 1.0–1.3 – moderately dry conditions, 0.7–1.0 – dry conditions, 0.4–0.7 – very dry conditions.

$$\mathrm{I_{DM}} = \frac{12\mathrm{P}}{\mathrm{t_{av.}+10}} \quad (2)$$

Where: P and $t_{av.}$ – the amount of precipitation and average air temperature in the respective month.

This indicator, with adaptation, classifies the climate type of the territory into: arid $I_{DM} < 10$; semi-arid $10 \le I_{DM} < 20$; transitional $20 \le I_{DM} < 24$; semi-humid $24 \le I_{DM} < 28$; humid $28 \le I_{DM} < 35$; very humid $35 \le I_{DM} \le 55$; extremely humid $I_{DM} > 55$.

$$K_h = \frac{P}{E} \quad (3)$$

Where: K_h – moisture coefficient; P – total precipitation for the analysed period, mm; E – evapotranspiration (mm) for the analysed period, calculated according to the Formula 4), mm.

$$E = 0{,}0018 \times (25 + t)^2 \times (100 - a) \quad (4)$$

Where: t – the average air temperature for the period, °C; a – the average relative humidity for the analysed period, %. The degree of humidification was assessed according to a gradation: $K_h > 1.0$ – territory (period of time) with excessive humidification, K_h close to 1 – optimal humidification, K_h = 1.0–0.6 – unstable humidification, K_h = 0.6–0.3 – insufficient humidification.

A generalized assessment of the hydrothermal regimes of the oilseed radish growing season within the years of research is presented in Table 2. Taking into account the optimal parameters for the growth processes of oilseed radish plants according to our previous long-term estimates (Tsytsiura, 2020), the years of research were placed in the following order of increasing favorability of growth processes: 2018–2021–2022–2023–2020–2019.

Table 2 Indicators of hydrothermal support of the vegetation period of oilseed radish, 2018–2023 (period from sowing to green pod phase (BBCH 72–75)

Year	Sum of precipitation, mm (IV-VI)	$t_{aver.}$, °C (IV–VI)	Months of the growing season								
			IV			V			VI		
			HTC	I_{DM}	K_h	HTC	I_{DM}	K_h	HTC	I_{DM}	K_h
2018	170.8	16.38	0.29	10.8	0.19	0.31	7.2	0.12	4.40	103.7	2.31
2019	398.5	15.39	0.57	33.5	0.72	4.90	111.0	3.29	1.68	41.4	0.96
2020	343.8	13.67	0.09	36.4	0.50	5.33	106.4	3.18	1.55	37.3	0.89
2021	282.8	13.26	0.23	38.8	0.96	3.13	66.7	1.64	1.68	39.8	1.00
2022	242.1	14.30	0.56	57.4	2.33	1.43	31.3	0.79	1.50	36.1	0.85
2023	239.8	14.18	1.54	91.5	3.33	0.08	1.9	0.04	1.64	38.9	0.87

2.3 Statistical Analysis

For the statistical evaluation of the results obtained, the basic and integration indicators of biological statistics were used in accordance with Wong (2018) in the statistical software Statistica 10 (StatSoft - Dell Software Company, USA, 2013), Past 4.0 software (Øyvind Hammer, Norway, 2014) and the R software package (version R statistic 3.1.2, 2014). The following indicators were used for statistical evaluation of the obtained averages: arithmetic mean (± standard deviation) and coefficient of variation. To assess the closeness of the relationship between the indicators, Spearman's correlation analysis was applied with the estimation of values for the level of statistical significance $p < 0.05–0.001$.

The selection of equations of dependence models was carried out using the software package CurveExpert Professional v. 2.7.3 software package (Hyams Development) and Matlab R2016a software (TheMathWorks Inc., Natick, MA, USA).

The reliability of the difference in indicators within the inter-annual comparison was assessed on the basis of analysis of variance with correction of the results according to the Tukey's test with the Bonferroni correction (for the level of $p < 0.05$). To compare the regression models, we used the coefficient of determination (R^2), adjusted coefficient of determination (R^2_{adj}), root mean square error (RMSE), and relative root mean square error (RRMSE).

The degree of orrelations was estimated by the value of the coefficient of determination d_{xy} (%) (Wong, 2018) (Formula 5)

$$d_{yx} = r_{ij}{}^2 \times 100 \quad (5)$$

Where: r_{ij} is the correlation coefficient between the i-th and j-th indicator.

The scale for d_{xy} was used to assess the closeness of the relationship between the indicators: 10–30 – weak; 30–50 – moderate; 50–70 – significant; 70–90 – high; 90–99 – very high.

3 Results and discussion

Based on the results of accounting for the architectonics of the aerial part of oilseed radish plants, several types of plants were identified in the total array of established variants of its pre-sowing design according to the nature of stem branching and the formation of generative axes of 1–3-th order. In the course of long-term systematization and evaluation, the following types were identified: none-branch broom shape (Fig. 1, I, a), few-branch broom shape (Fig. 1, I, b–d), multibranch broom shape (Fig. 1, I, e–g). Its morphological differences in the yellow-green pod phase (BBCH 80–84) are presented in the same positions in variant II, and the ideotypic scheme of typical plants is presented in the same positions in variant III. The formed agrocenosis of oilseed radish within the studied variants of pre-sowing design formed a different character of both the general vegetative and productive architectonics of plants. Similar features of identifying plant morphotypes under different technology variants were noted in winter rape (Sikorska et al., 2023; Ma et al., 2023) and different types of mustard (Singh et al., 2022). The analysis of the morphotypic profile of agrocenosis according to Li et al. (2023) allowed to assess the effectiveness of the relevant technologies for growing cruciferous crops and determine its optimal options. This conclusion was confirmed on oilseed radish agrocenoses of different densities. The nature and direction of the formation depended on the studied variants of plant density, the area of its individual nutrition and fertilizer rates (Table 3).

The height of plants was minimal in the variants with the maximum density of cenosis both in row and wide-row sowing methods. In comparing the extreme limits of the variants, the difference was 9.9% for the unfertilized background and 28.2% for the variant with $N_{90}P_{90}K_{90}$. The maximum value of the indicator was noted in the variants of $N_{90}P_{90}K_{90}$ application at the nutrition area of the plant of 50 cm^2 for row sowing and 100 cm^2 for wide-row sowing. The value of this indicator was 16.4% and 15.8% higher than the average for the variants of row and wide-row sowing, respectively. It was found that the linear growth processes of the oilseed radish stem was determined by both the level of competition between plants and the optimization of mineral nutrition. Further increase in the nutrition area obviously caused a disparity in the growth of radial and weight growth in the plant over the processes of linear elongation. The process of intensive growth of plant mass, additional productive branching with a decrease in the altitudinal gradient of the localization of the generative-seed part, noted in a number of studies (Gan et al., 2016; Yahbi et al., 2022). This is also confirmed by similar assessments of a number of cruciferous plant species (Rondanini et al., 2017; Li et al., 2023) and the results of comparing the habitus of plants of different productive architectures (Fig. 1, I–II, positions a and g). The applied fertilizer variants performed both a growth-stimulating role and a stimulating one due to the increase of intraspecific competition of plants at its individual nutrition area in the range of 25–33.30 cm^2 with a row seeding method.

This resulted in the absence of a positive effect in the growth of plant height in these variants compared to the unfertilized background in the fertilizer variants $N_{90}P_{90}K_{90}$ (average decrease of 18.8% with positive growth at level of 10.6% for the introduction of $N_{30}P_{30}K_{30}$ and 19.4% for the introduction of $N_{60}P_{60}K_{60}$). With the wide-row sowing method, the significance of increasing growth at the level of maximum fertilization in the variants was achieved at the nutrition area in the range of 66.6–200 cm^2. For the variant of wide-row sowing, the increase in stem height was 9.1% for the application of $N_{30}P_{30}K_{30}$ and 16.2% for the application of $N_{60}P_{60}K_{60}$ and 19.5% for the application of $N_{90}P_{90}K_{90}$. For the variants of row sowing with rate $N_{90}P_{90}K_{90}$ at low soil fertility potential was established at a plant nutrition area of 50.0 cm^2. For the wide-row sowing variant, the limit of expediency at a similar fertilizer rate, taking into account the established significance of the growth, was noted at the plant nutrition area of 66.6 cm^2.

The outlined nature of growth processes was also confirmed by the assessment of the nature of stem branching with a natural steady tendency to reduce the height of the stem before its first branching. The index of reduction of this indicator for the extreme technological variants studied was 2.23 and 3.08, respectively, within the fertilizer variants $N_0P_0K_0$ and $N_{90}P_{90}K_{90}$. As a result, an increase in the plant's nutrition area with a corresponding decrease in the yield rate creates a compensatory morphological effect of increasing the number of stem branches with a consistent shift in proportions from linear growth to radial growth, while filling the high-altitude living space through additional branching. This is clearly confirmed by the results of Fig. 1 (position II, a–g). It should be noted that for oilseed radish plants, certain classifying differences have been established in the nature of the height of lateral branching, which positively correlated with the plant density. These morphotypes dominate in the variants of a certain plant density in terms of the average number of lateral branches. At the nutrition area in the range from 25 to 50 cm^2 $plant^{-1}$, the number of lateral branches was either completely absent (Fig. 1 (I, II, a), Fig. 2, a) or reached the value of 3 (Fig. 1 (I, II, b–c), Fig. 2, b–c). In combination with the growth of the nutrition area in the variants of wide-row sowing, the number of lateral branches increased significantly with a decrease in height to the first branch (Fig. 1 (I, II, e–g), Fig. 2, e–g). For row sowing, the height to the first branch of stem decreased by 0.37 cm on the unfertilized background and by 0.38 cm on the $N_{90}P_{90}K_{90}$ background per 1 cm^2 increase in the nutrition area of the plant. For the variant of wide-row sowing, similar indicators were at the level of 0.11 cm and 0.19 cm.

