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SHAPE PARAMETERS AND CRUSHING FORCE OF SUNFLOWER SEEDS IN THE FIRST GENERATION (F1)

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Sunflower is one of the most important crops both in Ukraine and worldwide. In this study, the results of research on the morphological characteristics and physico-mechanical properties of sunflower seeds (*Helianthus annuus* L.) in parental lines and their F1 hybrids are presented. The main focus was on for evaluating seed shape and studying inheritance patterns of shape parameters and hull crushing force. A total of 196 sunflower lines from the collection of the Institute of Oilseed Crops of NAAS were used for the analysis. It was found that crossing lines with contrasting shapes (round × Elongated) leads to negative overdominance of crushing force in hybrids. For most hybrid combinations, positive overdominance was observed for seed area. The study of seed shape inheritance in the analyzed hybrid combinations revealed a diverse pattern—from positive overdominance in L06 × 178A (*hp = 1.70*) to negative intermediate dominance in Skh75A × 168b nv (*hp = −0.30*). The offspring of the combination L06 × VK464 demonstrated the most significant increase in roundness (*θa = 68.83 ± 3.201°; hp = 1.70*). Negative overdominance was identified for area parameters *Sda* (*hp = −1.21*) and *Sac* (*hp = −2.54*), as well as negative dominance for *Scb* (*hp = −0.83*) in the combination Skh75A × 168b vt, where the parental lines exhibited the most contrasting seed shapes.

Keywords: sunflower, seed, shape, hybrid, inheritance, domination

Introduction. Sunflower (Helianthus annuus) is one of the leading sources of edible and industrial oil worldwide and in Ukraine.

In addition to oil processing, sunflower seeds are used as raw material for the confectionery industry. This industry directs breeding toward the development of large-seeded varieties and hybrids with good physical and mechanical seed properties, a high thousand-seed weight, a kernel yield (hulling coefficient) of no less than 0.6–0.7, and other valuable traits.

The morphology of seeds has been described in many scientific works. UPOV distinguishes four forms of sunflower seeds, relying on visual descriptions rather than precise measurements. Sunflower seeds are divided into three types, differing, among other things, in shape and size characteristics. Oilseed varieties are characterized by smaller, narrower seeds. Intermediate (dual-purpose) varieties have seed shapes and sizes that allow their use in both the oil and confectionery industries (Nikonchuk, 2014).

Confectionery varieties are also easier to dehull (Hladni et al., 2017). Previously studied that when seeds are used as feed for poultry, birds prefer darker seeds (Vedmedeva, 2022). Among the physical parameters, more spherical seeds are known to have greater crushing force (Khodabakhshian et al., 2024). Perevalov L. I.

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points out the need to develop new, more efficient methods for processing sunflower seeds (Perevalov, 2021).

Particular attention should be paid to modern sunflower lines, as breeding for high oil content has led to deterioration in technological properties of seeds due to the fusion of the pericarp with the kernel (Shtepan et al., 2017). In technological processes, high seed crushing force leads to premature wear of equipment and increased energy consumption (Shevchuk et al., 2018).

Digital imaging using cameras and various image analysis software is already widely used for plant phenotyping (Delwiche et al., 2013). Perez E. E. used a scanning electron microscope in his study (Perez et al., 2007), while Polat M. Y. used a household scanner for measurements (Polat et al., 2013). Herasim V. applies machine vision technology for varietal and quality processing of large volumes of seeds in cleaning and sorting machines (Herasim, 2024).

The inheritance patterns of sunflower seed productivity traits have been well studied. For example, inheritance of the thousand-seed weight in F1 hybrids generally follows an intermediate pattern, leaning toward the better parental component (Kirichenko et al., 2018).

Among seed phenotype traits, coloration has been studied the most, and genetic factors influencing sunflower seed coloration are well known (Vedmedeva et al., 2022). Automated systems for determining morphological characteristics through image processing algorithms are also primarily focused on color (Aliiev et al., 2025). Seed shape, however, is much less studied, both in phenotyping and within classical approaches. For example, it has been established that elliptical shape in chickpea seeds is determined by three genes (Hossain et al., 2010). Soroka A. I., in a study on the inheritance of round sunflower seed shape, indicates that this trait is controlled by several pairs of genes (Soroka et al., 2017).

