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FORMATION OF PLANT DENSITY IN WINTER RAPE (*BRASSICA NAPUS* L.) CROPS DEPENDING ON DIFFERENT TECHNOLOGICAL ASPECTS OF CULTIVATION

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Topicality. *The formation of plant density is a determining factor in the effective use of potential in the winter rape cultivation under conditions of climatic risks and limited resources. The study of dependence of plant density on the sowing method, seeding rate and agricultural background justifies an adaptive approach to increasing crop productivity.* ***Purpose.*** *To study the influence of sowing method, seeding rate and level of mineral nutrition, as well as their interaction on the formation of winter rape plant density, with further justification of optimal technological parameters to ensure a stable disposition of crops and increase the efficiency of agrocenosis.* ***Materials and Methods.*** *Two genotypes of winter rape, Antariia variety and Exagon hybrid, were used in the experiments. Two sowing methods (conventional row and wide-row), four seeding rates, three variants of agricultural background were studied: control (no fertilisers), mineral nutrition ($N_{120}P_{60}K_{90}$) and fertilisers in combination with the growth regulator Caramba. Field method (phenological observations, plant density records at different development stages), laboratory method (determination of laboratory germination, field germination, indicators of plant overwintering), mathematical and statistical method (analysis of variance, regression analysis and graph analytics) were used in the experiments.* ***Results.*** *It was found that the plant density of winter rape largely depends on a combination of technological factors. The Exagon hybrid is more responsive to the agricultural background compared to the Antariia variety, which was manifested in higher rates of plant overwintering and adaptability to changing technological conditions. The constructed multiple regression model showed a statistically significant dependence of the plant density on the seeding rate, agricultural background and their interaction, which allows predicting the optimal plant density parameters before harvesting.* ***Conclusions.*** *It was found that the most stable and effective plant density is formed by combining wide-row sowing with a seeding rate of 0.8–1.0 million seeds/ha and combined application of fertilisers with a growth regulator. The results of our research are of practical importance for implementation and can be used to improve seeding rates and fertilisation systems, taking into account the biological characteristics of winter rape variety or hybrid.*

Key words: *winter rape, plant density, seeding rate, sowing methods, variety, hybrid, multiple regression model.*

Introduction. Winter rape (*Brassica napus* L.) is one of the leading oil crops in global and domestic agriculture, playing an important role in the food, technical, and feed industries. High profitability of cultivation, multifunctionality of production, and adaptability to temperate climates are factors contributing to growing interest in intensifying cultivation technologies for this crop [1, 2]. In modern agro-economic conditions, the improvement of technological methods aimed at forming an optimal crop structure, in particular, effective plant density, as key factors in rapeseed yield, is becoming increasingly important.

The issue of effective utilisation of agro-ecological potential as a component of natural resources is becoming particularly relevant in the context of resource constraints and climate challenges. The agro-ecological potential of a region is determined by the capability of soils, biota, climatic and hydrological conditions to ensure sustainable biological productivity without the risk of ecosystem degradation. Therefore, the issue of the adaptability of agricultural technologies to specific crop growing conditions comes to the fore [3–5].

Despite the increase in winter rape acreage in Ukraine, the cultivation of this crop remains largely extensive. Average yields are significantly lower than global averages, lagging behind by 40–50 %. Production efficiency cannot be improved without adherence to technological discipline, the use of intensive agricultural techniques and the involvement of material resources [6].

An important role in this process is played by the formation of plant density as an indicator of the realisation of genotype potential in speci-

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fic agricultural conditions.

Planting density is an integral indicator that reflects the combined influence of technological and biological factors, including seeding rates, mineral nutrition levels, sowing type, variety or hybrid characteristics, weather conditions, and growth regulators. Establishing the optimal density is important for forming a uniform, lodging-resistant and maximally productive agrocenosis. At the same time, the effectiveness of each of the agrotechnical factors depends significantly on the accompanying conditions, resulting in the need to study their synergistic effect, especially within the framework of adaptive technologies.