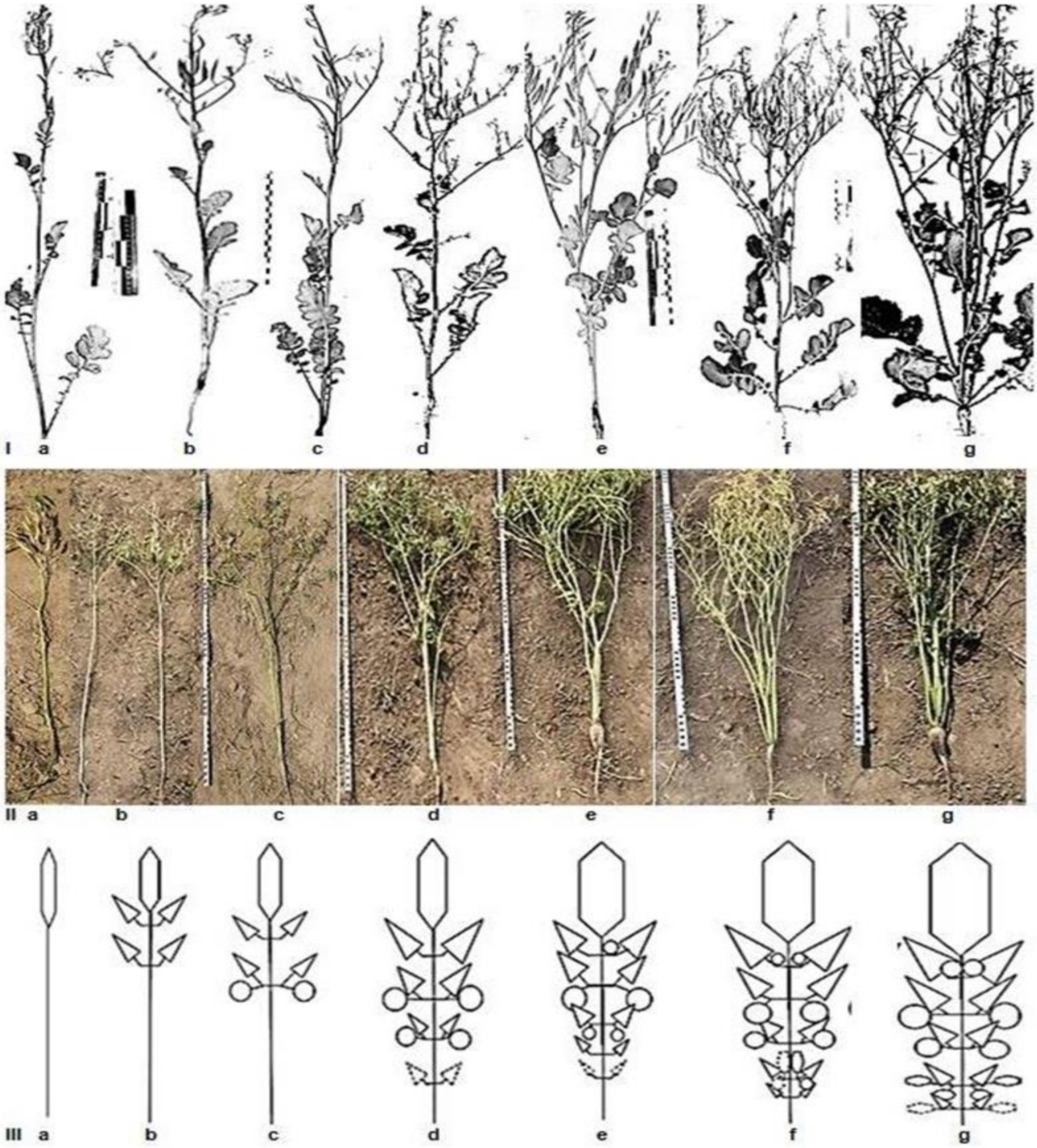

Fig. 1 Main types of oilseed radish plants by the nature of stem branching and branching of generative axes of 1–3-th order: I: a – no-branch broom shape, b–d – few-branch broom shape, e–g – multibranch broom shape; II – morphological differences of plants in the phase of yellow-green pod (BBCH 80–84) for the same positions of types by the nature of branching; III – ideotypical scheme of oilseed radish plants of different types of branching of generative axes (symbols ⬡ – main inflorescence of the stem; ▷ – inflorescences of lateral branches of the first tier order; ○ – inflorescences of branches of the second tier order; ⬭ – inflorescences of branches of the third tier order (hatching of structures indicates the presence of a structural element in individual plants, the size of the element symbolizes its morphological development), 2018–2023

Table 3 Basic indicators of the general architectonics of the stem of oilseed radish plants under different technological variants of pre-sowing design for the phenological phase of the brown pod (BBCH 84–87), 2018–2023

Sowing rate and sowing method	Fertilize*	Plant height, cm	Height to the first branch, cm	Number of lateral branches, pcs. plant^{-1}	Stem diameter, mm	Morphological index of the stem
4.0 million, row (25**)	1	$82.7 \pm 11.3^{a**}$	78.6 ± 11.3^{q}	0.3 ± 0.3^{a}	2.4 ± 0.85^{a}	34.5 ± 7.12^{q}
	2	85.9 ± 12.7^{b}	77.4 ± 10.9^{q}	0.7 ± 0.6^{c}	2.9 ± 0.91^{a}	29.6 ± 7.71^{o}
	3	90.4 ± 13.9^{c}	75.9 ± 10.5^{p}	0.6 ± 0.4^{b}	3.1 ± 0.96^{b}	29.2 ± 7.03^{o}
	4	85.4 ± 14.8^{b}	73.5 ± 11.1^{o}	0.5 ± 0.3^{b}	2.8 ± 0.89^{a}	30.5 ± 6.94^{p}
3.0 million, row (33.30)	1	86.8 ± 13.7^{b}	69.2 ± 11.9^{n}	1.7 ± 0.5^{c}	6.3 ± 1.22^{d}	13.8 ± 3.72^{i}
	2	97.3 ± 14.7^{e}	74.6 ± 12.3^{o}	1.9 ± 0.7^{c}	7.2 ± 1.30^{e}	13.5 ± 3.89^{i}
	3	108.1 ± 15.8^{h}	80.2 ± 10.7^{r}	2.2 ± 0.8^{d}	8.0 ± 1.38^{f}	13.5 ± 4.05^{i}
	4	106.2 ± 16.2^{g}	76.4 ± 8.8^{p}	1.9 ± 0.9^{c}	7.8 ± 1.51^{e}	13.6 ± 3.81^{i}
2.0 million, row (50)	1	90.5 ± 13.8^{c}	55.8 ± 10.2^{i}	2.3 ± 1.1^{d}	7.9 ± 1.22^{f}	11.5 ± 2.56^{e}
	2	103.2 ± 14.9^{f}	69.4 ± 11.4^{n}	2.7 ± 1.3^{e}	8.6 ± 1.31^{g}	12.0 ± 2.19^{f}
	3	112.1 ± 16.5^{i}	65.6 ± 9.9^{m}	3.3 ± 1.5^{f}	9.6 ± 1.38^{h}	11.7 ± 2.45^{e}
	4	114.9 ± 17.9^{j}	60.2 ± 10.5^{k}	3.5 ± 1.5^{f}	9.9 ± 1.52^{i}	11.6 ± 2.07^{e}
1.0 million, row (100)	1	91.8 ± 13.9^{c}	50.5 ± 9.7^{g}	3.3 ± 1.5^{f}	9.5 ± 1.39^{h}	9.7 ± 1.98^{d}
	2	102.8 ± 15.2^{f}	48.2 ± 10.5^{f}	3.9 ± 1.4^{g}	11.2 ± 1.50^{j}	9.2 ± 2.07^{c}
	3	109.6 ± 16.8^{h}	42.3 ± 9.9^{e}	4.1 ± 1.5^{g}	12.2 ± 1.59^{k}	9.0 ± 1.93^{c}
	4	111.4 ± 18.3^{i}	40.9 ± 11.8^{e}	4.3 ± 1.5^{h}	12.7 ± 1.78^{k}	8.8 ± 1.88^{c}
2.0 million, wide-row (50)	1	90.3 ± 10.9^{c}	52.3 ± 14.2^{h}	1.0 ± 0.3^{d}	3.2 ± 0.72^{b}	28.2 ± 4.38^{n}
	2	94.1 ± 11.9^{d}	50.6 ± 15.1^{g}	1.3 ± 0.5^{d}	3.7 ± 0.81^{b}	25.4 ± 4.09^{i}
	3	97.2 ± 12.5^{e}	50.4 ± 13.3^{g}	1.5 ± 0.5^{c}	4.1 ± 0.87^{c}	23.7 ± 3.93^{k}
	4	98.1 ± 13.1^{e}	51.9 ± 14.7^{h}	1.4 ± 0.3^{d}	3.6 ± 0.95^{b}	27.3 ± 5.07^{m}
1.5 million, wide-row (66.60)	1	95.6 ± 14.7^{d}	50.8 ± 13.9^{g}	2.3 ± 0.7^{d}	6.6 ± 1.07^{d}	14.5 ± 3.05^{j}
	2	104.5 ± 15.3^{g}	57.2 ± 14.5^{j}	2.7 ± 0.8^{e}	7.2 ± 1.23^{e}	14.5 ± 3.39^{j}
	3	112.9 ± 16.9^{i}	60.4 ± 15.1^{k}	3.1 ± 0.6^{e}	8.2 ± 1.44^{f}	13.8 ± 3.07^{i}
	4	115.8 ± 17.5^{j}	62.2 ± 16.6^{i}	3.4 ± 0.7^{f}	8.8 ± 1.56^{g}	13.2 ± 2.98^{h}
1.0 million, wide-row (100)	1	93.7 ± 15.7^{d}	50.4 ± 14.2^{g}	3.7 ± 1.1^{g}	7.8 ± 1.30^{e}	12.0 ± 2.51^{f}
	2	107.4 ± 17.2^{h}	51.7 ± 15.4^{g}	4.3 ± 1.2^{h}	8.6 ± 1.49^{g}	12.5 ± 2.41^{g}
	3	115.7 ± 18.1^{j}	54.2 ± 16.1^{i}	4.6 ± 1.4^{h}	9.2 ± 1.64^{h}	12.6 ± 3.02^{g}
	4	119.3 ± 18.9^{k}	52.6 ± 16.3^{h}	5.3 ± 1.7^{i}	9.7 ± 1.85^{h}	12.3 ± 2.44^{f}
0.5 million, wide-row (200)	1	90.9 ± 15.0^{c}	35.2 ± 18.3^{d}	4.7 ± 1.8^{h}	12.2 ± 1.96^{k}	7.5 ± 2.75^{b}
	2	98.3 ± 16.4^{e}	32.6 ± 19.2^{c}	5.4 ± 1.9^{h}	13.6 ± 2.11^{i}	7.2 ± 2.65^{a}
	3	104.9 ± 17.6^{g}	28.4 ± 20.4^{b}	5.8 ± 2.1^{i}	15.1 ± 2.54^{m}	6.9 ± 2.93^{a}
	4	109.5 ± 19.1^{h}	23.9 ± 21.5^{a}	6.1 ± 2.3^{i}	16.0 ± 2.91^{n}	6.8 ± 3.08^{a}