Existing methods for determining sunflower seed shape rely mainly on visual assessment, while most studies are limited to measuring dimensional characteristics (length, width, volume). Given the wide range of sunflower seed applications and the scale of industrial processing, it is important to develop a digital description of seed shape, identify its components, determine its relationship with crushing force, establish inheritance patterns, and identify genotypes with high breeding potential for confectionery use of sunflower (Helianthus annuus).

Objective: To investigate the inheritance patterns of sunflower seed shape, as well as seed area and crushing force, among first-generation (F1) hybrids.

Materials and Methods. For the study, 196 sunflower (Helianthus annuus L.) lines from the collection of the Institute of Oilseed Crops of NAAS, grown in 2019 and 2020, were analyzed. From these, lines with contrasting traits in the measured seed parameters were selected, and their plants were crossed in 2023. Seed material from maternal lines, paternal lines, and their offspring was included in the study of inheritance using samples from the 2024 harvest.

The plants were grown in the breeding nursery of the Institute of Oilseed Crops of NAAS, located on the outskirts of the city of Zaporizhzhia. The sunflower cultivation technology was conventional (Aksenov et al., 2013). Plant density was 40,000 plants per hectare, and the plot area was 10 m². Seeds of the parental forms were obtained through self-pollination under individual isolators. F1 hybrid seeds were obtained by manual pollination of emasculated parental plants under individual isolators.

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Seed samples of the lines were studied over three years; however, seeds from the 2024 harvest were used to determine inheritance patterns. Weather conditions during the 2024 growing season significantly deviated from long-term averages, with increased drought and higher temperatures, which negatively affected overall seed quality and filling.

The parameter "seed crushing force" was obtained using an experimental device developed by Aliiev E.B. The tested sample is placed on the lever of a load cell, and force is gradually applied using a mechanical press. Data from the load cell are recorded and displayed in real time on a monitor. At the moment of seed failure, the operator observes a sharp drop in force values, usually accompanied by an audible cracking sound. Further loading is then stopped, and the "crushing force" parameter is defined as the maximum force recorded before failure (Busarov, 2025).

For measurements, 10 randomly selected well-filled seeds were taken per sample. The measured parameters included thousand-seed weight, kernel weight, and crushing force. Whole seeds were photographed using a macro camera from two angles (Aliiev, 2022). The obtained images were processed using computer software developed in the Python programming language (Vedmedyev et al., 2022).

The algorithm of the developed program was designed to determine seed size parameters - length, width, thickness, and area, as well as those of its components. A quadrilateral was constructed between the extreme coordinates of width and length, and the areas of seed parts located outside this quadrilateral were calculated separately. The algorithm also made it possible to determine the angles between the vertices of the quadrilateral and divided the lines constructed along the seed's length and width at their intersection point. The components of seed measurements are illustrated in the schematic diagram (Fig. 1).

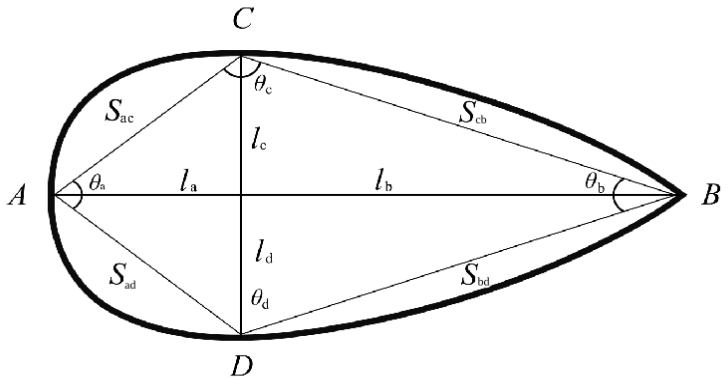

Fig.1. **Components of sunflower seed shape parameters**

Notes: l_a – first part of length; l_b – second part of length; l_c – first part of width; l_d – second part of width; θ_a – angle at point A; θ_b – angle at point B; θ_c – angle at point C; θ_d – angle at point D; S – seed area in pixels; S_{ac} – area of the 1st section outside the quadrilateral; S_{cb} – area of the 2nd section outside the quadrilateral; S_{bd} – area of the 3rd section outside the quadrilateral; S_{ad} – area of the 4th section outside the quadrilateral; h – seed width; w – seed length

Source: developed by the author

The methodology established by the Ukrainian Institute for Plant Variety Examination (UIPVE) defines four main shapes of sunflower achenes, corresponding

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to the international UPOV classification—Elongated, Narrow ovoid, Broad ovoid, and round. Shape assessment is performed subjectively.