Based on the results of previous studies [7, 8], the plant height of winter rape varies significantly depending on the sowing method and plant density in the crop. With wide-row sowing, a tendency to reduce plant height is observed, which is explained by the increased feeding area. With conventional row sowing, winter rape forms taller plants with thinner stems and lower number of side shoots, which indicates competition for resources in conditions of increased density [9, 10]. This effect is enhanced under conditions of excessive plant density and limited feeding area. In turn, sowing dates and seeding rates significantly affect the quality of autumn development of winter rape crops and the degree of its overwintering [11].

The feeding system plays a significant role in the structure of winter rape cultivation technology. Winter rape requires a high availability of nutrients in an accessible form throughout the growing season [12, 13], as it is characterised by a long period of intensive nitrogen consumption. Therefore, fractional application of nitrogen fertilisers is advisable, taking into account the physiological and biochemical demands of the crop. In addition, the timely application of nitrogen fertilisers before sowing or in the early stages of development is essential to ensure the formation of a vegetation cover that is resistant to winter stress [14–16].

Winter rape belongs to nitrogen-loving crops, which are characterised by a long period of intensive nitrogen absorption. Given this, distributed (fractional) application of nitrogen fertilisers ensures optimal and timely availability of nutrients throughout the growing season [17, 18]. The application of nitrogen before sowing or in the autumn (in the form of feeding) at a rate of 30–40 kg active ingredient/ha is effective after the cultivation of grain crops as predecessors. Late application of nitrogen (after the 4–5 true leaf stage) leads to excessive accumulation of water in plant tissues, which negatively affects the hardening process and reduces winter hardiness [19, 20].

It has been proven that the use of growth regulators contributes to the complete realisation of crop potential, in particular, by influencing germination energy, branching level, ripening time, and resistance to abiotic and biotic factors [21, 22]. Growth regulators help improve the phytosanitary condition of crops and can reduce pesticide costs when used as part of an integrated protection approach. According to the results of long-term studies, a stable increase in yield of 10–13 % was reached, when such formulations were used in combination with other components of the cultivation technology [23, 24].

In addition, the adaptive effectiveness of agricultural practices largely depends on weather conditions – precipitation, temperature, and duration of growing season, which is particularly relevant in the context of climate change. Winter rape seeds are highly susceptible to low temperatures even at the germination stage, which affects the terms of vernalisation and the dynamics of the transition to the generative stage [25, 26].

The relevance of the study is driven by the need to improve winter rape cultivation technology in conditions of resource constraints, growing climate risks, and requirements for crop sustainability. Determining the patterns of plant density formation depending on the sowing method, seeding rate, mineral nutrition and their interaction provides a scientifically sound basis for improving the efficiency of agricultural technologies. Comprehensive consideration of these factors contributes to a balance between productivity, environmental sustainability of agricultural systems, and economic feasibility of production. Thus, the results of the study are of great theoretical and practical importance for the development of adaptive sowing schemes for winter rape that will ensure high yields in changing environmental conditions.

The research was aimed at establishing patterns in the formation of plant density in winter rape crops depending on the sowing method, seeding rates, mineral nutrition levels and interaction between these factors, with a view to optimising cultivation parameters and ensuring a stable crop structure.

The objective of the research is to analyse the impact of sowing methods on the dynamics of crop structure formation, plant survival after overwintering and plant density before harvesting, to compare the response of different genotypes (Antariia variety and Eksahon hybrid) to changes in technological factors in the process of plant density formation and determining the optimal agrotechnical conditions to ensure high adaptability and productivity of winter rape crops.

Materials and Methods. Research on the effect of sowing method, seeding rates, mineral nutrition, and their interaction on the formation of winter rape plant density was conducted on the experimental fields of the Institute of Feed Research and Agriculture of Podillia of NAAS of Ukraine (Vinnytsia region), located in the forest-steppe agroclimatic zone with typical moisture conditions and typical dark grey soils, during 2010–2014. The cultivation technology for winter rape was in accordance with the generally accepted recommendations for the Forest-Steppe zone and provided optimal conditions for realizing the potential of the crop. The predecessor in the crop rotation was winter wheat, which is a typical crop for growing winter rape in the region.

