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THE DEVELOPMENT OF AN OPTIMAL SOWING MODEL TO ENSURE MAXIMUM PRODUCTIVITY OF HIGH-OLEIC SUNFLOWER HYBRIDS UNDER THE CONDITIONS OF THE SOUTHERN STEPPE OF UKRAINE

S u m m a r y

Background. High-oleic sunflower hybrids are of strategic importance for ensuring both high yield and superior oil quality, particularly under the increasingly arid conditions of the Southern Steppe of Ukraine. The optimization of sowing parameters – especially row spacing and plant density – plays a key role in improving productivity, resource-use efficiency and crop adaptability. However, the interaction between genotype and spatial sowing configuration remains insufficiently studied under variable climatic conditions. This study aimed to determine an optimal sowing model for high-oleic sunflower hybrids by integrating yield performance, seed quality indicators and environmental adaptability. Field experiments were conducted in 2019 ÷ 2021 on southern chernozem soils using a multifactorial design that included seven hybrids, four row spacing options (15 ÷ 70 cm) and six plant density choices (35,000 ÷ 60,000 plants/ha).

Results and conclusions. The results demonstrated that yield formation was significantly influenced by the interaction between hybrid genotype and sowing parameters. Average yields ranged from 2.36 to 2.85 t/ha, with the highest productivity achieved at the row spacing of 30 ÷ 45 cm and the plant density of 45,000 ÷ 50,000 plants/ha. Narrowing row spacing from 70 to 45 ÷ 30 cm increased yield by 12 ÷ 18 %, while excessive density (55,000 ÷ 60,000 plants/ha) reduced individual plant productivity. Oil content varied between 48.9 % and 51.6 %, whereas oleic acid content remained stable (74.4 ÷ 90.8 %), indicating strong genetic control of this characteristic. Optimal configurations improved soil moisture retention and reduced drought stress, allowing for stable crop performance in diversified weather conditions. The integrated sowing model – combining specific hybrids with 30 ÷ 45 cm row spacing and 45,000 ÷ 50,000 plants/ha – provides a practical, resource-efficient solution for maximizing yield and maintaining high seed quality in the Southern Steppe of Ukraine.

Key words: Sunflower, hybrids, planting density, row spacing, yield, seed quality

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Introduction

Sunflower is a strategic crop in global agricultural production, accounting for more than 10 % of the world's vegetable oil output. High-oleic hybrids occupy a special position among sunflower varieties, as they combine high yield with superior quality, which determines their value for the production of food products and industrial oils. For Ukraine, which has long maintained a leading position in global sunflower oil exports, the improvement of cultivation technologies has become particularly relevant due to climate change, increasing moisture deficits and the need to enhance resource efficiency.

An increase in sunflower productivity through foliar application of micronutrients was confirmed by Kovalenko et al. [27], who established a significant effect of micronutrients on plant growth, development and yield formation. Similarly, Domaratskiy et al. [11] demonstrated the effectiveness of biological crop protection methods under the arid conditions of the Steppe, emphasizing that the optimization of sowing density should be combined with the greening of cultivation technologies. One of the key responses to climate-related risks is the diversification of oilseed crop structures, as confirmed by the study of Hamayunova et al. [17], which highlighted the importance of adapting agricultural production to the increasing aridization of the Southern Steppe of Ukraine. In a broader context, the role of agricultural biologization is steadily increasing. Shebanin et al. [46] showed that the introduction of biological products and soil-protective technologies in the production of grain and industrial crops not only improves environmental sustainability, but also ensures yield stability. Thus, modern scientific research confirms the feasibility of the comprehensive optimization of sunflower cultivation technologies under Steppe conditions, which is consistent with previous Ukrainian studies aimed at improving energy efficiency, biologization and resource conservation in the production of high-oleic hybrids.

Shebanin et al. [47] developed and implemented energy-saving technologies for sunflower cultivation in the southern regions of Ukraine. The authors demonstrated that the application of these technologies reduced energy costs, while maintaining high yield levels, thereby confirming the need for integrated optimization of production processes. The effect of biological preparations on the productivity of high-oleic sunflower hybrids was investigated by Panfilova et al. [39]. Their results showed that the use of biological products had a positive effect on seed oil content and quality indicators, expanding the potential for biologization within modern cultivation technologies. Domaratskiy et al. [10] focused on optimizing water consumption of high-oleic hybrids under Steppe conditions in Ukraine. The authors demonstrated that the rational regulation of plant density reduced moisture deficits and increased the efficiency of soil resource use under rainfed conditions.

Machine learning algorithms for predicting oil content in sunflower hybrids were applied by Cvejić et al. [8]. Their study showed that combining agronomic and morphological features with modern data analysis methods improved the accuracy of forecasts when selecting promising hybrids. The influence of sowing dates, planting density and hybrid characteristics on sunflower yield and seed quality was examined by Partal [40], who established that the optimization of sowing dates and plant density is a decisive factor in yield formation and seed quality, in line with current research trends. Finally, Shah et al. [44] conducted a multi-location analysis of the stability of high-oleic sunflower hybrids in terms of oleic acid content and yield in Pakistan. The study found that both oleic acid concentration and yield remained stable across different climatic conditions, confirming the plasticity of these hybrids and the importance of their targeted selection for specific agro-ecological zones.

The influence of sowing dates on increasing the drought tolerance of rapeseed, taking into account their effect on yield and seed quality indicators, was investigated by Ahmadi and Sarhangi [1]. The results obtained are also relevant for sunflower, as they confirmed the role of adapting spatial and temporal parameters in reducing the negative effects of temperature stress. Ghaffari et al. [15] examined the variability of agronomic features in sunflower hybrids of different types. Their study showed that genetic and morphological differences had a significant effect on productivity, highlighting the need to consider hybrid adaptability when selecting optimal cultivation schemes.