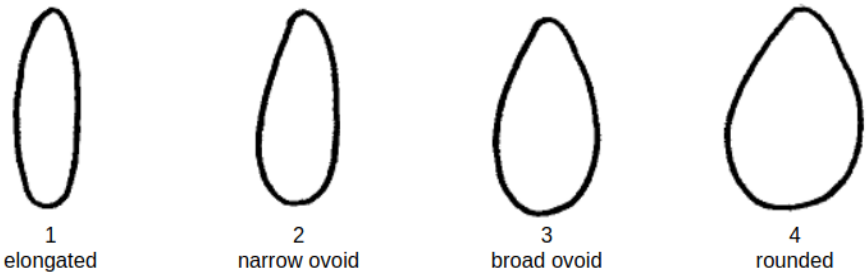

Fig. 2. **Shapes of sunflower achenes according to the UPOV classification**
Source: developed by the author

After analyzing and studying the collection of lines, the main parameter related to shape was selected—the value of angle *θa* (Busarov et al., 2025). In this study, the UPOV methodology was used to determine shape, along with a classification of the corresponding forms based on observed values of *θa*:

- Elongated: $\theta_a < 60$
- Narrow ovoid: $60 < \theta_a < 65$
- Broad ovoid: $65 < \theta_a < 70$
- Rounded: $70 < \theta_a$

The degree of trait dominance in first-generation hybrids was determined using the formula of G. M. Beil and R. E. Atkins (Beil et al., 1965):

$$h_p = \frac{F_1 - MP}{P - MP}, \quad (1.1)$$

where: F_1 − the arithmetic mean value of the trait in first-generation hybrids; MP – the arithmetic mean of the trait values of the two parental forms; P – the arithmetic mean of the parental form with the higher expression of the trait.

Based on the calculated degree of dominance, the pattern of inheritance was determined according to the following values:

- hp = 0 – no dominance;
- hp > +1.0 − positive overdominance (heterosis);
- +0.5 < hp ≤ +1.0 − positive dominance;
- −0.5 ≤ hp ≤ +0.5 − intermediate inheritance;
- −1.0 ≤ hp < −0.5 − negative dominance;
- hp < −1.0 – negative overdominance (depression)

Results and Discussion. Nine parental lines with contrasting expressions of the studied parameters were selected. The lines were described and presented in Tables 1 and 2. Table 1 shows lines with more rounded seed shapes, while Table 2 presents lines with more Elongated seeds.

Samples of the Skh75A line had large and heavy seeds, as confirmed by the thousand-seed weight parameter (m = 111.43 ± 6.05 g). These samples also exhibited high hull content (73.29 ± 1.472%). At the same time, a high kernel weight (m = 70,082 ± 0,0049 g) was observed, which is not typical for most studied sunflower samples.

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Table 1

Average values seed parameters of 1st part parental lines (2024)

Line name	Skh75A	164g	160v	L06
Shape according to UPOV	Rounded	Broad ovoid	Broad ovoid	Narrow ovoid
Angle θa	71.21±4.127	66.96±3.880	68.46±2.539	62.83±3.441
Area, mm^2	315.81±15.243	165.36±5.022	214.01±9.783	125.79±3.684
Sac, mm^2	15.40±3.113	12.39±1.426	9.83±1.426	11.48±1.122
Scb, mm^2	24.35±5.906	18.79±0.871	16.18±1.181	14.93±1.178
Sbd, mm^2	19.75±4.128	17.53±1.876	25.93±1.355	15.99±1.369
Sda, mm^2	14.14±3.267	10.78±1.281	14.95±1.151	12.14±1.118
Thousand-seed weight, g	111.43±6.05	19.16±0.961	29.77±7.97	74.62±0.978
Crushing force, N	47.30±5.708	27.80±4.141	25.90±5.098	47.90±5.54
Kernel weight, g	0.082±0.0049	0.009±0.0008	0.020±0.0063	0.053±0.0006
Hull content, %	73.29±1.472	48.33±3.173	21.05±3.315	71.59±0.745
Width, mm	18.12±0.545	12.32±0.142	14.62±0.558	9.42±0.128
Length, mm	28.33±0.313	20.35±0.416	23.24±1.096	16.85±0.205
Thickness, mm	15.88±0.471	8.21±0.896	9.97±0.366	7.64±0.319

Source: developed by the author

Correspondingly high values of crushing force were also recorded (F = 47.30 ± 5.708 N). The seed shape of Skh75A, classified as round according to UPOV, was confirmed by measurements, showing high values of angle θa (71.21 ± 4.1271°), indicating a distinctly pronounced roundness compared to other samples.