The study compared two sowing methods: wide-row (45 cm row spacing) and conventional row (15 cm). Four seeding rates were studied: 0.4, 0.6, 0.8, and 1.0 million germinated seeds/ha, as well as three agro-background variants: control (without fertiliser application); mineral nutrition ($N_{120}P_{60}K_{90}$); and mineral nutrition ($N_{120}P_{60}K_{90}$) in combination with the Caramba growth regulator (1.0 l/ha). The study was conducted on two genotypes of winter rape – the Antariia variety and the Eksahon hybrid, which differ in terms of initial growth intensity, biomorphological characteristics, and adaptability.

Registration and analysis of field germination, plant survival after overwintering, and plant density before harvesting were carried out in accordance with the methodological recommendations for field studies with cruciferous crops [27]. Statistical processing of the results was performed using analysis of variance and regression analysis with MS Excel and Statistica 10.0 software, which allowed us to assess the influence of the main factors and create multiple forecasting models.

Results and Discussion. Optimal plant density is one of the main factors in the formation of highly productive winter rape agrocenoses. Plant density directly affects the level of competition between plants for light, nutrients, and moisture, and also determines the efficiency of nutrient utilisation, resistance to lodging, and yield potential. In the current conditions of intensive development of cultivation technologies, an important challenge is to establish the patterns of plant density formation for different sowing rates, agricultural backgrounds, and the application of growth regulators.

According to the results of studies that examined the dynamics of the formation of the plant density in winter rape of the Antariia variety using a wide-row sowing method, combining four seeding rates (from 0.4 to 1.0 million germinated seeds per hectare) on three different backgrounds: control (without fertilisers), mineral nutrition – $N_{120}P_{60}K_{90}$, and $N_{120}P_{60}K_{90}$ + Caramba growth regulator (1.0 l/ha).

Data analysis shows that seeding rates and agricultural background significantly affect the formation of winter rape plant density during growing season. The highest field germination and plant density before harvesting were achieved by using complete mineral nutrition in combination with the Caramba growth regulator, which indicates the synergistic effect of these factors on plant viability and resistance.

Thus, when applying $N_{120}P_{60}K_{90}$ + Caramba (1.0 l/ha) at a seeding rate of 1.0 million seeds/ha, the highest number of plants at harvest time was recorded – 75 plants/m², which corresponds to 88.2 % survivability.

At the same time, even with lower seeding rates (0.6–0.8 million seeds/ha), the plant density at the end of the growing season remained high – over 80 %.

In the control variant without fertilisers and growth regulator, there was a tendency towards a decrease in field germination (to 82.5 %) and significant thinning of crops during the winter period, especially at minimum seeding rates (0.4–0.6 million seeds/ha), where plant survival until harvest did not exceed 72–74 %.