Note: * Fertilizer variant: 1 – $N_0P_0K_0$; 2 – $N_{30}P_{30}K_{30}$; 3 – $N_{60}P_{60}K_{60}$; 4 – $N_{90}P_{90}K_{90}$; ** Area of plant nutrition, cm^2 plant^{-1}; different letters indicate values that differed significantly from each other in the column direction for each indicator in the table based on the results of the comparison using the Tukey's test with the Bonferroni correction.

At the same time, for row sowing, on average for all variants for this indicator, an increase of 6.1% compared to the unfertilized background was noted only for the variant of application $N_{30}P_{30}K_{30}$. For the fertilizer variants $N_{60}P_{60}K_{60}$ and $N_{90}P_{90}K_{90}$, a consistent decrease in the value of the indicator to the unfertilized control was noted in the amount of 2.1% and 4.9%. In the variant of the wide-row sowing method, consistent increases to the unfertilized control were found in the values of 1.8%, 2.5% and 1.0%, respectively. It was proved that at denser cenoses, fertilization at rates of 60–90 kg ha^{-1} increased the overall cenotic stress and provided an increase in the height gradient of lateral branches, in contrast to the agrocenoses with a nutrition area of more than 100 cm^2 plant^{-1}.

There was a steady increase in the index for reducing the rate of growth in all years of research with the maximum number of lateral branches in the variant with a nutrition area of 200.10 cm^2 on the background of $N_{90}P_{90}K_{90}$ application. The growth rate of this indicator in a sequential series of growth of the nutrition area of the studied variants in comparison with the unfertilized background was 0.138 branching per variant. For variant of $N_{90}P_{90}K_{90}$ application the same indicator was 0.175 branching per variant. The use of mineral fertilizers had an overall positive effect on the growth of the indicator with a consistent decrease in the seeding rate and an increase in the nutrition area of plant. For the row sowing method, in the long-term average, a positive increase in the indicator to the unfertilized variant was recorded 21.1% and 10.7% at the fertilizer rates of $N_{30}P_{30}K_{30}$ and $N_{60}P_{60}K_{60}$ respectively. For the variants of wide-row sowing, positive increases were noted for all variants of additional fertilization in the sequential value of 17.1%, 28.2% and 38.5%. As a result, a regularity in the change in the architecture of the stem of oilseed radish plants was established. With a decrease in the seeding rate and an increase in the area of individual plant nutrition, oilseed radish was capable of a compensatory growth effect that led to an increase in the number of lateral branches and a decrease in the height of its placement on the stem. This feature allowed to form different morphotypes of plants on agrocenoses of significantly different seeding patterns. The specified morphotypes were with complete absence of branching (Fig. 2, a), branching in the middle part of the stem (Fig. 2, d), branching in the lower part of the stem (Fig. 2, e) and radial branching (at the base of the stem) at the level of the root collar of the plant stem (Fig. 2, f).

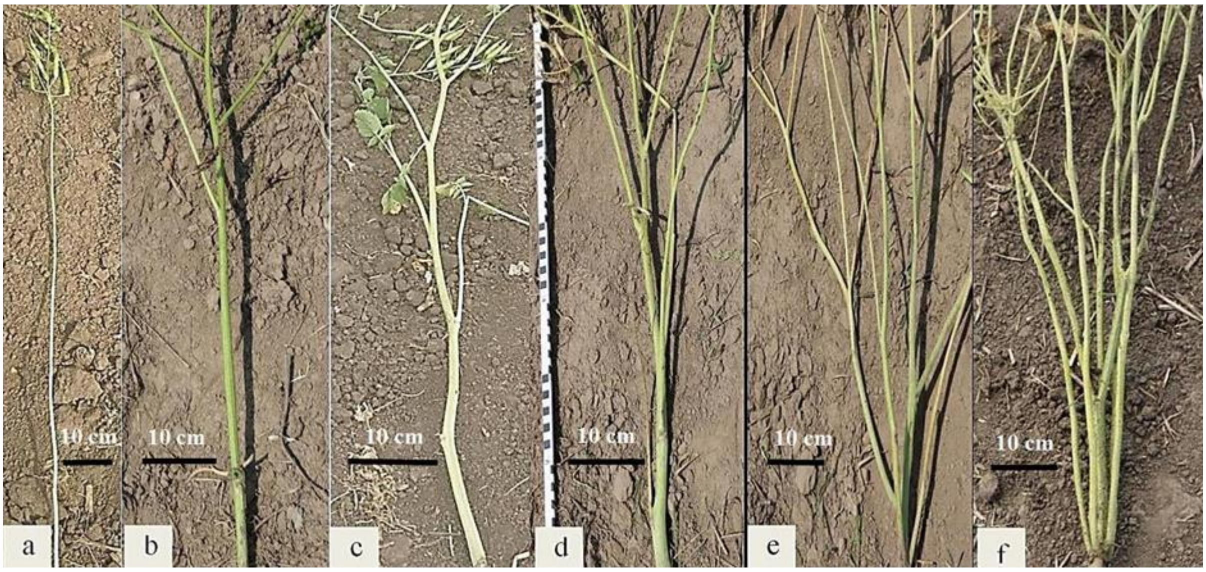

Fig. 2 Type of branching by the height of the first lateral branch, 2021 (a – no branching: b – branching in the upper part of the stem; c – branching in the middle part of the stem; d, e – branching in the lower parts of the stem; f – branching at the base of the stem)

Based on the results of the surveys, branching in the middle part of the stem was observed at seeding rates of 1.0–2.0 million germinating seeds ha^{-1} for row sowing and 1.0–1.5 million germinating seeds ha^{-1} for wide-row sowing. The variants with lower branching and branching at the level of the root collar were characteristic of the wide-row sowing method at a seeding rate of 0.5 million germinating seeds ha^{-1} and in some years at a seeding rate of 1.0 million germinating seeds ha^{-1}. It was also determined that the nature of branching within a certain seeding rate and, accordingly, the nutrition area has a certain interannual variation within the standard deviation for the average (Fig. 3–4).

If evaluate the results obtained with those of other cruciferous crops, should note both a number of similarities and a number of significant differences. Compensatory effects was known and used from the point of view of technological adaptation of modern winter rape genotypes. In modern systems of agricultural technologies, the ability of rapeseed to lateral branching with the possibility of obtaining a higher yield level with a decrease in productive stem length was considered as an aspect of the ability to cultivate hybrid or variety in different soil and climatic zones at different sowing dates (Sun et al., 2016; Zhang et al., 2020; Qing et al., 2021). It has also been established (Wang et al., 2022) that the nature of lateral branching has a certain genetic basis in terms of controlling productive architectonics and the type of branching of monopodial and sympodial. It has been noted (Rondanini et al., 2017; Sokólski et al., 2023) that modern genotypes of winter rape are less responsive to changes in plant nutrition area than genotypes of older breeding practices for the purpose of its cultivation in wide agrotechnological ranges (so-called effect of controlled compensation). For wild cruciferous species, this mechanism was more pronounced, especially when its grow under favorable hydrothermal conditions (Yang et al., 2022). This approach is considered as a useful adaptation for the conservation and spread of the species (Yuan et al., 2023). For different mustard species, the compensatory effect was more pronounced in white and black mustard (Sunagar & Pandey, 2024). In spring oilseed rape, the intensity of branching with changes in the nutrition area was a less conditioned property, which caused a number of difficulties due to the need for more precise observance of the seeding rate in the formation of its agrocenoses (Wynne et al., 2020).

Fig. 3 A number of morphotypes of oilseed radish plants by stem branching at a sowing rate of 0.5 germinating seeds ha^{-1} on the background of $N_{60}P_{60}K_{60}$, 2018.

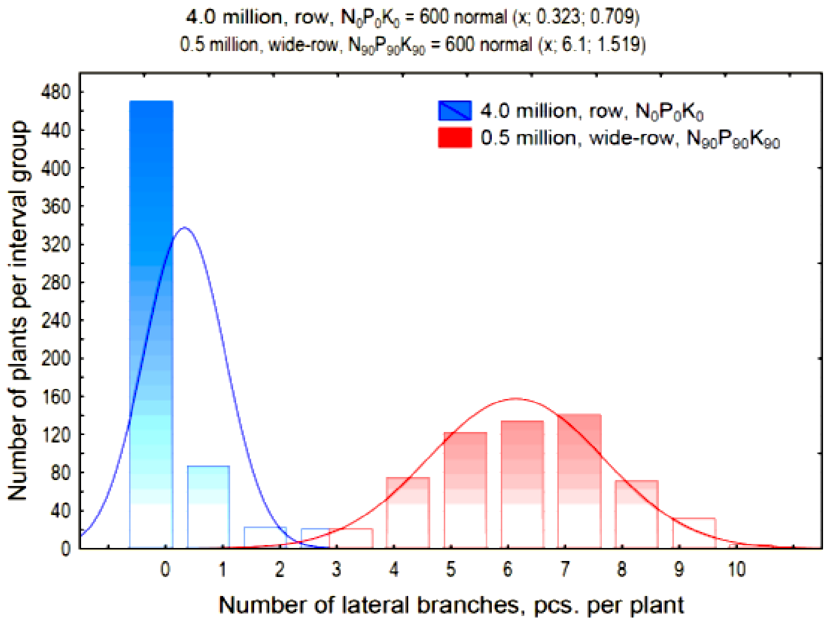

Fig. 4 Histogram of the distribution of the indicator of 'number of lateral branches of the stem' for the limiting technological options for the undercropping design of oilseed radish agrocenosis (for the combined data set of repetition–years (N=600)) for the period 2018–2023)

As for the typification of branching, for other cruciferous plants, it was carried out in general terms to model winter rape plants (Ma et al., 2023) and the possibility of adjusting the yield of a number of cruciferous species due to tiered productive lateral branching (Rondanini et al., 2017; Zhang et al., 2020). In view of the results obtained, the established compensatory mechanism was valuable for the so-called flexible technological solutions in the pre-sowing design of its seedling agrocenoses in order to avoid the risks of reducing seed yields due to thinning, damage to the peduncle of the main axis, etc.