Additionally, Skh75A stands out for its large values of area components at their maximum expression: Sac, Scb, Sbd, and Sda exceed those of most other samples, as well as other samples within the Skh75A line itself. This makes the line exceptional in terms of size among the studied material.

Table 2

Average values of seed parameters of 2nd part parental lines (2024)

Line name	VK464	168b nv.	168b vt.	165ar2	178A
Shape according to UPOV	Narrow ovoid	Narrow ovoid	Elongated	Elongated	Elongated
Angle θa	64.19±4.275	60.51±3.792	42.18±2.840	48.25±1.995	45.59±2.960
Area, mm^2	181.27±8.502	123.65±8.323	174.20±7.272	203.55±6.889	148.04±3.901
Sac, mm^2	13.13±1.615	22.32±11.55	23.40±2.726	15.82±0.899	11.95±1.248
Scb, mm^2	20.06±1.799	17.41±6.224	15.76±0.957	16.27±1.170	18.07±1.489
Sbd, mm^2	23.90±2.425	28.99±8.501	16.07±2.028	8.39±1.110	20.75±1.669
Sda, mm^2	14.56±1.569	29.73±13.725	19.57±1.287	8.39±1.275	13.65±1.424
Thousand-seed weight, g	81.49±3.602	18.78±1.143	28.23±3.715	33.70±5.29	33.60±1.16
Crushing force, N	34.90±3.886	24.00±6.21	31.30±5.098	35.20±4.54	15.30±1.730
Kernel weight, g	0.053±0.0025	0.010±0.0005	0.019±0.0021	0.021±0.0038	0.020±0.0003
Hull content, %	35.09±0.396	54.77±1.037	69.46±1.764	61.62±2.728	39.83±1.741
Width, mm	11.81±0.282	12.81±2.790	10.58±0.367	12.68±0.215	7.92±0.143
Length, mm	21.99±0.173	19.99±2.756	21.82±0.288	26.25±0.593	23.36±0.342
Thickness, mm	8.11±0.288	6.92±2.08	7.58±0.594	10.94±0.165	6.21±0.123

Source: developed by the author

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Line L06 was classified according to UPOV as having a Narrow ovoid seed shape (θa = 62.83 ± 3.441°). This line was also characterized by a large thousand-seed weight (m = 74.62 ± 0.978 g) and high seed crushing force (F = 47.90 ± 5.54 N). At the same time, it showed relatively low values of seed thickness (w = 9.42 ± 0.128 mm) and width (h = 7.64 ± 0.319 mm).

A low level of hull content was observed in line 160v (21.05 ± 3.315%), which also had long seeds (l = 23.24 ± 1.096 mm). These samples were classified under the UPOV category "Broad ovoid" (θa = 68.46 ± 2.539°). Despite these characteristics, their crushing force was much lower than average (F = 21.05 ± 3.315 N).

Line 164g showed a low thousand-seed weight (m = 19.16 ± 0.961 g) despite having large dimensional components, particularly length (l = 20.35 ± 0.416 mm) and width (h = 12.32 ± 0.142 mm).

VK464 exhibited high seed weight values but lower hull content (35–37%) and approximately half the seed width (11–12 mm). At the same time, this line stood out for its high thousand-seed weight (m = 81.49 ± 3.602 g).

Line 178A showed a significant difference between seed length (l = 23.36 ± 0.342 mm) and width (w = 7.92 ± 0.143 mm). The width values were the smallest among all lines included in the study. crushing force was also among the lowest (F = 15.30 ± 1.73 N). At the same time, this line had considerable seed length (23–25 mm), close to the average across the entire collection.

Line 168b nv differed from other samples by having the lowest thousand-seed weight (m = 18.78 ± 1.143 g), but it showed crushing force values closer to the average (F = 24.00 ± 6.21 N), indicating atypical characteristics. This combination may suggest a significant influence of seed shape on crushing force. This line also had the smallest seed area among all selected samples (S = 123.65 ± 8.323 mm²).