Thus, the results of the study confirm that

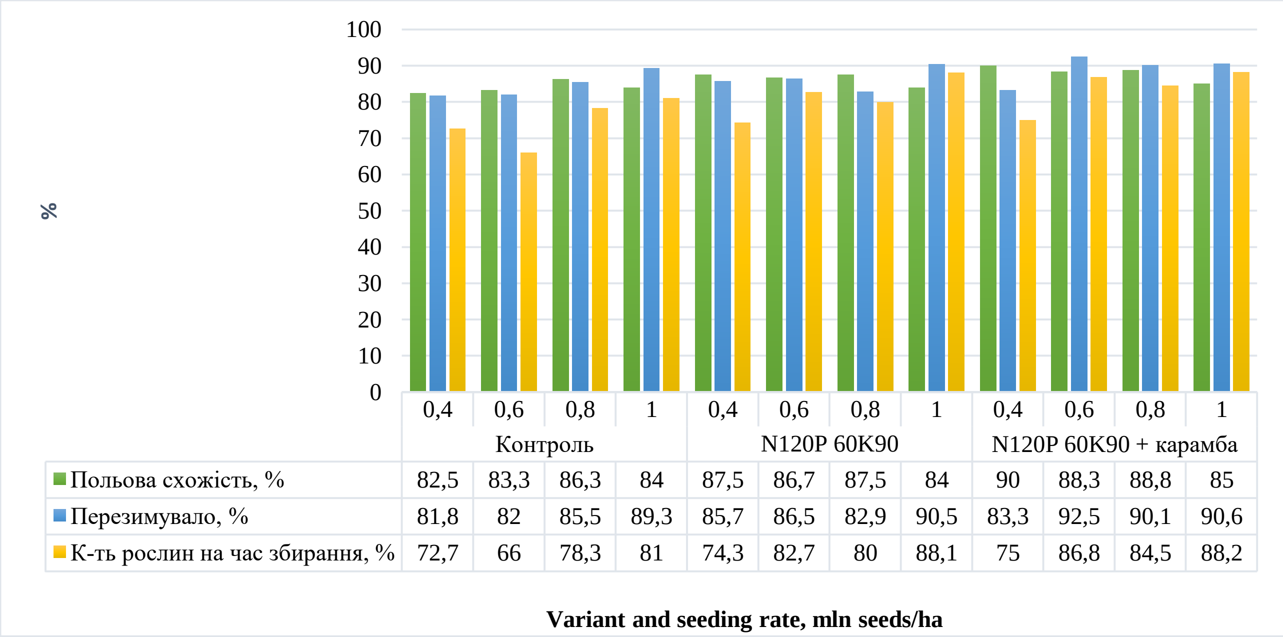


Fig. 1 The effect of seeding rates, application rates of fertiliser and growth regulators on the formation of plant density in winter rape of Antariia variety under wide-row sowing (average for 2010–2014).

the best realisation of density potential is observed with an optimal combination of a seeding rate of 0.8–1.0 million seeds/ha with the application of mineral nutrition and a growth regulator. Such conditions ensure stable formation of productive stem density, increase germination energy and winter hardiness, and reduce the risk of crop thinning, which is an important prerequisite for obtaining high and stable yields.

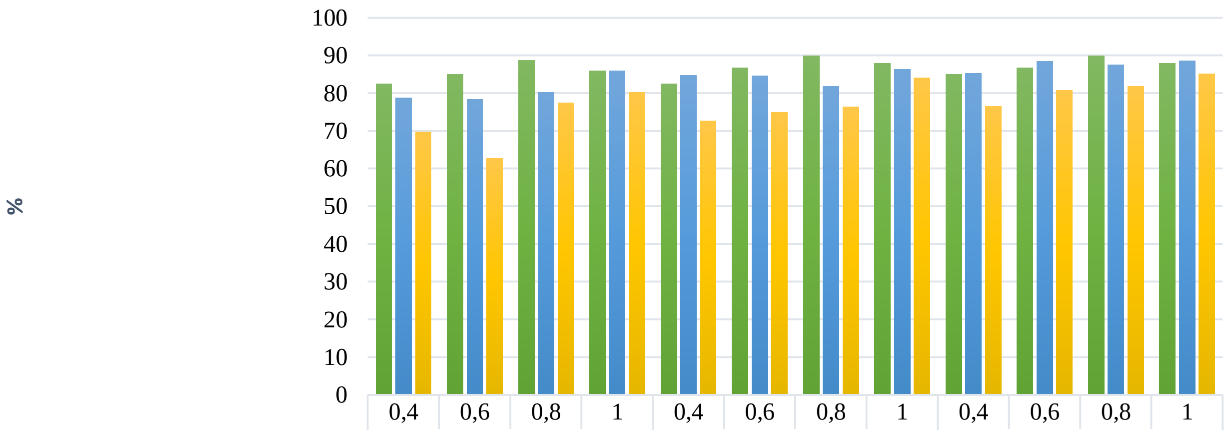
The results of the study, which focused on the high-yielding winter rape hybrid Eksahon, characterised by intensive initial growth and susceptibility to nutritional conditions, indicate a close relationship between seeding rate, the agricultural background and the ability of the hybrid to form a stable plant density throughout the growing season. In the control variant (without fertilisers and growth regulator), there was a regular increase in the number of seedlings and surviving plants along with an increase in the seeding rate. At the same time, at a low seeding rate (0.4 million seeds/ha), field germination was only 82.5 %, and only 69.7 % of plants survived until harvest, which is insufficient to ensure a high yield (Fig. 2).