Sharma and Kaila [45] applied a multivariate statistical analysis to assess the relationships between yield and seed quality characteristics. The authors confirmed that a comprehensive analysis of the interaction between morphological and biochemical features allows for a more accurate determination of optimal productivity parameters. Kafle [21] analyzed the influence of nitrogen fertilizer application methods and rates on sunflower yield, as well as oil and protein content. It was found that a rational combination of nitrogen application rates and fertilizer placement technologies had a significant effect on seed quality indicators, confirming the necessity of considering plant nutrition within the system of agrotechnical measures. The generalization of the studies reviewed showed that the formation of sunflower yield and seed quality indicators is determined by a combination of agrotechnical, genetic and climatic factors. The optimization of planting density and row spacing, ensuring adequate moisture supply and the rational use of resources remain critical, which necessitates further comprehensive research under different agroecological conditions.

The aim of this study was to determine the optimal sowing parameters for high-oleic sunflower hybrids in order to achieve a combination of high yield and superior seed quality characteristics. To accomplish this aim, the following objectives were defined:

1. To investigate the influence of row spacing and plant density on the yield of high-oleic sunflower hybrids.
2. To analyze changes in crop structural elements depending on agrotechnical measures.
3. To establish the characteristics of seed quality formation and the adaptability of agrocenoses to climatic conditions.

Materials and methods

The study was conducted in between 2019 and 2021 at the Educational, Scientific and Practical Centre of Mykolaiv National Agrarian University, located in the Southern Steppe zone of Ukraine. The soil conditions of the experimental sites were represented by southern chernozem, residually weakly saline, heavy loamy loess soils with a neutral soil reaction (pH 6.8 ÷ 7.2). During the three-year study period, fluctuations in nutrient content were observed in the arable soil layer (0 ÷ 30 cm). In 2020, under the conditions of precipitation deficit, a reduction in the content of mobile phosphorus was recorded (39 mg/kg), whereas in 2019 and 2021, under higher moisture availability, this indicator ranged from 44 to 46 mg/kg. The humus content remained stable throughout the study, varying within 3.1 ÷ 3.3 %. Changes in nitrate nitrogen and exchangeable potassium content were not significant and remained within the ranges of 15 ÷ 25 mg/kg and 389 ÷ 425 mg/kg respectively. The soil profile was characterized as follows: Hn (0 ÷ 30 cm) – humus-accumulative horizon; Hp(i) (30 ÷ 60 cm) – humus-transitional horizon; Phi(k) (60 ÷ 85 cm) – horizon of humus inflows; Ph (85 ÷ 95 cm) – transitional horizon; PK (95 ÷ 140 cm) – carbonate horizon; Pk (below 140 cm) – carbonate loess. The agroclimatic conditions of each growing season were characterized using data from the iMETOS automatic weather station (iMETOS 3.3, Pessl Instruments), including average monthly air temperature, relative humidity and total precipitation for the period April-October. In 2020, a pronounced precipitation deficit was recorded in July–August, whereas in 2019 and 2021 higher moisture availability was observed in May-July.

The objects of the study were high-oleic sunflower hybrids: ES Aromatic SU, Colombi, LG5492 HO CL, P64GE118, MAS 86OL, SI Arko and P64GG106. The selection of these hybrids was based on their widespread use in commercial production in Ukraine and their classification as high-oleic types, which are of strategic importance for the development of the oil and fat sector. The multifactorial field experiment included three factors: A – hybrid (7 levels); B – row spacing (70 cm as the control, 45 cm, 30 cm and 15 cm); C – plant density (35,000, 40,000, 45,000, 50,000, 55,000 and 60,000 plants per hectare), forming a full factorial design of 7×4×6. Each experimental treatment was replicated three times using a block design. The accounting plot area was 50 m², with border rows excluded to minimize edge effects. The number of plants included in the calculations was determined within the accounting plots, where the average plant density for each treatment was recorded to assess productivity and seed quality.

Field observations included phenological and biometric measurements. For each experimental treatment, at least 50 plants were evaluated to determine head diameter, thousand-seed weight and individual plant productivity. Head diameter was measured at full maturity on a representative sample of plants from each treatment using a caliper with an accuracy of 0.1 cm. Thousand-seed weight was determined using laboratory electronic scales with an accuracy of 0.01 g on samples dried to standard moisture content. Individual plant productivity was assessed based on seed mass per plant. Yield was calculated in t/ha based on threshing of the accounting area, with adjustment to standard moisture content. Quality indicators included crude oil content, which was determined using the extraction method with an organic solvent in accordance with ISO 659:2009 [20]. The fatty acid composition, including the proportion of oleic acid, was analyzed by gas chromatography of methyl esters prepared according to the American Oil Chemists' Society (AOCS) method Ce 2-66 [4]. Moisture supply conditions were assessed based on the reserves of productive moisture in the 0 ÷ 50 cm soil layer during the key stages of organogenesis, namely inflorescence emergence (BBCH 51), full flowering (BBCH 65) and seed filling (BBCH 75), as well as the field indicators of drought stress during the periods of high temperatures (July-August), when average daily air temperatures exceeded 30 °C and maximum values reached 35 ÷ 38°C.

The optimal sowing model was determined on the basis of three main criteria: (1) yield, defined as the maximum seed yield per unit area (t/ha); (2) seed quality, expressed by oil content and oleic acid concentration; and (3) ecological adaptability, reflecting resistance to stress factors such as moisture deficiency and high temperatures. To evaluate these criteria, the following methods were applied: an analysis of variance to compare sowing options, a multivariate statistical analysis to identify relationships between sowing parameters and experimental outcomes, and an analysis of the effects of agrotechnical measures on seed quality using gas chromatography to determine fatty acid composition [4].