Line 168b vt, classified by UPOV as having Elongated seeds, had the lowest θa values (42.18 ± 2.840°).

Line 156ar2 demonstrated values close to the average for thousand-seed weight and crushing force, slightly higher than average hull content, and slightly lower than average thickness. Line L06 had a higher thousand-seed weight while exhibiting relatively small seed dimensions in both length (16–18 mm) and width (~9 mm), which is nearly half of the average values.

These parameters indicate that the collection of lines studied is highly diverse, allowing for the investigation of inheritance of individual components. First-generation hybrids (F1) were obtained through targeted crosses using the following combinations:

Skh75A × 165ar2, Skh75A × 164g, Skh75A × 168b vt, 160v × 168b vt, L06 × VK464, L06 × 178A, Skh75A × 168b nv, Skh75A × 160v.

When determining inheritance of individual traits, only those combinations in which the parental lines significantly differed in the respective trait are presented in the following tables. All measurements with insignificant or borderline differences were excluded.

Table 3 presents the average values of seed hull crushing force in sunflower lines and hybrids.

For the parameter "crushing force," negative values of the inheritance coefficient were observed in a significant number of hybrid combinations. For the combinations Skh75A × 165ar2, Skh75A × 164g, and L06 × VK464, the inheritance coefficient values indicate negative overdominance (depression) of this trait in hybrid samples. These combinations with negative overdominance had maternal lines with round seed shape and paternal lines with Elongated or Narrow ovoid seed shapes.

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Table 3

Inheritance of sunflower seed hull crushing force, N

Maternal line		Paternal line		F1 hybrid	
Name	$F, \bar{x}$	Name	$F, \bar{x}$	$F, \bar{x}$	hp
Skh75A	47.30±5.708	165ar2	35.24±4.54	33.31±3.567	-1.32
		164g	27.80±4.141	22.91±3.719	-1.50
		168b nv	24.00±6.21	26.35±3.043	-0.80
		160v	25.90±5.098	53.76±1.650	1.61
L06	47.90±5.54	178A	15.30±1.730	43.85±4.620	0.75
		VK464	34.90±3.886	46.05±3.292	-1.38

Source: developed by the author

At the same time, positive dominance (hp = 1.61) was observed in the hybrid combination Skh75A × 160v (round × Broad ovoid forms), and intermediate inheritance (hp = 0.75) was observed in the combination Skh75A × 178A.

The crushing force values obtained in the study indicate that using parental forms with Elongated seed shape together with a round maternal line results in hybrids with lower crushing force than the maternal parent. In contrast, using a Broad ovoid form as the maternal line and an Elongated form as the paternal line produces hybrids with significantly higher crushing force.

These results suggest that although crushing force strongly depends on the maternal line in hybrid combinations, paternal lines with contrasting seed shapes also have a significant influence.

Table 4 presents the values of angle θa measured from images of sunflower seeds. This angle was selected as the primary descriptor of seed shape based on the results of previous studies (Busarov et al., 2025).

A maternal line with a round seed shape crossed with lines 165ar2 and 168b vt (Elongated forms) and 168b nv (Narrow ovoid form) produced hybrids in which the seed shape of Skh75A × 165ar2 remained within the Elongated category according to UPOV. However, the measured values of angle θa showed a shift toward values characteristic of greater roundness. At the same time, high values of the inheritance coefficient were not observed (hp = −0.15), indicating low-degree intermediate inheritance.

Table 4

Inheritance of the angle θa in sunflower seed images

Maternal line		Paternal line		F1 hybrid	
Name	$\theta a, \bar{x}$	Name	$\theta a, \bar{x}$	$\theta a, \bar{x}$	hp
Skh75A	71.21±4.127	165ar2	48.25±1.995	57.96±2.406	-0.15
		168b nv	60.51±3.792	64.24±2.818	-0.30
		168b vt	42.18±2.840	62.07±1.592	0.37
160v	68.46±2.539	168b vt	42.18±2.840	65.25±3.884	0.76
L06	62.80±4.127	178A	45.59±2.960	68.83±3.201	1.70

Source: developed by the author

Among the obtained hybrid lines, the values of angle θa were distributed according to UPOV within the range from Elongated to Broad ovoid forms. None of

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the hybrids analyzed in this study fell into the "round" category according to the UPOV classification.