The application of mineral nutrition contributed to the stabilisation of growth processes and increased winter hardiness of plants. At a seeding rate of 1.0 million seeds/ha, 84.1% of plants survived and field germination exceeded 88 %. The mineral nutrition option with the Caramba growth regulator proved to be the most effective for all seeding rates. The highest overwintering rates (up to 88.6 %) and maximum plant density before harvesting (up to 85.2 %) were observed.

The results were particularly demonstrative for a seeding rate of 0.8 million seeds/ha against the background of complete mineral fertilisation with growth regulator Caramba (1.0 l/ha) where the crop density at harvest was 59 plants/m², which is the optimal indicator for ensuring high yields without excessive thickening. The high efficiency of the combined cultivation technology is associated with better root system development, more uniform growth in the early stage, and an increase in the adaptive potential of plants.

Thus, the results of the study confirm that for the Eksahon hybrid, the optimal conditions for plant density formation are a seeding rate of 0.8–1.0 million seeds/ha in combination with mineral nutrition $N_{120}P_{60}K_{90}$ and treatment with a growth regulator Caramba, which ensures a high level of field germination, plant survival after overwintering and a stable crop structure until harvest. This highlights the advisability of integrating controlled nutrition and growth elements into modern cultivation technologies for winter rape.

A comparison of the research results presented in Fig. 1 and Fig. 2 allows us to observe the differences in plant density formation between the Antariia variety and the Eksahon hyb-



	Контроль				N120P 60K90				N120P 60K90 + карамба			
	0,4	0,6	0,8	1	0,4	0,6	0,8	1	0,4	0,6	0,8	1
Польова схожість, %	82,5	85	88,8	86	82,5	86,7	90	88	85	86,7	90	88
Перезимувало, %	78,8	78,4	80,3	86	84,8	84,6	81,9	86,4	85,3	88,5	87,5	88,6
К-ть рослин на час збирання, %	69,7	62,7	77,5	80,2	72,7	75	76,4	84,1	76,5	80,8	81,9	85,2

Variant and seeding rate, mln seeds/ha

Fig. 2 The effect of seeding rates, application rates of fertiliser and growth regulators on the formation of plant density in Eksahon hybrid of winter rape under wide-row sowing (average for 2010–2014).

rid under wide-row sowing conditions, depending on the seeding rate and nutrient background.

The Eksahon hybrid had higher initial field germination and better plant survival rates throughout the growing season compared to the Antariia variety on all agricultural backgrounds and at all seeding rates. In fact, the actual plant density before harvesting at a seeding rate of 1.0 million germinated seeds/ha and application of $N_{120}P_{60}K_{90}$ + Caramba (1.0 l/ha) was 75 plants/m² (88.2 % survivability) for the Antariia variety compared to 85.2 % for the Eksahon hybrid, which indicates the greater adaptive potential of the hybrid, due to the heterotic nature of the hybrid form and better initial characteristics.

For both genotypes, maximum plant density values before harvesting were achieved with complete mineral nutrition combined with a growth regulator, which confirms the effectiveness of this agricultural practice for winter rape crops in general.

An increase in plant density in the Antariia variety between the control and $N_{120}P_{60}K_{90}$ + Caramba (1.0 l/ha) was on average 7–10 %, while this increase reached +10–13 % in the Eksahon hybrid, confirming the greater susceptibility of the hybrid to nutrition and growth regulation conditions.

For both genotypes, the best results were obtained at a seeding rate of 0.8–1.0 million germinated seeds/ha. This plant density of winter rape ensured the following: maximum utilisation of field germination potential; reduced risks of overcrowding and competition between plants; high uniformity of nutrient distribution; stability of crop structure until harvest.