A statistical analysis was performed using a three-factor analysis of variance model (A×B×C) for yield, yield structure components and quality indicators, with an assessment of main effects and two-factor interactions. The assumptions for the application of parametric tests were verified by testing the normality of residuals (Shapiro-Wilk test) and the homogeneity of variances (Levene's test). Differences between means were evaluated using multiple comparisons (Tukey's HSD test) at a significance level of $\alpha = 0.05$. Effect sizes were expressed as partial η^2, and 95 % confidence intervals were calculated for key mean values. In the cases where the assumption of normality was violated, a non-parametric rank-based approach (Kruskal–Wallis test) was applied, followed by post hoc Dunn's tests with Bonferroni correction [28]. The detection of single outliers was performed using Grubbs' test [16].

The field experiment was conducted in accordance with current requirements for agricultural field research and environmental management, in particular the provisions of ISO 14001:2015 [19]. Weather conditions were monitored using an iMETOS automatic weather station (iMETOS 3.3, Pessl Instruments). The field experiment was conducted in compliance with generally accepted methodological standards. This experimental design made it possible to reproducibly assess the influence of genotype and spatial sowing parameters on the productivity and seed quality of high-oleic sunflower hybrids under the conditions of the Southern Steppe.

Results

Analysis of seed yield of high-oleic sunflower hybrids

The seed yield of high-oleic sunflower hybrids under the conditions of the Southern Steppe of Ukraine was determined by the combined effects of the genetic characteristics of the hybrids, row spacing and plant density. Based on the average results of the three-year study (2019 ÷ 2021), significant differences among the hybrids were identified. The highest yield levels were recorded for the ES Aromatic SU (2.85 t/ha) and SI Arko (2.77 t/ha) hybrids, which consistently exceeded the overall experimental mean. The differences in their yield performance compared with the other variants were statistically significant ($p < 0.05$). The Colombi and MAS 86OL hybrids produced yields close to the average values, whereas P64GE118, LG5492 HO CL and P64GG106 were characterized by lower productivity. Overall, the mean yield ranged from 2.36 to 2.85 t/ha, depending on the combination of experimental factors (Table 1).

Table 1. Seed yield of high-oleic sunflower hybrids depending on row spacing and plant density (2019 ÷ 2021) [t/ha]

Hybrid	Average yield [t/ha]	Optimal row spacing [cm]	Optimal density [pcs./ha]
ES Aromatic SU	2.85	30 ÷ 45	45,000 ÷ 50,000
Colombi	2.64	45	45,000
LG5492 XO CL	2.50	45	45,000
P64GE118	2.43	30 ÷ 45	50,000
MAS 86OL	2.58	30 ÷ 45	50,000
SI Arko	2.77	30 ÷ 45	45,000 ÷ 50,000
P64GG106	2.36	45 ÷ 70	45,000 ÷ 50,000

Explanatory notes: source: compiled by the authors

The analysis of the effect of row spacing revealed a clear pattern: reducing row spacing from 70 to 45 cm resulted in a significant increase in yield for most hybrids. Further narrowing of row spacing to 30 cm maintained this positive effect, although the difference compared with 45 cm was not always statistically significant. A statistically significant difference was observed between 70 and 45 cm ($p < 0.05$), whereas the difference between 45 and 30 cm was observed at the trend level ($p > 0.05$). The lowest yield values were recorded at a row spacing of 15 cm, which can be attributed to excessive competition for light and moisture. Thus, on average, the most effective row spacing range was 45 ÷ 30 cm, providing an optimal balance between individual plant productivity and stand density.

An analysis of plant density showed that yield increased as density rose from 35,000 to 50,000 plants per hectare, after which a gradual decline was observed. At the density of 55,000 ÷ 60,000 plants per hectare, the negative effects of excessive thickening became particularly evident, leading to a reduction in seed mass per plant. Under the experimental conditions, the optimal average plant density was 45,000 ÷ 50,000 plants per hectare, which ensured the highest yield when combined with the row spacing of 30 ÷ 45 cm.

The interaction between the factors “Hybrid×Row spacing” confirmed that different hybrids responded differently to changes in the spatial arrangement of crops. The ES Aromatic SU and MAS 86OL hybrids were the most sensitive to reduced row spacing, demonstrating a significant yield increase when row spacing was reduced from 70 to 45 and 30 cm. In contrast, the P64GG106 hybrid showed stable yield values regardless of row spacing, indicating a high level of plasticity. The interaction “Hybrid×Plant density” showed that optimal density levels varied according to genotype. This interaction was statistically significant ($p < 0.05$), confirming genotype-specific responses to plant density. For ES Aromatic SU and P64GE118, maximum yields were achieved at the density of 50,000 plants per hectare, whereas for Colombi and LG5492 HO CL the optimal density of 45,000 ÷ 50,000plants per hectare, whereas for P64GE118 the maximum yield was achieved at 50,000 plants per hectare; for Colombi and LG5492 HO CL, the optimal density was 45,000 plants per hectare. The SI Arko and P64GG106 hybrids maintained stable yields across a wide range of density choices, without pronounced fluctuations.

Weather conditions during the growing seasons had a substantial influence on the realization of yield potential [34, 35]. In 2019, when sufficient precipitation was recorded in May-June (173.2 mm), average yields reached 2.8 ÷ 3.0 t/ha. In 2020, dry conditions with minimal precipitation in June-August (only 46.0 mm in total) led to a yield reduction of 20 ÷ 25 %, depending on the experimental variant, with the Colombi and LG5492 HO CL hybrids being the most affected. In 2021, favorable weather conditions, with precipitation in June-July exceeding 187.4 mm, enabled the hybrids to fully realize their genetic potential, achieving maximum yields of 3.1 ÷ 3.2 t/ha.