The combination of the maternal line Skh75A with line 168b nv demonstrated a moderate degree of negative intermediate inheritance (hp = −0.30). The combination of the same maternal line with the paternal line 168b vt showed positive intermediate inheritance (hp = 0.37). According to this parameter, the hybrid falls into the "Broad ovoid" category under UPOV, while the parental lines belong to different categories. The Skh75A samples were classified as "round," whereas the 168b nv samples were classified as "Elongated," with a high degree of expression of this trait (θa = 42.18 ± 2.840°).

Among other combinations, higher values of the inheritance coefficient were observed. The combination 160v × 168b vt demonstrated positive dominance (hp = 0.76), while L06 × 178A showed positive overdominance (hp = 1.70). It should be noted that these combinations were obtained by crossing lines with less rounded seeds. In the case of L06 × 178A, both parental lines were no more rounded than "Narrow ovoid." However, the resulting F1 hybrid samples were more rounded (θa = 68.83 ± 3.201°), allowing their classification as "Broad ovoid" under UPOV, despite the cross involving a Narrow ovoid maternal line and an Elongated paternal line.

Table 5 presents data on the inheritance of sunflower seed area. The results show various inheritance coefficients, but all of them are positive, indicating that F1 hybrids reproduce seed area at the level of, or higher than, the parental lines.

Table 5

Inheritance of sunflower seed area, mm²

Maternal line		Paternal line		F1 hybrid	
Name	$S, \bar{x}$	Name	$S, \bar{x}$	$S, \bar{x}$	hp
Skh75 A	315.81±15.243	165ar2	203.55±6.889	330.41±16.340	1.26
		164g	165.36±5.022	311.33±13.966	0.94
		168b nv	123.65±8.323	319.17±16.189	1.03
		160v	214.01±9.783	272.58±10.350	0.15
160v	214.01±9.783	168b vt	123.65±8.323	243.81±8.972	2.50
L06	125.79±3.684	VK464	181.27±8.502	263.36±12.807	3.50
		178A	148.04±3.901	305.45±11.658	15.15

Source: developed by the author

For the combination L06 × 178A, the inheritance coefficient showed a high level of overdominance for the parameter "seed area" (hp = 15.15). Indeed, the F1 hybrid seed area in this combination (S = 305.45 ± 11.658 mm²) was several times higher than that of both the paternal (S = 125.79 ± 3.684 mm²) and maternal (S = 148.04 ± 3.901 mm²) forms. In this cross, parental components with relatively small seed area were used, yet the hybrid exhibited strong heterosis for this trait.

In another combination involving the same maternal line L06 but a different paternal line VK464—which had a larger seed area than the previous 178A—the dominance coefficient was lower (hp = 3.50).

The maternal line Skh75A was characterized by large seeds in initial measurements (S = 315.81 ± 15.243 mm²), which exceeded the average value for the collection (S = 195.2 mm²). In crosses with paternal lines 165ar2 and 168b nv, hybrid

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seed samples exceeded parental values in size, demonstrating overdominance for this parameter.

Overall, dominance and overdominance were observed in five combinations where lines with different seed shapes were crossed, while intermediate inheritance was observed in the combination of a round line with a Broad ovoid one (Skh75A × 160v). This latter case can be explained by relatively small differences in shape and more pronounced differences in size between the parental lines.

An important parameter for determining seed shape is the area of the protrusion between points C and A (Fig. 1), which characterizes the roundness of the blunt tip of the seed – its base. The inheritance results for this parameter are presented in Table 6.

The table includes results for crosses between a round and Elongated form (Skh75A × 168b vt), a Rounded and Narrow ovoid form (Skh75A × 168b nv), a round and Broad ovoid form (Skh75A × 160v), and a Narrow ovoid × Narrow ovoid combination (L06 × VK464). In all these combinations, there was a significant difference in this area between parental components.

The following degrees of dominance were identified: negative overdominance (hp = −1.21) in the combination involving line 168b vt, where the most contrasting parental forms were present—round and Elongated seed shapes. The combination Skh75A × 160v showed positive overdominance (hp = 1.30), involving round and Broad ovoid forms, which could be considered more similar to each other than the other crosses. However, this area parameter highlights differences between lines related to seed roundness. In other combinations, low-level intermediate inheritance was observed, both negative and positive.