At lower seeding rates (0.4–0.6 million seeds/ha), both genotypes showed a decrease in plant density before harvesting to 65–75 % of the seeding rate, this could be critical under stressful conditions.

Thus, the Eksahon hybrid exceeds the Antariia variety in terms of field germination, plant survivability after overwintering, and actual plant density before harvesting at all agricultural backgrounds and seeding rates, which indicates higher adaptability and stability of growth indicators of hybrid.

The application of mineral nutrition in combination with the Caramba growth regulator is an effective technological practice for both genotypes, providing maximum plant survivability and stable crop formation until the end of the growing season. The optimal seeding rate to achieve high and uniform plant density was found at 0.8 million seeds/ha for both genotypes, allowing us to achieve better results with less seeding rates and reduced competition between plants.

Thus, the results of the study indicate the need for a differentiated approach to the selection of cultivation practices, which should be based on the biological characteristics of the variety or hybrid, as well as considering the type of sowing method, the nature of mineral nutrition and the application of growth regulators. The variation in plant density in response to changes in seeding rate and agricultural background indicates the non-linear nature of the influence of these factors and confirms the feasibility of mathematical modelling.

For this purpose, a multiple regression model was constructed to account for the interaction between seeding rate and agrobackground, allowing us to quantitatively assess their impact on plant density formation before harvesting and forecast the behaviour of the hybrid under different growing conditions.

The statistical dependence is presented as an equation:

$$Y=a+b_1\times X_1+b_2\times X_2+b_3\times(X_1\times X_2),\quad (1)$$

where:

Y – actual plant density before harvesting, pcs/m²;

X_1 – seeding rate, million germinated seeds/ha;

X_2 – agricultural background:

1 – control (no fertilisers),

2 – fertiliser ($N_{120}P_{60}K_{90}$),

3 – fertiliser ($N_{120}P_{60}K_{90}$) + Caramba growth regulator *(1.0 l/ha)*;

$X_1\times X_2$ – interactive (cross) effect of interaction between agricultural background and seeding rate;

a, b_1, b_2, b_3 – regression coefficients that characterize the strength of the influence of the respective variables. The initial data for the model are presented (Table 1).

Table 1. Initial data (average values)

X_1 mln/ha	X_2 agro-background	Y plant density plants/m²	X_1 mln/ha	X_2 agro-background	Y plant density plants/m²	X_1 mln/ha	X_2 agro-background	Y plant density plants/m²²
0.4	1	27.9	0.4	2	30.8	0.4	3	34.2
0.6	1	38.0	0.6	2	42.7	0.6	3	45.3
0.8	1	48.6	0.8	2	53.6	0.8	3	59.0
1.0	1	54.6	1.0	2	59.5	1.0	3	64.0

Based on empirical modelling data, the following coefficient values were obtained:

$$Y=16.8+41.2\times X_1+3,5\times X_2+5.3\times (X_1\times X_2),\quad (2)$$

where:

16.8 – model constant reflecting the base value of the forecast plant density at zero values of independent variables (conditional starting point with no practical meaning);

41.2 – increase in plant density (plants/m²) for each increase in seeding rate by 1 million seeds/ha with constant agricultural background;

3.5 – the effect of each level of agricultural background on plant density at a fixed zero level of seeding rate (conditional value);

5.3 – interactive effect, reflecting a change in the forecast with simultaneous growth of X_1 and X_2, i.e. an additional increase in plant density caused by synergy between the seeding rate and the quality of the agricultural background. This coefficient is particularly important as it demonstrates that the effectiveness of each increase in seeding rates is enhanced by improving the agricultural background, which is logical: better nutrition availability and growth regulation increase the realisation of seed potential.

Using formulas for models (1) and (2), we will predict the plant density before harvesting under the following conditions:

- seeding rate X_1=0.8 mln/ha;
- agrobackground X_2=3 (fertiliser + retardant (Caramba growth regulator)).