An analysis of agrotechnical measures under contrasting weather conditions showed that sowing schemes with the row spacing of 30 ÷ 45 cm and plant density of 45,000 ÷ 50,000 plants per hectare remained optimal. These combinations retained their relative advantages both under the dry conditions of 2020 and under the wetter conditions of 2019 and 2021, indicating better comparative adaptability, rather than complete yield stability under the variable climatic conditions of the Southern Steppe of Ukraine.

Overall, the results of the three-year field study demonstrated that the highest average productivity was achieved by the ES Aromatic SU (2.85 t/ha), SI Arko (2.77 t/ha) and Colombi (2.64 t/ha) hybrids. The most favorable conditions for the formation of consistently high yields in the Southern Steppe of Ukraine were identified as the row spacing of 30 ÷ 45 cm combined with the planting density of 45,000 ÷ 50,000 plants per hectare.

Formation of yield structure elements of high-oleic sunflower hybrids

The formation of productivity in high-oleic sunflower hybrids was determined by a combination of key yield structure elements, including head diameter, thousand-seed weight and seed yield per plant. All these parameters depended on plant density and row spacing, as well as on the genetic characteristics of the hybrids (Table 2).

Table 2. Average indicators of yield structure elements of high-oleic sunflower hybrids (2019 ÷ 2021)

Hybrid	Head diameter, cm [35,000→60,000/ha]	Thousand-seed weight [g]
ES Aromatic SU	22.8 → 17.6	59
Colombi	22.1 → 16.8	57
LG5492 XO CL	21.0 → 15.9	55
P64GE118	19.6 → 15.5	61
MAS 86OL	21.4 → 16.1	56
SI Arko	22.5 → 17.3	58
P64GG106	18.8 → 15.2	53

Explanatory notes: source: compiled by the authors

The average head diameter over the three years of the study decreased with increasing plant density. At the density of 35,000 plants per hectare, mean values ranged from 18.8 to 22.8 cm, depending on the hybrid, whereas at 60,000 plants per hectare they declined to 15.2 ÷ 17.6 cm. The reduction in head diameter when plant density increased from 35,000 to 60,000 plants per hectare was statistically significant

($p < 0.05$). The largest heads were formed by the ES Aromatic SU (22.8 cm) hybrid, followed closely by SI Arko (22.5 cm) and Colombi (22.1 cm). The smallest head diameter was recorded for the P64GG106 hybrid (18.8 cm at 35,000 plants per hectare and 15.2 cm at 60,000 plants per hectare). The decrease in head diameter with increasing stand density showed a consistent pattern and was accompanied by a reduction in seed mass.

Thousand-seed weight varied within the range of 53 ÷ 61 g depending on the experimental treatment. The highest thousand-seed weight was recorded for the P64GE118 hybrid (61 g), while the lowest was observed for P64GG106 (53 g). Differences in thousand-seed weight between the lowest and the highest plant density choices were statistically significant ($p < 0.05$). At low density (35,000 ÷ 40,000 plants per hectare), the highest thousand-seed weight values were obtained, whereas increasing density to 55,000 ÷ 60,000 plants per hectare resulted in a reduction of this indicator by 8 ÷ 12 %. Spatial configuration also influenced the expression of yield potential. At row the spacing of 30 ÷ 45 cm, thousand-seed weight was higher than at 70 cm, as a more uniform distribution of plants provided improved conditions for photosynthetic activity and the formation of generative organs. In contrast, excessive narrowing of row spacing to 15 cm did not promote an increase in seed weight, as it intensified competition for moisture and nutrients.

A comparative analysis of the hybrids revealed differences in their capacity to form large heads and seeds. The ES Aromatic SU hybrid exhibited the largest head diameter, with slightly lower values recorded for SI Arko and Colombi. The highest thousand-seed weight was characteristic of P64GE118, whereas P64GG106 was distinguished by both the smallest head diameter and the lowest seed weight. The MAS 86OL hybrid consistently occupied intermediate positions for both features, combining moderate head size with relatively high seed weight.

An important aspect was the compensatory capacity of the plants [24, 25, 26]. At the row spacing of 30 ÷ 45 cm, even under increased plant density, the hybrids formed relatively larger heads compared with the traditional 70 cm spacing, which can be attributed to a more uniform utilization of the nutrition area. In combination with optimal plant density, this created favorable conditions for the formation of well-developed seeds and the achievement of high yields.

Thus, the analysis of yield structure elements confirmed a consistent decrease in head diameter and seed weight with increasing crop density, while also demonstrating the compensatory effect of reduced row spacing within the range of 30 ÷ 45 cm. The optimal balance between individual plant productivity and yield per unit area was achieved at the density of 45,000 ÷ 50,000 plants per hectare, which is consistent with the total yield data.

Seed quality: Oil and oleic acid content

Seed quality parameters of high-oleic sunflower hybrids were formed under the influence of agrotechnical factors, among which plant density and row spacing were decisive. On average, over the period of 2019 ÷ 2021, seed oil content ranged from 48.9 to 51.6 %, while oleic acid content varied from 74.4 to 90.8 %, depending on the hybrid. The patterns identified indicate that, although quantitative yield parameters were strongly influenced by spatial sowing configuration, qualitative characteristics also exhibited clear variability, resulting from the combined effects of genetic features and growing conditions (Table 3).