Certain peculiarities of formation under changes in the parameters of pre-sowing design of oilseed radish agrocenosis were noted for the stem diameter (Table 3, Fig. 5). An increase in the stem diameter was found with an increase in both the nutrition area of one plant and fertilization. The growth rates for row and wide-row sowing methods were different. The index of the ratio between the average formed stem diameter in the variant of wide-row sowing and in the variant of row sowing was 1.13 with the same consistent positive dynamics of formation with a decrease in the seeding rate for both sowing variants. As for other stem morphological traits, the expediency of using fertilizers at a rate of 60–90 kg ha^{-1} of active ingredient in the variants of row sowing with an increase to the unfertilized variant of 14.6% at the rate of $N_{30}P_{30}K_{30}$ and 10.0% at the rate of $N_{90}P_{90}K_{90}$ was proved. With the wide-row sowing method, the increase in the fertilizer rate had a significant positive effect on the increase in stem diameter for all fertilizer application options with a incremental value of 17.1%, 28.2% and 38.5% respectively to the unfertilized variant. At the same time, a more pronounced morphological disparity between the intensity of development of the degree of stem branching and the formed aboveground biomass with the development of diametric stem tissues and its resistance to lodging was confirmed in oilseed radish than was noted in winter rape (Sikorska et al., 2023) and various types of mustard (Abraha et al., 2024). This property can contribute to lodging of oilseed radish plants at seeding rates of 3 and 4 million germinating seeds ha^{-1}, especially in the variants of fertilization of 60 and 90 kg ha^{-1} for row sowing and in the variants of 1.5–2.0 million germinating seeds ha^{-1} at the rate of 90 kg ha^{-1} for wide-row sowing. From this point of view, the expediency of using a wide-row method of sowing oilseed radish has been proved for seed production.

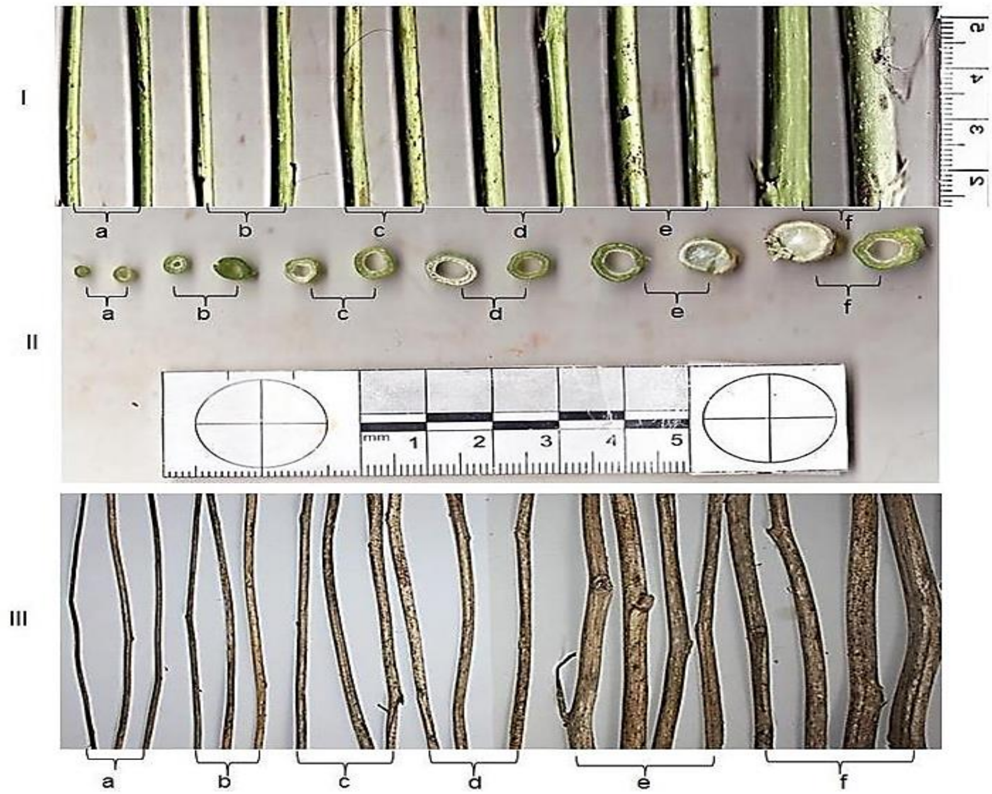

Fig. 5 Dynamic series of stem diameter at the base within the analyzed array of pre-sowing design of oilseed radish cenosis, 2019 (I – stems at the green pod stage of BBCH (62–65); II – cross-section of the stem at the base for the green pod phase (BBCH 62–65); III – stems for the phenological phase of the brown pod (BBCH 84–87); typical plant stems and its diameter cross-sections at the base against the background of $N_{90}P_{90}K_{90}$ application at the seeding rate (million germinating seeds ha^{-1}): row sowing a – 4.0; b – 3.0; c – 2.0; wide-row sowing: d – 1.5; e – 1.0; f – 0.5

Assessment of the value of the stem diameter in oilseed radish in comparison with different types of cruciferous crops showed its close value for the recommended technological variant of pre-sowing design of crop agrocenoses in the interval of plant density. Thus, for winter rape, its value ranged from 4.2–20.0 mm (Frieß et al., 2020), for mustard 4.6–21.7 mm (Kayaçetin et al., 2018; Sunagar &

Pandey, 2024), for spring rape 3.6–14.2 mm (Kuksa & Komarova, 2017; Wynne et al., 2020). At the same time, the growth rate of stem diameter with a decrease in the seeding rate was characteristic of winter rape and mustard in the range of 0.043–0.097 mm cm^{-2} of individual plant area (Yahbi et al., 2022). The obtained average long-term growth rates of oilseed radish stem diameter in the range of 0.095–0.132 mm cm^{-2} of individual plant area under row sowing and 0.060-0.083 mm cm^{-2} of individual plant area under wide-row sowing was proved more sensitive response of oilseed radish by changing the stem morphology to the improvement in the combination of nutrition area–fertilizer. Taking into account the indicated rates of relative growth of the stem diameter, this reaction was more significant in case of row sowing. An additional indicator of the resistance of cruciferous species to the already mentioned stem lodging (Qing, et al., 2021) was the stem morphological index. Its level, which in cruciferous plants provided high resistance to stem lodging, was estimated in the range of 5–12 (Grundas & Skubisz, 2008). Based on these conclusions, the probability of stem lodging of oilseed radish in the variant of row sowing will be minimal at a seeding rate of 1.0–2.0 million germinating seeds ha^{-1} and at a seeding rate of 0.5–1.0 million germinating seeds ha^{-1} with a wide-row sowing method.

The influence of different variants of pre-sowing design of oilseed radish agrocenoses on its productive architectonics and the level of seed productivity was proved (Table 4).

Table 4 Basic indicators of productive architectonics of oilseed radish plants and biological seed productivity under different technological options for pre-sowing design of its cenosis at the phenological phase of the brown pod (BBCH 84–87), 2018–2023