Then, substituting the data into the equation, we obtain:

$$Y=16.8+41.2\times 0.8+3.5\times 3+5.3\times (0.8\times 3);$$

$$Y=16.8+32.96+10.5+12.72=72.98 \text{ plants/m}^2.$$

Therefore, the model predicts that under the specified conditions, plant density will be approximately 73 plants/m², indicating effective plant survivability and a stable crop structure. It should be noted that the empirical value of plant density is 59 plants/m² in the Table 1, i.e. the model slightly overestimates the forecast, which may be due to the smoothed nature of the model and its statistical generalisation.

Thus, the proposed model enables quantitative assessment of the interaction between technological factors in order to plan plant density of crops based on available resources.

Figure 3 presents a heat map, which is a graphical interpretation of the developed multiple regression model.

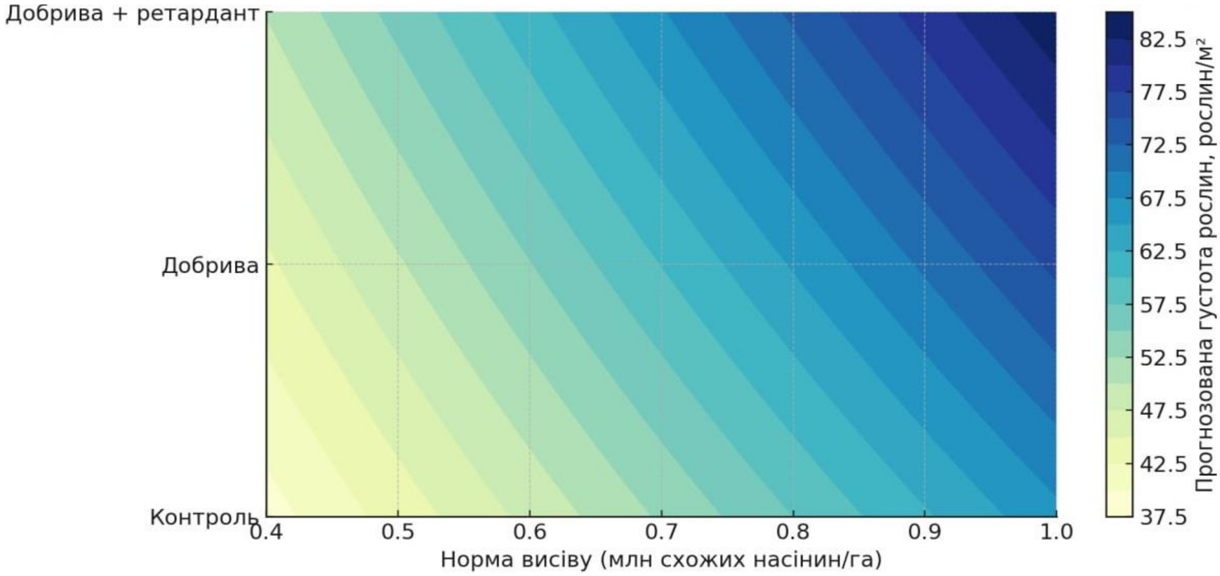


Fig. 3. Heat map of the forecasted plant density of winter rape (Eksahon hybrid).

Therefore, the forecasted plant density is directly proportional to the seeding rate, regardless of the background, so an increase in the seeding rate from 0.4 to 1.0 million seeds/ha is accompanied by an increase in plant density of crop. The effect of the agricultural background is cumulative: the change from control to fertiliser application, and then to a combination of fertilisers and a retardant (growth regulator), leads to a stable increase in plant density.

Maximum plant density (70–75 plants/m²) is achieved with a seeding rate exceeding 0.9 million/ha, agricultural background with fertilisers and a retardant (Caramba growth regulator).

The synergistic effect of the interaction $X_1 \times X_2$ is clearly evident in the form of a more pronounced colour gradient in the upper part of the graph (agricultural background 3), confirming the importance of a comprehensive approach.