Table 3. Oil and oleic acid content in seeds of high-oleic sunflower hybrids (2019 ÷ 2021)

Hybrid	Oil content [%]	Oleic acid content [%]	Range of variation in density choices [35,000-60,000/ha]
ES Aromatic SU	50.6	89.8	88.9 → 85.6
Colombi	50.1	90.8	87.6 → 84.7
LG5492 XO CL	48.9	89.1	85.6 → 83.4
P64GE118	50.8	74.4	73.8 → 71.3
MAS 86OL	49.6	90.0	89.0 → 86.8
SI Arko	50.3	89.5	87.4 → 85.2
P64GG106	51.6	84.6	84.1 → 82.5

Explanatory notes: the arrow (→) indicates the change in oleic acid content with increasing plant density from 35,000 to 60,000 plants/ha; source: compiled by the authors

With an increase in plant density from 35,000 to 60,000 plants per hectare, a tendency towards a reduction in oil content was observed. This decrease was statistically significant when plant density increased from 35,000 ÷ 40,000 to 55,000 ÷ 60,000 plants per hectare ($p < 0.05$). At the density of 35,000 ÷ 40,000 plants per hectare, seed oil content reached 51.2 ÷ 52.6 %, whereas at 55,000 ÷ 60,000 plants per hectare it declined to 47.8 ÷ 48.6 %. This trend indicates a limitation of the photosynthetic capacity of individual plants and intensified competition for nutrients and moisture under the conditions of crop thickening [32, 33]. At the same time, the row spacing of 30 ÷ 45 cm promoted higher oil content compared with the conventional 70 cm spacing, which is associated with the more uniform utilization of the nutrition area and reduced soil moisture losses. In contrast, excessive narrowing of row spacing to 15 cm resulted in a more pronounced decrease in oil content, as the negative effects of excessive stand density outweighed the benefits of reduced inter-row distance.

A comparison of hybrids with respect to oil content revealed significant differences among them. The highest average oil content over the three-year study period was recorded for P64GG106 (51.6 %) and ES Aromatic SU (50.6 %). The Colombi, SI Arko and MAS 86OL hybrids were characterized by stable oil content values in the range of 49.6 ÷ 50.3 %, whereas LG5492 HO CL exhibited the lowest value (48.9 %). Regardless of the growing season, these inter-hybrid differences persisted, indicating a predominantly genetic determination of oil content, accompanied by a certain degree of ecological plasticity.

The oleic acid content of the seeds generally remained relatively stable under different agrotechnical treatments, although its level was largely determined by a genotype [29, 38]. On average, over the three years, oleic acid content ranged from 74.4 to 90.8 %. Row spacing had no significant effect on this parameter, whereas increased plant density tended to reduce oleic acid content by 1.5 ÷ 2.0 % compared with less dense stands. At the density of 35,000 ÷ 45,000 plants per hectare, oleic acid content ranged from 86.8 to 90.8 %, while at 60,000 plants per hectare it decreased to 83.4 ÷ 85.6 %. However, the differences among density treatments did not reach statistical significance ($p > 0.05$).

A comparative assessment of hybrids based on oleic acid content showed that the highest values were characteristic of Colombi (90.8 %), MAS 86OL (90.0 %) and SI Arko (89.5 %). Overall, the results confirmed that agrotechnical practices had a more pronounced effect on total oil content than on oleic acid concentration. Increasing plant density reduced oil content, but did not substantially alter the qualitative status of the seeds. All studied hybrids retained their high-oleic character, ensuring their suitability for production use regardless of variations in spatial sowing parameters.

Adaptation of agrocenoses of high-oleic sunflower hybrids to the environmental conditions of the Southern Steppe

The formation of yield in high-oleic sunflower hybrids under the conditions of the Southern Steppe of Ukraine largely depended on the capacity of agrocenoses to adapt to moisture deficit and elevated air temperatures. The study conducted between 2019 and 2021 made it possible to identify the patterns of crop moisture utilization depending on row spacing and plant density, as well as to assess the resistance of the hybrids to stress factors (Table 4).

Narrowing row spacing had a significant effect on crop water consumption. Under the traditional row spacing of 70 cm in the dry year of 2020, intensive evaporation from the soil surface was observed, which led to a reduction in plant water supply during the critical period of head formation. Reducing row spacing to 45 and 30 cm promoted more uniform shading of the soil surface and reduced moisture losses. Differences in the frequency of wilting were statistically significant ($p < 0.05$). On average,

Table 4. The influence of row spacing and plant density on the moisture supply of sunflower crops (average for 2019 ÷ 2021)

Option	Soil moisture reserves (0-50 cm) [mm]	Degree of wilting in dry years*	Resistant hybrids
70 cm × 60,000	54	High	–
45 cm × 50,000	62	Low	ES Aromatic SU
30 cm × 50,000	65	Low	P64GE118, MAS 86OL
15 cm × 55,000	56	Average	–

Explanatory notes: estimate based on frequency of observations of wilting signs in July-August; source: compiled by the authors

this made it possible to retain 8 ÷ 12 % more soil moisture in the 0 ÷ 50 cm layer compared with the control treatment. The highest levels of soil moisture retention were recorded in variants with the row spacing of 30 cm, particularly in years characterized by elevated temperatures and precipitation deficits. The excessive narrowing of row spacing to 15 cm did not provide additional benefits, as it intensified plant competition and led to the uneven utilization of water resources. The effect of stand density on water consumption proved to be decisive in balancing the overall water demand of the agrocenosis with available moisture reserves [2, 43]. At the density of 35,000 ÷ 40,000 plants per hectare, water consumption per unit area was lower, while more favorable conditions for individual plant water supply were observed. Increasing density to 55,000 ÷ 60,000 plants per hectare raised the intensity of moisture use by 15 ÷ 18 %, resulting in more rapid depletion of the arable soil layer. This effect was particularly evident in 2020, when the reserves of productive moisture in the 0 ÷ 50 cm soil layer at the beginning of July were 22 ÷ 25 mm lower in high-density variants compared with the optimal treatments.