Table 6

Inheritance of the area components *Sac* and *Sda* from sunflower seed images, mm²

Maternal line		Paternal line		F1 hybrid	
Name	S_{ac}, $\bar{x}$	Name	S_{ac}, $\bar{x}$	S_{ac}, $\bar{x}$	hp
Skh75A	15.40±3.113	168b vt	23.40±2.726	14.58±2.313	-1.21
		160v	9.83±1.426	16.24±1.338	1.30
L06	11.48±1.122	VK464	13.13±1.615	11.21±3.625	-0.25
Name	Sda $\bar{x}$	Name	Sda $\bar{x}$	Sda $\bar{x}$	hp
Skh75A	14.14±3.267	168b vt	19.57±1.287	9.95±1.934	-2.54
		165ar2	8.39±1.275	16.40±6.718	1.79
L06	12.14±1.118	VK464	14.56±1.569	11.13±2.969	5.07

Source: developed by the author

The area Sda is, by symmetry, analogous to the area Sac. However, in practice, both halves of the seed cannot be fully identical, since the sunflower head (capitulum) is round and convex, and seeds are arranged within it in a curved pattern. Therefore, identical results from the two halves of a seed cannot be obtained.

Nevertheless, as shown in Table 6, the obtained results for the inheritance of area Sda largely correspond to the inheritance pattern of area Sac. Negative overdominance was confirmed in the combination Skh75A × 168b vt. However, there is a significant deviation in the combination L06 × VK464, where positive

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overdominance was observed for the Sda area. This is associated with strong deformation (curvature) of the seeds of line L06 and its hybrids.

The capitula of lines and hybrids involving L06 have a convex shape and a gradual development of seeds within the head, which strongly distorts the seed symmetry axis. This indicates that seed shape is influenced not only by genes directly controlling shape, but also by genes affecting other plant traits, particularly capitulum morphology.

Other seed area components reflect the sharpness of the seed tip by which it attaches to the capitulum. In Figure 1, this parameter is designated as Scb. In the combination Skh75A × 165ar2, positive overdominance was observed (hp = 1.71) (Table 7). Among other combinations involving the maternal line Skh75A, such as Skh75A × 168b vt, negative dominance (hp = −0.83) and weak negative intermediate inheritance (hp = −0.27) were recorded for this parameter. For the combination L06 × VK464, weak negative intermediate inheritance was observed (hp = −0.97). The combination Skh75A × 165ar2 demonstrated strong positive overdominance (hp = 2.79). At the same time, the combination L06 × VK464 showed negative dominance.

If we compare the results of these two potentially symmetric areas, we again obtain confirmation of positive overdominance in certain crosses.

Table 7

Inheritance of the area components *Scb* and *Sbd* from sunflower seed images, mm²

Maternal line		Paternal line		F1 hybrid	
Name	Scb $\bar{x}$	Name	Scb $\bar{x}$	Scb $\bar{x}$	hp
Skh75A	24.35±5.906	165ar2	16.27±1.170	24.19±4.748	1.71
		168b vt	15.76±0.957	16.49±2.830	-0.83
		160v	16.18±1.181	19.15±1.412	-0.27
L06	14.93±1.178	VK464	20.06±1.799	12.57±2.870	-0.97
Name	Sbd $\bar{x}$	Name	Sbd $\bar{x}$	Sbd $\bar{x}$	hp
Skh75A	19.75±4.128	165ar2	8.39±1.110	27.02±3.886	2.79
L06	15.99±1.369	VK464	23.90±2.425	12.65±2.242	0.44

Source: developed by the author

This combination appears to be remarkably successful because it involves two lines with fundamentally different seed shapes – round and Elongated. Therefore, across all seed shape parameters, it shows either positive or negative overdominance. At the same time, the cross L06 × VK464 again exhibited intermediate inheritance in this case (−0.97 and 0.44).

In the study by Soroka A. I., sunflower hybrids obtained from crosses between round and Elongated lines demonstrated intermediate inheritance values (Soroka et al., 2017). A cross between a round line with a length-to-width ratio of 1.22 and an Elongated line with a ratio of 1.66 produced F1 hybrids with ratios of 1.48 and 1.50, indicating positive dominance for this parameter.

In our study, the results showed a more diverse pattern, and the degree of inheritance depended on the specific combination: ranging from weak negative intermediate dominance in the hybrid Skh75A × 168b nv (hp = −0.30) to strong positive overdominance in the cross L06 × 178A (hp = 1.70). Notably, none of the

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hybrids obtained from the round maternal line Skh75A inherited its shape category, showing only a low degree of intermediate dominance.