Sowing rate and sowing method	Fertilizer*	Plant survival rate, %	Number of pods, pcs. per plant	Seed weight per plant, g	1000 seed weight, g	The level of biological seed yield, t ha^{-1}***
4.0 million, row (25**)	1	78.1 ± 6.3^{a}	12.4 ± 3.6^{a}	0.31 ± 0.11^{a}	8.3 ± 1.22^{a}	0.97 ± 0.34^{a}
	2	79.3 ± 7.9^{b}	14.8 ± 4.1^{b}	0.39 ± 0.15^{b}	8.5 ± 1.25^{a}	1.24 ± 0.48^{c}
	3	80.2 ± 8.1^{b}	16.2 ± 5.6^{c}	0.36 ± 0.17^{a}	8.8 ± 1.29^{b}	1.15 ± 0.55^{b}
	4	78.6 ± 8.4^{a}	14.5 ± 4.2^{b}	0.30 ± 0.18^{a}	8.9 ± 1.31^{b}	0.94 ± 0.57^{a}
3.0 million, row (33.30)	1	83.2 ± 5.8^{c}	17.1 ± 2.9^{c}	0.47 ± 0.12^{c}	8.6 ± 1.28^{a}	1.18 ± 0.30^{b}
	2	85.7 ± 7.1^{d}	19.7 ± 3.2^{d}	0.51 ± 0.14^{c}	8.9 ± 1.31^{b}	1.31 ± 0.36^{d}
	3	88.2 ± 7.3^{e}	20.8 ± 3.4^{e}	0.54 ± 0.16^{d}	9.3 ± 1.33^{c}	1.43 ± 0.42^{e}
	4	84.4 ± 7.7^{c}	19.9 ± 4.2^{d}	0.49 ± 0.20^{c}	9.5 ± 1.39^{c}	1.24 ± 0.50^{c}
2.0 million, row (50)	1	86.7 ± 7.2^{d}	21.9 ± 5.7^{f}	0.68 ± 0.13^{e}	9.7 ± 1.25^{c}	1.18 ± 0.23^{b}
	2	88.2 ± 7.5^{e}	23.3 ± 5.9^{g}	0.79 ± 0.12^{f}	10.0 ± 1.49^{d}	1.40 ± 0.21^{e}
	3	89.4 ± 7.3^{f}	25.5 ± 6.1^{i}	0.91 ± 0.15^{g}	10.3 ± 1.53^{d}	1.63 ± 0.27^{g}
	4	86.3 ± 6.9^{d}	24.2 ± 6.5^{h}	1.02 ± 0.18^{h}	10.6 ± 1.58	1.78 ± 0.31^{h}
1.0 million, row (100)	1	90.1 ± 7.1^{f}	45.0 ± 9.1^{l}	1.62 ± 0.18^{j}	10.0 ± 1.61^{d}	1.47 ± 0.16^{e}
	2	93.3 ± 5.7^{i}	47.7 ± 9.8^{m}	1.73 ± 0.20^{k}	10.4 ± 1.72^{d}	1.62 ± 0.19^{g}
	3	93.7 ± 6.1^{i}	50.1 ± 10.3^{n}	1.87 ± 0.22^{l}	10.6 ± 1.74^{e}	1.76 ± 0.21^{h}
	4	94.4 ± 4.9^{j}	53.2 ± 10.6^{p}	2.09 ± 0.22^{m}	10.8 ± 1.79^{e}	1.97 ± 0.21^{j}
2.0 million, wide-row (50)	1	83.5 ± 6.3^{e}	32.0 ± 7.4^{i}	0.89 ± 0.15^{g}	8.7 ± 1.34^{a}	1.57 ± 0.26^{f}
	2	84.2 ± 6.8^{f}	34.3 ± 7.9^{j}	1.05 ± 0.17^{h}	9.0 ± 1.38^{b}	1.86 ± 0.30^{i}
	3	84.7 ± 5.9^{f}	35.8 ± 8.5^{k}	1.12 ± 0.19^{i}	9.2 ± 1.33^{c}	2.00 ± 0.34^{j}
	4	83.5 ± 6.2^{e}	33.6 ± 9.1^{j}	1.04 ± 0.21^{h}	9.4 ± 1.39^{c}	1.87 ± 0.38^{i}
1.5 million, wide-row (66.60)	1	90.2 ± 6.3^{f}	51.6 ± 11.2^{o}	1.72 ± 0.24^{k}	9.4 ± 1.59^{c}	2.34 ± 0.33^{l}
	2	91.5 ± 6.8^{g}	53.9 ± 11.6^{p}	1.94 ± 0.24^{l}	9.6 ± 1.63^{c}	2.67 ± 0.33^{n}
	3	92.7 ± 6.1^{h}	55.3 ± 12.4^{q}	2.08 ± 0.27^{m}	10.0 ± 1.67^{d}	2.90 ± 0.38^{o}
	4	93.4 ± 5.1^{i}	57.4 ± 13.1^{r}	2.27 ± 0.28^{n}	10.2 ± 1.71^{d}	3.20 ± 0.39^{p}
1.0 million, wide-row (100)	1	88.7 ± 5.9^{e}	71.1 ± 15.6^{s}	2.74 ± 0.31^{o}	10.2 ± 1.82^{d}	2.44 ± 0.19^{m}
	2	91.9 ± 4.2^{g}	73.6 ± 16.7^{t}	2.91 ± 0.40^{p}	10.5 ± 1.85^{e}	2.68 ± 0.29^{n}
	3	92.3 ± 4.4^{h}	78.8 ± 17.2^{u}	3.18 ± 0.45^{q}	11.0 ± 1.89^{f}	2.94 ± 0.37^{o}
	4	93.5 ± 5.5^{i}	81.4 ± 17.8^{v}	3.44 ± 0.52^{r}	11.3 ± 1.95^{f}	3.22 ± 0.42^{p}
0.5 million, wide-row (200)	1	88.4 ± 5.1^{e}	90.7 ± 18.9^{w}	3.49 ± 0.58^{r}	10.8 ± 1.81^{e}	1.55 ± 0.26^{f}
	2	90.2 ± 4.3^{f}	92.9 ± 19.2^{x}	3.53 ± 0.67^{r}	11.0 ± 2.06^{f}	1.60 ± 0.30^{f}
	3	93.1 ± 3.5^{i}	94.7 ± 20.1^{y}	3.78 ± 0.70^{s}	11.2 ± 2.19^{f}	1.78 ± 0.33^{h}
	4	94.8 ± 3.1^{j}	97.8 ± 20.8^{z}	4.29 ± 0.85^{t}	11.6 ± 2.24^{g}	2.04 ± 0.40^{k}

Note: * Fertilizer variant: 1 – $N_0P_0K_0$; 2 – $N_{30}P_{30}K_{30}$; 3 – $N_{60}P_{60}K_{60}$; 4 – $N_{90}P_{90}K_{90}$; ** Area of plant nutrition, cm^2 $plant^{-1}$ (different letters indicate values that differed significantly from each other in the column direction for each indicator in the table based on the results of the comparison using the Tukey's test with the Bonferroni correction); *** The yield is adjusted for the survival rate of plants in the variant and the actual planting density.

It is known (Hernández et al., 2022) that plant survival for the period of reaching physiological maturity is one of the reliable criteria for the effectiveness of designing the agrocenosis of cruciferous plant species. The maximum survival rate of oilseed radish plants was maximum in the variants of the minimum seeding rate for both the row variant (average increase in fertilizer variants to the maximum seeding rate of 13.8%) and the variant of the wide-row sowing method (average increase in fertilizer variants to the maximum seeding rate of 7.65%). The average levels of plant survival for the two sowing methods were significantly different. The average level of plant survival for conventional row sowing was 86.2% and was 89.8% for wide-row sowing. According to the statements, the optimal agrotechnological variant of agrocenosis management should ensure the level of plant safety at the date of harvesting at the level of 90%. Based on this, with certain tolerances, such a level for oilseed radish was achievable in the range of 1.0–2.0 million germinating seeds ha^{-1} for row sowing and 0.5–1.0 million germinating seeds ha^{-1} for wide-row sowing.

In terms of the number of pods per plant, the wide-row and row sowing methods had significant differences with a ratio index of 2.43 (the long-term average for the wide-row method was 26.6 pods, for the row method was 64.7). This distribution pattern positively correlated with the already noted increase in lateral branching of the stem and the participation of these branches in the formation of the idiotypic structure of the generative part (Fig. 1, III). Changes in the individual plant nutrition area had a direct resulting effect on the level of formation of the indicator with a positive dynamic with its increase. The average dynamic increase in the number of pods with a change in the plant nutrition area per 1 cm^2 for the row sowing method was 0.43 on the unfertilized background and 0.52 on the background with the aplication of $N_{90}P_{90}K_{90}$. For the wide-row method of sowing, similar indicators were 0.39 and 0.43, respectively. Such a difference in dynamics in favor of the row sowing method indicated the sensitivity of oilseed radish plants to optimization of plant nutrition area, given the higher cenotic stress for this indicator for the row sowing method. The application of additional mineral nutrition was on average effective for the row seeding method in terms of the number of pods for the application rates of $N_{30}P_{30}K_{30}$ and $N_{60}P_{60}K_{60}$, providing an increase to the unfertilized variant at the level of 9.4 and 6.7%, respectively. In the variant of the wide-row sowing method, positive increases were noted for all variants of additional fertilization with successive increases in the range of fertilizer rate growth of 3.8–7.8–10.1%. The level of variability of the indicator should be noted. The coefficient of variation at the level of 29.0% was maximum in the variant of the highest density of oilseed radish agrocenosis in the variant of row sowing and gradually decreased to the level of 20–21% to the variant of the minimum density for wide-row sowing. These results was in line with previous studies (Tsytsiura, 2022) on the role of phytocoenotic stress in the formation of reproductive effort and overall generative development of oilseed radish with changes in planting density. In addition, by comparing the number of lateral branches and the total number of pods per plant in different variants studied, the heterogeneity of its reproductive effort in the tiered height structure of oilseed radish plants was proved. In addition, the obtained index of the number of pods per plant in oilseed radish was lower than for other cultivated species of cruciferous plants. For example, in winter rape, with similar indicators of cenosis density, was at the level of 55–80 pods, and in variants of sparse sowing it reached 150–200 (Hernández et al., 2022; Sikorska et al., 2023). For white mustard, which has similar density variations in the zone of unstable moisture for similar intervals, the number of pods ranged from 30–60 to 120–180 (Sunagar & Pandey, 2024). Spring oilseed rape had indicators close to those determined for oilseed radish (Kayaçetin et al., 2018; Wynne et al., 2020). Given these data, low-density agrocenoses will have advantages over continuous row seeding options to achieve an effective level of oilseed radish seed yield in contrast to common cruciferous species.

The weight of 1000 seeds, despite the high genetic determinism in cruciferous plant species (Yahbi et al., 2022), also depended on the combination of factors studied. This was confirmed by the average results of the index for row (9.6 g) and wide-row (10.2 g) sowing and the increases from the effect of mineral fertilizers under these sowing methods at the level of 2.1–3.3% and 2.6–8.7%. The peculiarities of the formation of the indicator had a similar trend as for the number of pods within the studied variants. A high variability of the indicator was found at the level of 19.3%, especially in the variants with the maximum plant nutrition area at a seeding rate of 0.5 million germinating seeds ha^{-1} with $N_{90}P_{90}K_{90}$ application against the level of 14.7% for the variant with the minimum nutrition area at the same fertilization rate. This confirmed the conclusions about the suppressive effect of cenotic pressure on plants in the formation of the range of traits with high genetic determination (Gan et al., 2016) and was consistented with the nature of matrix variability of oilseed radish seeds within the generative part of plants (Tsytsiura, 2022).