Stress factors, particularly high air temperatures in July-August and prolonged periods without precipitation, affected crop resistance significantly [49, 50]. In the dry year of 2020, pronounced daytime wilting was observed at the plant density of 55,000 ÷ 60,000 plants per hectare combined with the row spacing of 70 cm. Reducing row spacing to 45 and 30 cm decreased the intensity of wilting due to improved soil moisture retention and more uniform utilization of the nutrition area. The lowest expression of stress symptoms was observed in variants with the density of 45,000 ÷ 50,000 plants per hectare and the row spacing of 30 ÷ 45 cm. Crop lodging intensity was generally low over the three-year period; however, in treatments with high plant density and the row spacing of 15 cm, an increased risk of mechanical lodging under wind loads was recorded. The highest stability with respect to lodging was observed at the density of 45,000 plants per hectare, regardless of a hybrid.

An analysis of the interaction "hybrid×agrotechnical measure" made it possible to identify the most adaptive combinations. The P64GE118 and MAS 86OL hybrids were characterized by higher drought resistance when grown at the row spacing of 30 ÷ 45 cm and the density of 50,000 plants per hectare. The ES Aromatic SU hybrid maintained stable agrocenosis under the conditions of 45 cm row spacing and density of 45,000 ÷ 50,000 plants per hectare. In contrast, the Colombi and LG5492 HO CL hybrids exhibited greater sensitivity to a moisture deficit, manifested as a reduction in individual plant productivity at increased density. The results obtained confirmed that the adaptability of agrocenosis of high-oleic sunflower hybrids to stressful environmental conditions is determined by the combined effects of spatial sowing parameters and the genetic characteristics of the hybrids. The highest levels of water use efficiency and sustainability were achieved with the row spacing of 30 ÷ 45 cm and plant density of 45,000 ÷ 50,000 plants per hectare, which remained stable even in years characterized by precipitation deficits and elevated temperature conditions.

Synthesis of an optimal sowing model for high-oleic sunflower hybrids

The generalization of the results obtained from the field studies conducted between 2019 and 2021 made it possible to develop an integrated sowing model for high-oleic sunflower hybrids under the conditions of the Southern Steppe of Ukraine. This synthesis was based on a comprehensive assessment of yield, yield structure elements and seed quality indicators, while also taking into account the ecological adaptability of the hybrids and the efficiency of resource utilization (Table 5).

Table 5. Generalized indicators of the optimal sowing model for high-oleic sunflower hybrids (average for 2019 ÷ 2021)

Hybrid	Yield [t/ha]	Oil Content [%]	Oleic Acid Content [%]	Optimal Density [pcs./ha]	Optimal Row Spacing [cm]
P64GE118	2.43	50.8	74.4	50,000	30 ÷ 45
MAS 86OL	2.58	49.6	90.0	50,000	30 ÷ 45
ES Aromatic SU	2.85	50.6	89.8	45,000 ÷ 50,000	30 ÷ 45

Explanatory notes: compiled by the authors

A comparative analysis showed that, over the three-year study period, the highest average yield was produced by the ES Aromatic SU hybrid (2.85 t/ha), whereas MAS 86OL (2.58 t/ha) and P64GE118 (2.43 t/ha) were characterized by slightly lower, but stable yield levels. The oil content of these hybrids ranged from 49.6 to 50.8 %, while the proportion of oleic acid varied between 74.4 and 90.0 %.

The optimal plant density was found to be genotype-dependent. For the P64GE118 and MAS 86OL hybrids, the most effective density was 50,000 plants per hectare, whereas ES Aromatic SU maintained high productivity over a wider range of density choices, namely 45,000 ÷ 50,000 plants per hectare, indicating its increased adaptive capacity. For all hybrids, the most effective row spacing was 30 ÷ 45 cm, which ensured a more uniform distribution of the nutrition area, more efficient use of soil moisture and lower cultivation costs compared with the traditional 70 cm spacing and the excessively narrow 15 cm spacing.

The integrated approach made it possible to develop a sowing model that simultaneously accounts for productivity, seed quality and environmental adaptability. This model involves the use of the P64GE118, MAS 86OL and ES Aromatic SU hybrids as the most promising for the conditions of the Southern Steppe. The recommended parameters include the row spacing of 30 ÷ 45 cm and planting density of 45,000 ÷ 50,000 plants per hectare. Under these conditions, yields of 2.43 ÷ 2.85 t/ha can be achieved, with a stable oil content of approximately 50 % and an oleic acid proportion exceeding 88 %. The economic feasibility of the proposed model is confirmed by the ratio between yield and the costs of seeds and other production resources. Increasing plant density beyond 50,000 plants per hectare did not result in further yield gains, but was associated with higher seed costs and a reduction in oil content. The use of row spacing of 30 ÷ 45 cm provided an optimal balance between cultivation costs and production efficiency (Figure 1). Thus, the synthesized model enables the achievement of a stable economic effect under the conditions of contrasting growing seasons.

The systematization of the data made it possible to develop a sowing model that integrates the genetic potential of the hybrids with rational agrotechnical practices. Sowing the P64GE118, MAS 86OL and ES Aromatic SU hybrids at the row spacing of 30 ÷ 45 cm and planting density of 45,000 ÷ 50,000 plants per hectare ensured a stable combination of high yield, oil content and oleic acid concentration. The results obtained confirm that this model is optimal for the conditions of the Southern Steppe of Ukraine.