In the small second-generation progeny obtained from the cross Skh75A × 165ar2, three out of fifteen offspring displayed a round shape, which corresponds to a single gene in the recessive state. Interestingly, the most significant increase in roundness was observed when crossing less rounded lines—specifically the Broad ovoid maternal line L06 (θa = 62.80 ± 4.127°) and the Elongated paternal form VK464 (θa = 45.59 ± 2.960°), resulting in F1 seeds with markedly increased roundness (θa = 68.83 ± 3.201°; hp = 1.70).

Regarding seed hull crushing force: R. Khodabakhshian noted that more spherical seeds tend to have higher crushing force (Khodabakhshian et al., 2011). In our study, the highest crushing force was observed in lines with round and Narrow ovoid seed shapes, while Elongated forms showed lower crushing force. Other seed shape components identified in this study were described and calculated for the first time.

Conclusions. Seed crushing force in most combinations (Skh75A × 165ar2, Skh75A × 164g, L06 × VK464) exhibited negative overdominance. However, in the combination Skh75A × 160v, positive overdominance was observed (hp = 1.61).

The use of paternal forms with Elongated seeds in combination with a round maternal line produces hybrids with lower crushing force than the maternal parent. In contrast, the use of a Broad ovoid paternal form increases crushing force in hybrids relative to both parents. Crosses between Narrow ovoid and Broad ovoid forms produce significantly higher crushing force in hybrids than in either parent. Therefore, crushing force associated with seed shape; however, it is not the only influencing factor.

Seed shape described by the angle θa in combinations involving the maternal line Skh75A predominantly shows intermediate inheritance.

For seed area, dominance and overdominance were observed in five combinations where lines with contrasting shapes were crossed, while intermediate inheritance was observed in the combination of a round line with a Broad ovoid one (Skh75A × 160v).

Different degrees of dominance were also observed among area components. Negative overdominance was identified for areas Sda (hp = −1.21) and Sac (hp = −2.54), as well as negative dominance for area Scb (hp = −0.83) in the combination Skh75A × 168b vt, where parental lines had the most contrasting seed shapes (round vs. Elongated). The combination Skh75A × 165ar2, involving the same shape contrast, showed positive overdominance for areas Sda (hp = 1.79), Scb (hp = 1.71), and Sbd (hp = 2.79).

The combination Skh75A × 160v (round and Broad ovoid forms) exhibited positive overdominance for Sac (hp = 1.30) and weak negative intermediate inheritance for Scb (hp = −0.27). Other combinations showed intermediate inheritance, except for L06 × VK464, which demonstrated strong asymmetry of area components and seed deformation.

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ПАРАМЕТРИ ФОРМИ ТА СИЛИ РУЙНУВАННЯ НАСІННЯ В ПЕРШОМУ ПОКОЛІННІ НАСІННЯ СОНЯШНИКА

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Соняшник є однією з найбільш важливих культур як в Україні так і в світі. У ході цієї наукової роботи отримано результати дослідження морфологічних характеристик та фізико-механічних властивостей насіння соняшнику (*Helianthus annuus L.*) у батьківських ліній та їхніх гібридів F1. Основну увагу приділено використанню цифрових методів оцінки форми насіння та вивченню характеру успадкування параметрів форми і сили руйнування лушпиння. Для аналізу використано 196 ліній соняшнику з колекції Інституту олійних культур НААН. Виявлено, що схрещування ліній з контрастними формами (округла × видовжена) призводить до негативного наддомінування сили руйнування у гібридів. Для більшості гібридних комбінацій характерне позитивне наддомінування за площею насінини. Дослідження успадкування форми насінини у використаних гібридних комбінаціях свідчить про різноманітний характер успадкування – від позитивного наддомінування у L06 × 178A (hp = 1,70) до негативного проміжного домінування у Skh75A × 168b nv (hp = –0,30). Нащадки комбінації L06 x VK464, продемонстрували найбільш суттєве збільшення округлості (θa = 68,83±3,201 °; hp = 1,70). Було встановлено негативне наддомінування параметрів площ Sda (hp = –1,21), Sac (hp = –2,54) та негативне домінування площі Scb (hp = –0,83) у комбінації Skh75A x 168b vt, де батьківські лінії були найбільш контрастні.

Ключові слова: соняшник, насіння, форма, гібрид, успадкування, домінування

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