Previous studies for the period 2013-2018 (Tsytsiura, 2021; 2022) also found that the inflorescence of oilseed radish within the studied technological variants had all the signs of vertical tiering with the formation of fruit elements of the upper, middle and lower zones. Accordingly, the difference in morphometry and weight characteristics of seeds obtained from the corresponding zones of the inflorescence was established. The difference in the morphological size of seeds was significant in comparing the lower and upper zones of the inflorescence, and the coefficient of variation of seeds obtained from the upper zone of the inflorescence on average for the same technological variants as in this article was 1.04-1.16 times higher. Under these conditions, the coefficient of variation of seed morphometry with increasing fertilizer rates from 0 to 90 kg ha^{-1} increased consistently by 1.8–2.3% for the upper and 0.9–1.7% for the lower zones of the inflorescence. These studies also showed a gradual increase in seed variation by 4.1–5.9% for the row seeding variant in the range of 1.0–4.0 million germinating seeds ha-1 and by 6.8–9.5% for wide-row seeding in the range of 0.5–2.0 million germinating seeds ha^{-1}. The value of the coefficient of variation of morphological parameters of seeds was maximum 24.9% at a seeding rate of 0.5 million germinating seeds ha-1 with an average value for the inflorescence and minimum 16.3%. at a rate of 4.0 million germinating seeds ha^{-1} on an unfertilized background. Certain patterns were also established for the weight of 1000 seeds. Thus, the average difference in similar technological variants of the experiment was 6.5% in comparing seeds from pods of the upper and lower zones of the inflorescence. The use of mineral fertilizers at a gradually increasing rate reduced the difference in the weight of 1000 seeds in comparison of seeds from pods of different zones by 1.3–3.7%. The maximum average difference in the value of the indicator for the two zones of pods was noted in the comparison of technological parameters of 4.0 and 0.5 million germinating seeds ha^{-1} on the level 8.8 and 8.2%, respectively, for the upper and lower zones of the inflorescence. The determined nature of the variability, taking into account the studies of Rondanini et al. (2017) and Parvin et al. (2019), should be reflected in the quality indicators of seeds and be taken into account in the recommendations for growing oilseed radish seeds at different seeding rates and nutrition area. These the questions that were set for study in 2020 and the results will be published soon.

The peculiarities of the dynamics of the formation of the number of pods per plant and the weight of 1000 seeds formed both an indicator of individual seed productivity and a generalizing feature of the biological level of yield. Due to the reduced combinatorics of the number of plants per unit area at different density variants, significantly higher levels of indicators were established for the wide-row sowing variants. As a result, the ratio of this method to the variant of row sowing averaged 2.77 in terms of individual seed productivity of plants and 1.64 in terms of biological yield. Under these conditions, for the variants of row sowing, the presence of growth to the unfertilized variant proved the feasibility of using fertilizer rates up to the limit of $N_{60}P_{60}K_{60}$ (increase for the norm of $N_{30}P_{30}K_{30}$ 16% and for the norm $N_{60}P_{60}K_{60}$ 7.2%). For the variant of wide-row sowing, the incremental dynamics was noted for all fertilizer options in the range from 11.5% for the $N_{30}P_{30}K_{30}$ variant to 21.8% for the $N_{90}P_{90}K_{90}$ variant. In interaction with the planting density, the maximum average yield by fertilizer variant was observed for the variant with the maximum nutrition area (100 cm^2) for row sowing 1.71 t ha^{-1} and for the variants with a nutrition area in the range of 66.6–100 cm^2 for wide-row sowing 2.80 t ha^{-1}. The same conclusions are confirmed by the results of cluster analysis in the consolidated system of indicators (Fig. 6). According to the Euclidean distance indicator, the efficiency of variants with a seeding rate of 1 million germinating seeds ha^{-1} (with an individual plant nutrition area of 100 cm^2) for row sowing and 0.5–1.0 million germinating seeds ha^{-1} (with an individual plant nutrition area of 100–200 cm^2) for wide-row sowing. The variant of wide-row sowing with a seeding rate of 1.5 million germinating seeds ha^{-1} occupied an intermediate niche between the options for using oilseed radish agrocenoses for seed and fodder-sideral purposes, which was consistented with the results of previous studies (Tsytsiura, 2020).

A preliminary assessment of the nature of the dynamics of the formation of general and productive indicators of stem and plant architectonics was logically confirmed by the application of correlation analysis (Table 5). The data confirmed the certain conjugation of morphological traits of oilseed radish plants and, in particular, for the indicators of seeding rate (plant nutrition area) and fertilization. The index of determination due to fertilization of the number of lateral branches of the stem was 30.5%, the number of pods 20.2%, individual seed productivity of plants 38.4%, weight of 1000 seeds 12.0% and the level of biological yield 31.6%. Due to the change in the plant nutrition area, similar determination indices were at the level of 74.6%, 73.1%, 82.4%, 64% and 64.1% respectively. Significantly lower determination for the fertilizer factor was explained by the multidirectional nature of the influence of fertilizer rates (increase and decrease), especially in variants of dense agrocenoses of row sowing, which formed a different type of dependencies and, according to Wong (2018), provided a lower level of resulting correlation closeness.

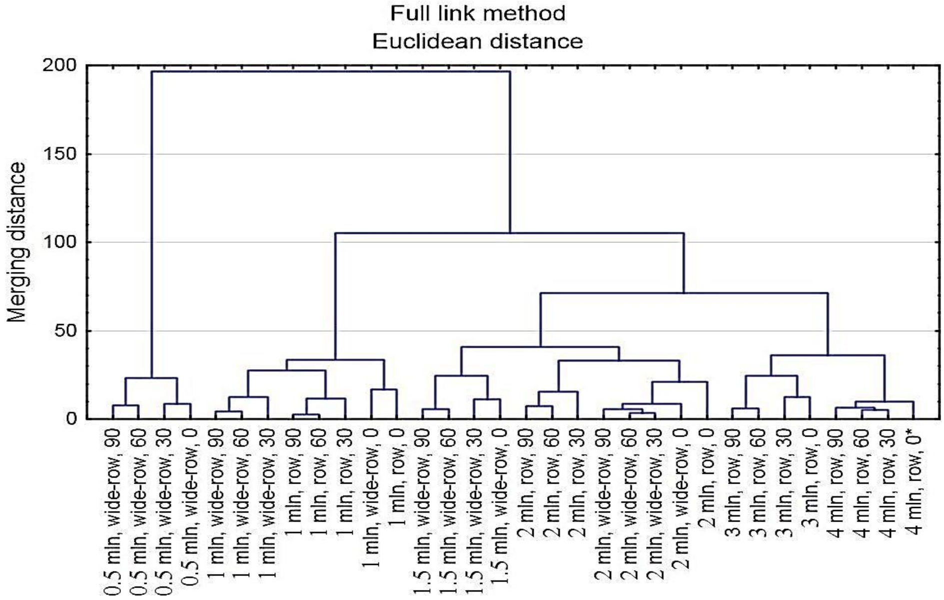

Fig. 6 Cluster analysis of the interaction of indicators of general stem architectonics and productive architectonics of oilseed radish plants under different technological options for pre-sowing design of its cenosis for the phenological phase of the brown pod (BBCH 84–87), 2018-2023. Note: *0 – $N_0P_0K_0$; 30 – $N_{30}P_{30}K_{30}$; 60 – $N_{60}P_{60}K_{60}$; 90 – $N_{90}P_{90}K_{90}$

Table 5 Spearman's rank correlation coefficients of the dependence of the indicators of general stem architectonics and productive architectonics of oilseed radish plants on the phenological phase of the brown pod (BBCH 84–87) (summary array of traits for the period 2018–2023 (*N=192*))

	2	3	4	5	6	7	8	9	10	11	12
1	0.000	0.646*	-0.417*	0.404*	0.552*	0.446*	0.312*	0.449*	0.620*	0.347*	0.562*
2		0.245*	-0.878*	0.821*	0.864*	-0.640*	0.594*	0.855*	0.908*	0.802*	0.804*
3			-0.235*	0.578*	0.636*	-0.579*	0.719*	0.397*	0.462*	0.703*	0.677*
4				-0.693*	-0.755*	0.535*	-0.720*	-0.835*	-0.819*	-0.727*	-0.554*
5					0.935*	-0.907*	0.700*	0.649*	0.751*	0.898*	0.460*
6						-0.848*	0.775*	0.839*	0.905*	0.969*	0.504*
7							-0.702*	-0.567*	-0.620*	-0.794*	-0.567*
8								0.753*	0.719*	0.764*	0.706*
9									0.969*	0.791*	0.678*
10										0.858*	0.619*
11											0.515*

Note: *significant correlation coefficients at $p<0.05$. Indicators: 1 = fertilizers in index terms (0 – $N_0P_0K_0$; 1 – $N_{30}P_{30}K_{30}$; 2 – $N_{60}P_{60}K_{60}$; 3 – $N_{90}P_{90}K_{90}$); 2 = area of plant nutrition (cm^2 plant^{-1}); 3 = plant height (cm); 4 = height to the first branch (cm); 5 = stem diameter (mm); 6 = number of lateral branches (pcs.); 7 = morphological index of the stem; 8 = plant survival rate (%); 9 = number of siliques (pcs. per plant); 10 = seed weight per plant (g); 11 = 1000 seed weight (g); 12 = level of biological seed yield (t ha^{-1})

Regarding the morphological traits of the plant classified as compensatory, an inverse moderate relationship was found with the height of the stem before the first branching (d_{xy}=30.7%) and the morphological index of the stem (d_{xy}=32.1%). The same character of closeness but of a direct forming nature was established for the indices of seed weight per plant (d_{xy}=38.3%) and the number of pods per plant (d_{xy}=6%). At the same time, taking into account the variants of correlation-pathway analysis in determining the relationships of the general and productive architectonics of other cruciferous crops (Parvin et al., 2019; Yahbi et al., 2022; Haq et al., 2023; Sikorska et al., 2023; Sunagar & Pandey, 2024), oilseed radish showed higher levels of response by changing the ratios of plant morphological traits to changes in plant nutrition area and lower levels to changes in fertilizer levels. This was due, as noted above, to the different threshold of fertilizer optimality for different density options and required individualization of fertilizer rates for each selected planting density in the case of oilseed radish.

The role of hydrothermal conditions in the realization of compensatory architecture of oilseed radish plants with changes in the area of plant nutrition in combination with increasing fertilizer rates was also proved (Table 6).