Conclusions. The results of long-term field studies confirm that the plant density of winter rape is formed as a result of complex interactions between the sowing method, seeding rate, mineral nutrition level, and biological characteristics of the variety or hybrid. Wide-row sowing combined with optimal seeding rates and balanced nutrition promotes the formation of a stable, uniform and productive agrocenosis.

The combination of a seeding rate of 0.8–1.0 million germinated seeds/ha with mineral nutrition ($N_{120}P_{60}K_{90}$) and the application of the Caramba growth regulator (1.0 l/ha) turned out to be the most effective. Under the above conditions, the highest plant survivability after overwintering (up to 88.6 %) and maximum plant density before harvesting (up to 75 plants/m²) were observed, indicating the high efficiency of the technological scheme. At the same time, the Eksahon hybrid proved to be more responsive to the agro-environmental conditions and was more adaptable than the Antariia variety, which is associated with the heterotic nature of the hybrid.

Regression analysis established a quantitative relationship between the main technological factors and the actual plant density, as well as revealing a significant synergistic effect of interaction between the seeding rate and the agricultural background. The constructed multiple regression models with factor interaction allow us to accurately forecast plant density before harvesting, depending on growing conditions.

Thus, obtained results are applicable in developing adaptive agrotechnical recommendations aimed at improving resource efficiency and ensuring stable crop yields in the Forest-Steppe zone of Ukraine.

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Юрчук С. С. Формування густоти рослин ріпаку озимого (Brassica napus L.) залежно від різних технологічних аспектів вирощування. *Зернові культури. 2025. 9 (1). 104–112.*

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Актуальність. Формування густоти стояння рослин є визначальним чинником ефективного використання потенціалу при вирощуванні ріпаку озимого в умовах кліматичних ризиків і обмежених ресурсів. Вивчення її залежності від способу сівби, норми висіву та агрофону обґрунтовує адаптивний підхід до підвищення продуктивності посівів. **Мета досліджень** – дослідження впливу способу сівби, норми висіву та рівня мінерального живлення, а також їхньої взаємодії на формування густоти стояння рослин ріпаку озимого, з подальшим обґрунтуванням оптимальних технологічних параметрів для забезпечення стабільної структури посівів та підвищення ефективності агроценозу. **Матеріали та методи.** У дослідах використовували два генотипи ріпаку озимого – сорт Антарія і гібрид Ексагон. Вивчали два способи сівби (звичайний рядковий (15 см) та широкорядний (45 см)), чотири норми висів 0,4; 0,6; 0,8 та 1,0 млн. схожих насінин/га,у, три варіанти агрофону: контроль (без добрив), внесення мінерального живлення ($N_{120}P_{60}K_{90}$) і добрива ($N_{120}P_{60}K_{90}$) в поєднанні з регулятором росту Карамба. Польові (фенологічні спостереження, обліки густоти на різних фазах розвитку), лабораторні (визначення схожості, польової схожості, показників збереження після зими), математичні та статистичні (дисперсійний, регресійний та графоаналітичний аналіз). **Результати.** Встановлено, що густота стояння рослин ріпаку значною мірою залежить від поєднання технологічних факторів. Гібрид Ексагон більш чутливий до агрофону, порівняно з сортом Антарія, що проявлялося в більш високих показниках збереження рослин і адаптивності до змін технологічних умов. Побудована модель множинної регресії показала статистично достовірну залежність густоти від норми висіву, агрофону та їх взаємодії, що дозволяє прогнозувати оптимальні параметри густоти перед збиранням. **Висновки.** Встановлено, що найбільш стабільна й ефективна густота рослин формується за умови поєднання широкорядної сівби з нормою висіву 0,8–1,0 млн насінин/га та використанням добрив у поєднанні з регулятором росту. Результати мають практичне значення для впровадження і можуть бути використані для вдосконалення норм висіву й системи удобрення з урахуванням біологічних особливостей сорту чи гібрида.

Ключові слова: *ріпак озимий, густота рослин, норма висіву, способи сівби, сорт, гібрид, модель множинної регресії*