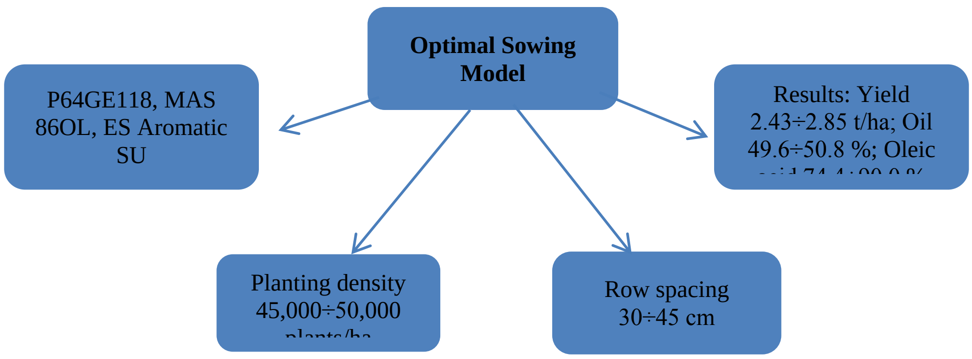

Figure 1. Synthesis of an optimal sowing model for high-oleic sunflower hybrids
Explanatory notes: source: compiled by the authors

Discussion

The results of the study confirmed that optimal sowing parameters not only increased yield, but also ensured more complete realization of seed potential in terms of quality indicators. This finding is consistent with the results of Lužaić et al. [31], who applied artificial neural network models to predict oil yield and demonstrated that the efficiency of mechanical oil extraction is determined by a combination of morphological and technological factors. In their study, as in the present research, increases in oil yield were directly associated with the optimization of spatial crop parameters. The relationship between moisture use efficiency and sunflower yield established in the experiment is also in agreement with the findings of Amarilla et al. [3], who identified a significant influence of pollinators on seed set, yield and oil chemical characteristics. Although their research focused on biological factors, whereas the present study addressed agrotechnical optimization, both approaches demonstrate that improving the efficiency of key resources (moisture or pollination) has a decisive effect on final productivity.

The results further confirmed that the optimization of plant density and row spacing ensured yields of 2.43 ÷ 2.85 t/ha with a stable oil content of approximately 50 % and an oleic acid concentration exceeding 88 %. These data are consistent with the findings of Motamed et al. [36], who reported that an optimal combination of crop density and nitrogen fertilization increased moisture use efficiency and sunflower productivity. Similarly, Kayın et al. [23] showed that variation in plant density affected yield and micronutrient uptake, which helps to explain the observed differences in the stability of seed quality parameters under the experimental conditions. The present study also demonstrated that even under the conditions of rainfall deficit, the P64GE118 and MAS 86OL hybrids maintained high oil content (up to 50 ÷ 51 %) and resistance to stress factors. This observation corresponds with the conclusions of Attia et al. [6], who emphasized the importance of breeding strategies aimed at combining yield and oil quality in oilseed crops under changing climatic conditions.

A similar conceptual approach was presented by Dudhe et al. [12], who substantiated the prospects for developing climate-resilient hybrids, which aligns with the results obtained in this study regarding the high adaptability of specific “hybrid×agrotechnical measure” combinations. The observed stability of high oleic acid content (74.4 ÷ 90.8 %) regardless of agrotechnical treatments confirms the predominantly genetic determination of this feature. Comparable conclusions were reported by Hussain et al. [18], who, based on genetic diversity analysis, demonstrated that oleic acid content is largely controlled by hereditary factors and remains stable across different soil and climatic conditions. This is consistent with the present findings, where agrotechnical measures primarily influenced yield, while having a much smaller effect on the oleic acid content of sunflower seeds.

The results confirming the stability of high oleic acid content regardless of agrotechnical practices are consistent with the genetic mechanisms described by Gao et al. [14]. The authors demonstrated that molecular markers and breeding strategies determine the fundamental basis of oil accumulation in oilseed crops, which explains the high heritability of oleic acid content in the hybrids used in this study. Similar conclusions were reported by Farooq et al. [13], who showed that the stability of oleic acid content in high-oleic sunflower hybrids was maintained under different temperature regimes. This finding corresponds well with the data obtained on fatty acid composition in seeds grown under the field conditions of the Southern Steppe.

The practical significance of the established optimal sowing model lies in the combination of high yield and improved seed quality, which enhances the prospects for environmentally sustainable production [30, 41]. This aspect is consistent with the conclusions of De Figueiredo et al. [9], who demonstrated the effectiveness of environmentally friendly solvents for oil extraction from high-stearin and high-oleic sunflower forms. Both approaches confirm that modern agricultural production is increasingly focused not only on quantitative indicators, but also on qualitative and environmental parameters. Another area of agreement concerns hybrid identification and selection. The use of morphological and productivity indicators in the present study to identify the most productive combinations corresponds with the approaches of Barrio-Conde et al. [7], who applied machine learning systems to classify sunflower hybrids based on seed characteristics. Both approaches indicate the integration of traditional agronomic methods with digital technologies in selecting the most suitable genotypes for specific growing conditions.

The finding that oleic acid content in the studied hybrids remained stable within the range of 74.4 ÷ 90.8 % is supported by long-term field observations by Angeloni et al. [5], who demonstrated that high-oleic sunflower hybrids maintained a stable fatty acid profile even under changing climatic conditions. Similarly, Premnath et al. [42] identified a quantitative feature loci controlling oil content and fatty acid composition in sunflower, emphasizing the genetic basis of the stability observed in the present study.

The obtained data on the stability of yield and quality parameters of high-oleic sunflower hybrids are also in agreement with the findings of Singh et al. [48], who demonstrated that the integration of genomic technologies with breeding approaches contributes to increased yield and enhanced nutritional value of sunflower seeds.

The results of the field studies on oleic acid variability were further supported by the work of Zhou et al. [51], who identified a quantitative feature loci controlling oleic acid content and key agronomic characteristics in sunflower. These findings explain the stability of the fatty acid composition observed in the P64GE118, MAS 86OL and ES Aromatic SU hybrids, which was expressed within the range of 74.4 ÷ 90.8 %. The results of the present research are also consistent with the review by Kaya et al. [22], which emphasized the role of high-oleic forms as a strategic direction for increasing the market value of sunflower. The applied significance of the study corresponds with the conclusions of Ollinger et al. [37], who demonstrated the feasibility of using high-oleic sunflower oil as a substitute for palm oil in the food industry. Taken together, these findings confirm that the stability of seed quality parameters has not only agronomic but also substantial nutritional and industrial importance.