Table 6 Spearman's rank correlation coefficients of the dependence of the indicators of general stem architecture and productive architecture of oilseed radish plants on hydrothermal parameters of vegetation for oilseed radish on the phenological phase of the brown pod (BBCH 84–87) (summary array of traits for the period 2018–2023 (*N=192*))

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	-0.288*	-0.577*	0.755*	0.955*	0.876*	0.881*	0.499*	0.458*	0.757*	0.520*	0.893*	0.646*	0.619*	0.839*	0.723*
2		0.502*	0.112	-0.181	-0.371*	0.461*	0.408*	-0.401*	-0.378*	-0.453*	-0.466*	-0.490*	-0.563*	-0.508*	-0.627*
3			-0.568*	-0.710*	-0.543*	0.459*	-0.391*	0.449*	0.548*	0.407*	0.475*	0.451*	0.406*	0.413*	0.501*
4				0.889*	0.419*	0.642*	0.688*	0.514*	0.727*	0.698*	0.730*	0.323*	0.548*	0.744*	0.503*
5					0.775*	0.797*	0.512*	0.506*	0.726*	0.531*	0.840*	0.670*	0.561*	0.798*	0.528*
6						0.727*	0.342*	0.326*	0.485*	0.367*	0.702*	0.510*	0.464*	0.606*	0.532*

Note: *significant correlation coefficients at $p<0.05$. Indicator indices: 1 = amount of precipitation during the growing season (mm); 2 = average daily temperature during the growing season (°C); 3 = average relative humidity of air (%); 4 = hydrothermal coefficient during the growing season (HTC); 5 = De Marton aridity index (I_{DM}); 6 = Vysotsky-Ivanov moisture coefficient (K_h); 7 = plant height (cm); 8 = height to the first branch (cm); 9 = stem diameter (mm); 10 = number of lateral branches (pcs.); 11 = morphological index of the stem; 12 = plant survival rate (%); 13 = number of siliques (pcs. plant^{-1}); 14 = seed weight per plant (g); 15 = 1000 seed weight (g); 16 = level of biological seed yield (t ha^{-1})

It has been determined that the amount of precipitation was crucial in ensuring the intensity of morphogenesis of oilseed radish plants at different seeding rates. The index of determination of plant morphological productivity indicators had the following values for the following traits: the number of lateral branches 57.3%, the height of the stem to the first lateral branching 25%, the number of pods per plant 41.7%, the weight of seeds per plant 38.3%, the weight of 1000 seeds 70.4% and the level of biological seed yield 52.3%. For the indicator of average daily temperature, the dominant nature of the dependencies was of the inverse type with a coefficient of decrease in the determination index in the range of 1.23–1.47. Such a heterogeneous influence led to a general decrease in the severity of the applied indicators of the hydrothermal regime of vegetation in the formation of the general and productive architectonics of oilseed radish plants with a decrease in the coefficient of determination by 13–27%. Based on this analysis, oilseed radish was classified as a crop with high sensitivity to moisture conditions and relative resistance to air temperature (according to the classification of Ahmad et al. (2021)), which puted it on a par with widespread mustard species (Kayaçetin et al., 2018) and spring rape (Kuksa & Komarova, 2017). However, oilseed radish was inferior in adaptability in terms of moisture supply to winter rape, where the level of determination of the main morphological traits of productive architectonics in relation to the amount of precipitation during the growing season was in the range of 25–44% (Agahi et al., 2020; Wu et al., 2022; Sikorska et al., 2023).

It should be noted that hydrothermal conditions of oil radish vegetation period according to previous studies (2013–2018) (Tsytsiura, 2020) also affect the ideotypic structure of its agrocenoses by the share of upper and lower tiers. These studies noted that the technological stand densities of plants in the interval of 1.0–2.0 million germinating seeds ha^{-1} at row sowing and 0.5–1.0 million germinating seeds ha^{-1} at wide-row sowing on the background of more than 60 kg ha^{-1} fertilizer lead to the appearance of plants with ultra-low vitality, and to the emergence of morphotypes, which significantly exceed typical plants by the average value of morphological parameters in the agrophytocenosis of oilseed radish.

The use of a system of mathematical models in assessing the relationship between the indicators of productive architectonics of oilseed radish plants and its nutrition area in the experiment showed the complex nature of the conjugate formation of these indicators (Table 7). These models were confirmed in the multiple regression analysis (Table 8). Taking into account the determined complex power-law nature of the formation of plant architectonics indicators depending on the area of its nutrition, an in-depth version of multiple nonlinear regression was used for the regression system on the levels of two and four parameter estimates. The obtained results and its graphical interpretation (Fig. 7) proved the presence in the system of pre-sowing design of oilseed radish agrocenoses of the optimal value of the individual plant nutrition area in the range of the studied interval of 25–200 cm^2, which, against the background of appropriate additional fertilization, guaranteed the achievement of maximum in the formation of indicators of productive architectonics, which will ultimately determine the level of the obtained seed yield.

Table 7 Functional expression for comparing the dependencies of indicators of general stem architectonics and productive architectonics of oilseed radish plants with the nutrition area of the plant for phenological stage of the brown pod (BBCH 84–87), 2018–2023

Variant of model	The equation depen-dencies	Extrapolated coefficients of the equation				Statistical parameters for assessing the reliability of fitting the actual dynamics to the theoretical expression of the equation				
		a	b	c	d	S	$R^2_{(adj.)}$	RMSE	RRMSE	*p*
Dependence parameters: y – number of lateral branches of the stem (pcs.); x – nutrition area of the plant (cm^2)										
Quadratic fit	$y=a+bx+cx^2$	-0.631	0.065	-0.00017	–	0.671	0.842	1.640	0.232	*<0.001*
Exponential Association	$y=a(b-e^{-cx})$	7.294	0.832	0.0131	–	0.673	0.859	1.514	0.209	*<0.001*
Hoerl Model	$y=ab^Xx^c$	0.0103	0.993	–	–	0.674	0.839	1.783	0.269	*<0.001*
Modified Geometric	$y=ax^{b/x}$	8.990	-0.176	–	–	0.668	0.832	1.814	0.301	*<0.001*
Modified Exponential	$y=ae^{b/x}$	7.312	-0.577	–	–	0.667	0.828	1.968	0.331	*<0.001*
Logarithm Fit	$y=a+b\ln(x)$	-6.848	2.352	–	–	0.665	0.819	2.045	0.342	*<0.001*
Vapor Pressure	$y=e^{a+b/x+c\ln(x)}$	1.475	-50.100	0.0925	–	0.676	0.838	1.789	0.273	*<0.001*
Weibull Model	$y=a-be^{-cx^d}$	5.944	6.862	0.00892	1.085	0.684	0.841	1.669	0.248	*<0.001*
Dependence parameters: y – number of pods per plant (pcs. $plant^{-1}$); x – nutrition area of the plant (cm^2)										
Modified Exponential	$y=ae^{b/x}$	87.917	-54.146	–	–	6.774	0.880	11.239	1.969	*<0.001*
Hoerl Model	$y=ab^Xx^c$	-0.0894	0.990	1.588	–	6.779	0.884	11.102	1.984	*<0.001*
Quadratic fit	$y=a+bx+cx^2$	-9.545	0.889	0.002585	–	6.798	0.883	11.092	1.977	*<0.001*
Vapor Pressure	$y=e^{a+b/x+c\ln(x)}$	5.403	-67.873	-0.166	–	6.803	0.882	11.078	1.939	*<0.001*
Richards Model	$y=a/(1+e^{(b-cx)})^{(1/d)}$	64.266	-0.358	0.0323	0.157	6.825	0.886	11.051	1.907	*<0.001*
Weibull Model	$y=a-be^{-cx^d}$	64.897	66.441	0.00142	1.548	6.805	0.887	10.936	1.844	*<0.001*
3rd degree Polynomial Fit	$y=a+bx+cx^2+dx^3+\ldots$	-14.533	1.112	-0.00518	0.0000084	6.887	0.884	11.087	1.959	*<0.001*
Dependence parameters: y – seed weight (g $plant^{-1}$); x – nutrition area of the plant (cm^2)										
3rd degree Polynomial Fit	$y=a+bx+cx^2+dx^3+\ldots$	0.121	-0.0276	0.00158	-0.000015	0.429	0.881	1.617	0.302	*<0.001*
MMF Model	$y=(ab+cx^d)/(b+x^d)$	-0.131	3898.37	4.639	1.842	0.417	0.892	1.544	0.228	*<0.001*
Quadratic fit	$y=a+bx+cx^2$	-0.552	0.0379	-0.00008	–	0.416	0.897	1.509	0.205	*<0.001*
Exponential Association	$y=a(b-e^{-cx})$	5.837	0.899	0.00709	–	0.436	0.878	1.781	0.351	*<0.001*
Exponential Association 2	$y=a(1-e^{-bx})$	8.373	0.00312	–	–	0.465	0.856	1.901	0.396	*<0.001*
Rational Function	$y=(a+bx)/(1+cx+dx^2)$	-0.499	0.0354	0.00306	-0.0000018	0.479	0.858	1.893	0.379	*<0.001*
Linear Fit	$y=a+bx$	0.0907	0.0202	–	–	0.498	0.835	2.159	0.427	*<0.001*

Taking into account the graphs of recessional surfaces, the interval of such an optimal nutrition area for oilseed radish was in the range of 80–160 cm^2. Moreover, the feasibility of the $N_{30}P_{30}K_{30}$ application options extended to the entire range of the determined optimal plant nutrition area. The rate of $N_{60}P_{60}K_{60}$ was appropriate for a nutrition area of 100–140 cm^2. The rate of $N_{90}P_{90}K_{90}$ was appropriate for use in the range of individual nutrition area over 140 cm^2.