Based on the synthesis of the comparative analysis, it was established that the data on yield and seed quality of high-oleic sunflower hybrids are consistent with both field-based and laboratory genetic studies conducted in different countries. The patterns identified – namely, the reduction in head diameter and seed weight with increasing plant density, the stability of oleic acid content under different sowing schemes and the improved efficiency of moisture use at optimal row spacing – are in line with current scientific evidence on the role of plant density, agrotechnical practices and genotypic characteristics in yield formation. Comparison with international studies confirms that the results obtained have broad scientific and practical relevance, and that the proposed integrated sowing model is capable of ensuring a combination of high yield and stable seed quality. Such consistency with contemporary scientific trends provides a sound basis for formulating conclusions and recommendations aimed at improving the cultivation technology of high-oleic sunflower hybrids.

Conclusions

1. During the three-year field study (2019 ÷ 2021) conducted in the Southern Steppe of Ukraine, optimal sowing parameters for high-oleic sunflower hybrids were identified, ensuring maximum productivity and stable seed quality characteristics. Yield was found to vary significantly depending on the combination of genotype, plant density and row spacing. The average yield across the experiment ranged from 2.36 to 2.85 t/ha. The most effective row spacing was 30 ÷ 45 cm, which promoted a more uniform distribution of the nutrition area, reduced moisture losses and increased yield by 12 ÷ 18 % compared with the traditional 70 cm spacing.
2. The analysis of yield structure elements confirmed a consistent pattern of decreasing head diameter (from 18.8 ÷ 22.8 cm to 15.2 ÷ 17.6 cm) and thousand-seed weight (from 59 ÷ 61 g to 53 ÷ 55 g) with increasing plant density, which was accompanied by a reduction in individual plant productivity. At the same time, the optimal combination of the plant density of 45,000 ÷ 50,000 plants per hectare with the row spacing of 30 ÷ 45 cm ensured the highest yield per unit area.
3. Quality indicators showed that seed oil content ranged from 48.9 to 51.6 %, while oleic acid content remained consistently high (74.4 ÷ 90.8 %) regardless of agrotechnical measures, confirming the high-oleic character of all studied hybrids.

4. The limitations of the study are related to the fact that the experiment was conducted within a single soil and climatic zone. Therefore, further research should be aimed at testing the proposed model in other regions and at evaluating its integration with resource-saving cultivation technologies.

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ROZWÓJ OPTYMALNEGO MODELU SIEWU W CELU ZAPEWNIENIA MAKSYMALNEJ PRODUKTYWNOŚCI WYSOKOOLEINOWYCH HYBRYD SŁONECZNIKA W WARUNKACH POŁUDNIOWEGO STEPU UKRAINY

S t r e s z c z e n i e

Wprowadzenie. Wysokooleinowe hybrydy słonecznika mają strategiczne znaczenie dla zapewnienia zarówno wysokiego plonu, jak i doskonałej jakości oleju, szczególnie w coraz bardziej suchych warunkach południowego stepu Ukrainy. Optymalizacja parametrów siewu – zwłaszcza rozstawy rzędów i gęstości roślin – odgrywa kluczową rolę w zwiększaniu produktywności, efektywności wykorzystania zasobów oraz zdolności adaptacyjnych upraw. Jednak interakcja między genotypem a przestrzenną konfiguracją siewu pozostaje niewystarczająco zbadana w warunkach zmiennego klimatu. Celem badań było określenie optymalnego modelu siewu dla wysokooleinowych hybryd słonecznika poprzez integrację plonowania, wskaźników jakości nasion oraz zdolności adaptacyjnych do środowiska. Doświadczenia polowe prowadzono w latach 2019 ÷ 2021 na glebach czarnoziemnych południowych, stosując wieloczynnikowy układ badań obejmujący siedem hybryd, cztery rozstawy rzędów (15 ÷ 70 cm) oraz sześć poziomów obsady roślin (35 ÷ 60 tys. roślin/ha).

Wyniki i wnioski. Uzyskane wyniki wykazały, że kształtowanie plonu było istotnie uzależnione od interakcji między genotypem hybrydy a parametrami siewu. Średnie plony mieściły się w zakresie od 2,36 do 2,85 t/ha, przy czym najwyższą produktywność osiągnięto przy rozstawie rzędów 30 ÷ 45 cm oraz obsadzie 45 ÷ 50 tys. roślin/ha. Zmniejszenie rozstawy rzędów z 70 do 45 ÷ 30 cm zwiększało plon o 12 ÷ 18 %, natomiast nadmierna gęstość (55 ÷ 60 tys. roślin/ha) obniżała produktywność pojedynczej rośliny. Zawartość oleju wahała się od 48,9 do 51,6 %, natomiast zawartość kwasu oleinowego pozostawała stabilna (74,4 ÷ 90,8 %), co wskazuje na silną kontrolę genetyczną tej cechy. Optymalne konfiguracje sprzyjały lepszemu zatrzymywaniu wilgoci w glebie oraz ograniczały stres suszy, zapewniając stabilne plonowanie w zróżnicowanych warunkach pogodowych. Zintegrowany model siewu – łączący określone hybrydy z rozstawą rzędów 30 ÷ 45 cm oraz obsadą 45 ÷ 50 tys. roślin/ha – stanowi praktyczne i zasobooszczędne rozwiązanie umożliwiające maksymalizację plonu przy jednoczesnym utrzymaniu wysokiej jakości nasion w warunkach południowego stepu Ukrainy.

Słowa kluczowe: Słonecznik, hybrydy, gęstość siewu, rozstawa rzędów, plon, jakość nasion