Table 8 Multiple regression dependence between indicators of compensatory stem architecture and technological parameters of pre-sowing design of its agrocenosis on the phenological phase of brown pod (BBCH 84–87) (average data for 2018–2023)

Qualitative indicator	Equation of dependence	Parameters of the equation				Statistical evaluation of components				
		x	y	z_1	z_2	Multiple R	Multiple $R^2_{(adj.)}$	F	df_1, df_2	*p*
Number of lateral branches, pcs. $plant^{-1}$	$-1.746+0.670x+0.065y-0.075x^2+0.0021xy-0.0002y^2$	Fertilizers in index terms*	Area of plant nutrition, cm^2 $plant^{-1}$	–	–	0.941	0.869	52,587	4.270	*<0.001*
Number of siliques, pcs. $plant^{-1}$	$-8.264-1.253x+0.889y+0.247x^2+0.0063xy-0.0026y^2$					0.940	0.866	51.094	4.270	*<0.001*
Seed weight per plant, g	$-1.056+0.099x+0.043y+0.0053x^2+0.0015xy-0.0001y^2$					0.948	0.883	59.653	4.270	*<0.001*
1000 seed weight, g	$7.108+0.326x+0.039y-0.009x^2+0.0001xy-0.0001y^2$					0.942	0.871	53.386	4.270	*<0.001*
Level of biological seed yield, t ha^{-1}	$-0.198+0.306x+0.036y+0.032x^2+0.0008xy-0.00015y^2$					0.751	0.500	8.714	4.270	*<0.001*
Level of biological seed yield, t ha^{-1}	$-3,697+0,306x+0.036y+0.022z_1+0.0000012xyz_1-0.032x^2-0.0001y^2-0.00003z_1^2$	Fertilizers in index terms*	Area of plant nutrition, cm^2 $plant^{-1}$	Amount of precipitation during the growing season, mm	Average daily temperature during the growing season, °C	0,797	0,624	53,727	6,185	*<0.001*
Level of biological seed yield,t ha^{-1}	$-36.878+0.306x+0.036y+5.183z_2-0.000028xyz_2-0.032x^2-0.0001y^2-0.182z_2^2$					0.760	0.564	42.179	6.185	*<0.001*

Note: *fertilizers in index terms (0 – $N_0P_0K_0$; 1 – $N_{30}P_{30}K_{30}$; 2 – $N_{60}P_{60}K_{60}$; 3 – $N_{90}P_{90}K_{90}$)

This was indicated by the angular nature of the slope of the reaction surface with an angle of growth in the direction of increasing fertilizer rate. A similar interval was determined from the standpoint of the main climatic parameters – the sum of precipitation and temperature (Fig. 7, b–c). This made it possible to adapt this technological solution to the hydrothermal regime of the research area. At the same time, the optimal levels of biological yield of oilseed radish seeds were combined at the determined optimal interval of the individual plant nutrition area, the amount of precipitation in a wide range from 260 to 420 mm and the average daily temperature at the level of 13.0–15.5 °C. It was also determined that an intensive increase in average daily temperatures (above 18–19 °C) against the background of a decrease in precipitation to the level of 129.3–170.8 mm (which was observed in 2015 and 2018) ensured the growth of idiotypes of plants of the lower tier in all variants of plant density and fertilization, which from the point of view of the compensatory ability of plants led to a general decrease in the number of lateral branches in the range of 23–38% with a general decrease in seed productivity of plants by at least 18.7–35.2%, respectively, for the nominal and maximum plant density in the experiment. It should be noted that a similar character of optimality in the interval between the variants of the nutrition area and row spacing configuration studied was also established for winter rape (Ahmad et al., 2021; Wu et al., 2022), spring rape (Agahi et al., 2021), white mustard (Kayaçetin et al., 2018) and other cruciferous plant species (Frieß et al., 2020). The determined technological interval of the nutrition area for oilseed radish differed from the recommended one for growing oilseed radish for seeds in the system of its multi-crop use for the conditions of the

European Union (Bhogal et al., 2020) within 60–80 cm^2. When applied to the conditions of the experimental scheme, this would correspond to a seeding rate in the range of 1.25–1.50 million germinating seeds ha^{-1}. In the interpretation of the determined interval of the nutrition area of 80–160 cm^2, this corresponded to a seeding rate of 0.80–1.25 million germinating seeds ha^{-1}. It was more optimal from the point of view of the determined long-term level of precipitation and average daily temperature during the vegetation period of oilseed radish.

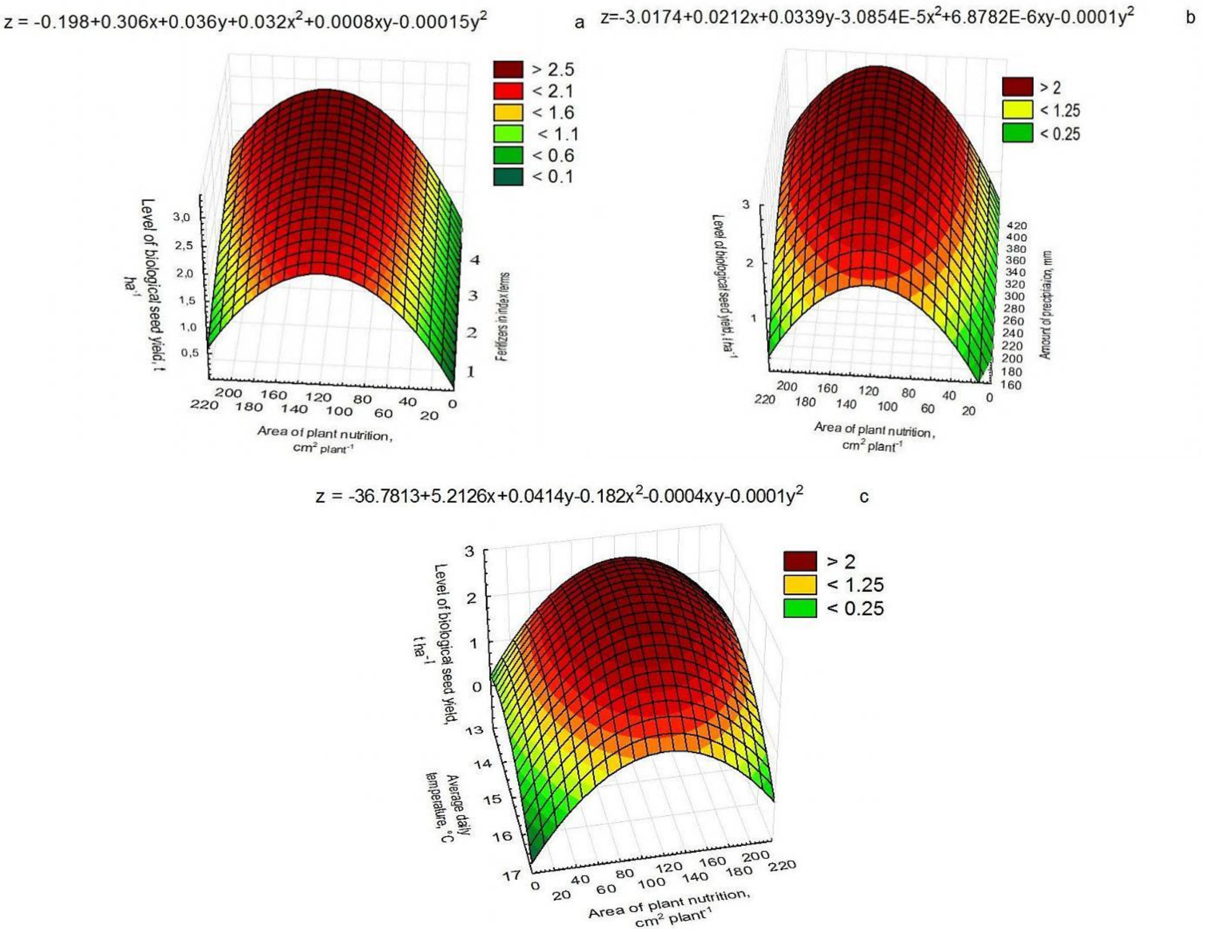

Fig. 7 Reaction surfaces of the dependences of indicators of the productive architecture of oilseed radish plants on the technological parameters of the pre-sowing construction of its agrocenosis and hydrothermal indicators of its vegetation period for phase of the brown pod (BBCH 84–87) (2018–2023)

4 Conclusions

The level of general and productive architectonics of oilseed radish plants depended on the size of the individual nutrition area against the background of variable rates of mineral fertilizers in the agrotechnological combination of row and wide-row sowing methods. Reducing the cenotic stress in the agrocenosis of oilseed radish by reducing the seeding rate ensured the realization of the compensatory potential of oilseed radish plants achieved through additional branching of the stem, development of these branches with a decrease in its height in relation to the total length of the stem and its participation in the formation of the plant's reproductive effort with the additional formation of the number of pods per plant. The combinatorics of such mechanism of reaction of oilseed radish plants had a complex step model character of formation with an average long-term gradient of growth of the biological level of seed yield cm^{-2} of reduction of the individual plant nutrition area of 0.014 t ha^{-1} cm^{-2} for the conventional row seeding method and 0.033 t ha^{-1} cm^{-2} for the wide-row method. The payback of 1 kg of active ingredient of mineral fertilizers was noted at the row sowing to the rate of application of $N_{30}P_{30}K_{30}$ with an average long-term indicator of 4.7 kg of seeds ha^{-1}. For wide-row sowing, the payback was set to the application rate of $N_{90}P_{90}K_{90}$ at the level of 6.8 kg of seeds ha^{-1}. The optimal agrotechnological interval of pre-sowing design of oilseed radish agrocenosis with an individual plant nutrition area of 80–160 cm^2 was established, which corresponded to a sowing rate of 1.0–1.25 million germinating seeds ha^{-1} for row sowing with the application of rate of mineral fertilizer $N_{30-60}P_{30-60}K_{30-60}$ and 0.80–1.0 million germinating seeds ha^{-1} for wide-row sowing with the application of rate of mineral fertilizer $N_{60-90}P_{60-90}K_{60-90}$. The implementation of the determined optimal variant of pre-sowing design of oilseed radish agrocenosis will have a high probability of potential implementation with the amount of precipitation during the growing season of oilseed radish at a level not lower than 260 mm and the average daily temperature for the period April-June in the range of 13–16.5 °C.

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