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Study of the distribution of phenotypic characteristics of sunflower seeds in a head of different genotypes

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Abstract: Nowadays, sunflower breeding needs new approaches and methods. Using computer-aided image analysis techniques combined with other data on the phenotyping subject creates a sound basis for selection. Selection work on the size and weight of sunflower seeds causes many complications related to the variety of seeds, even in one head. To solve this problem, field experiments, mathematical modelling, and computer processing of photographs were involved. As a result of combining the results of actual measurement and evaluation of photographic images, a method of measurement and determination of patterns of distribution of phenotypic characteristics of sunflower seeds in a head was developed. The methodology includes a developed mathematical model of the location of sunflower seeds in the head and a methodology for determining the geometric dimensions of the seeds from the image. The distribution patterns of geometric (length L, width W, thickness T) and mass (seed mass Ms, seed kernel mass Mk) parameters of seeds in the head were studied. The variability of the seed phenotype in the head was established depending on its location based on the material of four lines and the sunflower variety. A complex index of phenotypic characteristics of sunflower seeds I is introduced, defined as the product of the ranks of individual phenotypic parameters of seeds (L, W, T, Ms, Mk). A general pattern was determined, like three tiers with different phenotypic characteristics in each head. The possibilities of visualising the phenotype of seeds by their location in the head have been revealed.

Keywords: phenotypic characteristics; sunflower seeds; location in the head; distribution pattern; complex index; seed weight

INTRODUCTION

It is known, that obtaining a high yield and its quality are formed by the interaction of the genotype of plants (Vedmedeva & Nosal′, 2020) and the conditions of their cultivation (Polyakov et al., 2022). The result of this interaction is the phenotype of the plant. In global practice, there are quite a few studies of molecular genetics of individual sunflower traits (Yue et al., 2010, Hladni & Miladinović, 2019, Allen et al., 1988) and the study of the yield of diverse sunflower genetic material (Hladni et al., 2006, Cvejić et al., 2019). However, the study of the interaction of the sunflower genotype and its growing conditions from the point of view of creating mathematical models for phenotyping is a completely new approach to solving a known problem (Cast et al., 2022). The number of phenotypic traits that can be distinguished in sunflowers is quite large, but not all have significant genotypic separation. Different methods are used to describe these signs (Vedmedyeva et al., 2022), but modern methods, hardware and software provide their accurate forecasting and genotype assessment. Combining new technologies with knowledge of the morphology of organs and their parts in the sunflower plant will provide a high level of resolution in the phenotyping of genotypes and determine the relationships of individual traits (Phillips, 2010; Schurr, 2015). Therefore, the development and improvement of technologies for measuring and evaluating plant objects, in particular seeds, based on a set of traits in the breeding process is relevant and promising.

To solve this problem, efficient high-throughput phenotyping platforms have been developed previously. They use various methods of visualisation of objects; the visualisation is converted into quantitative data of complex signs related to growth, productivity and adaptation to biotic or abiotic stress (diseases, insects, drought and salinity) (Li et al., 2014). Phenotyping uses computer image analysis techniques combined with other data about an object (Afonnikov et al., 2016). To develop this direction, scientists from several countries united and created a joint scientific platform, the International Plant Phenotyping Network, which informs about research on plant phenotyping (International Plant Phenotyping Network - IPPN, 2024). These studies are financed under the EU programs "Horizon 2020" and "Horizon Evropa". Genetic studies of this program were carried out on model objects. For example, the genetics of photosynthesis was studied in Arabidopsis (Lazar et al., 2022). However, large objects are studied on platforms with the passage of time and considering the effects of environmental factors. Such developments found their application in analyzing the condition of plants and fields (Daviet et al., 2022).

Modern methods have a high resolution and allow visualization of multidimensional and multiparametric data (Li et al., 2014, Lei & Sun, 2023). Imaging methods quantify complex plant traits' growth dynamics in controlled ecological systems or the field. Image analysis algorithms are the main drivers for advancing research on plant phenotype quantification and its parts: roots, stems, leaves, seeds, flowers, etc.

Visible images are widely used in plant breeding due to their low cost and simplicity (Afonnikov et al., 2016). In a controlled environment, the images were used to analyze the following characteristics: shoot biomass, yield, germination rate, maturity, and morphology of the panicle, leaves, seeds, and root system. Standard image analysis preprocessing and segmentation algorithms are used for image processing. Working with image analysis libraries like OpenCV (Bradski & Kaehler, 2008) requires knowledge of programming skills. However, such packages as Image (Abràmoff et al., 2004) have a convenient windowed user interface, basic functions for solving the main tasks of image analysis, and the ability to form computational pipelines. The development of image analysis methods led to the creation of a large number of programs aimed at determining phenotypic characteristics (Afonnikov et al., 2016, Yang et al., 2021)

The paper (Barrio-Conde et al., 2023) presents the results of a study on the ability of deep learning algorithms to classify sunflower seeds. The images were used to create datasets for training, validating and testing the system. The AlexNet CNN model has been implemented for cultivar classification, particularly the classification of two to six cultivars. The classification model achieved an accuracy value of 100% for two classes and 89.5% for six classes.

Significant phenotypic variation in the size of sunflower seeds is known when conditions of nutrition, moisture, and intensity of competition change (Tigay & Tereshchenko, 2017). When growing plants of heterogeneous varieties-populations of sunflower in the absence of competition, under equal nutrition and water supply conditions, a high negative correlation was found between the number and size of seeds in the head.

Significant variability in the size of seeds is also observed within the head (Vasil'yeva et al., 2012, Vedmedeva et al., 2023). It is shown that the seeds of different zones of the head differ in absolute weight, huskiness and oiliness. The seeds of the peripheral zones of the head are larger than those of the central ones and have an increased huskiness and a reduced amount of oil.

Many works (Swinton, 2004; Swinton & Ochu, 2016; Borda & Bowen, 2020) are devoted to the problem of mathematical description of the location of sunflower seeds in a head. Research (Swinton & Ochu, 2016) evaluates the occurrence of the Fibonacci structure in the spirals of sunflower seed heads. This phenomenon has competing biomathematical explanations, and the basic premise is that observing both Fibonacci and non-Fibonacci patterns is informative for invoking such patterns. More complex Fibonacci structures, which were not previously reported, were also discovered in these studies. The article (Swinton, 2004) presents the results of Turing's fundamental research, which is devoted to the mathematical description of the morphogenesis of plant flowers. The article claims about the appearance of Fibonacci numbers in placing seeds in a sunflower head.

The practical yield of large seeds from the sample has been studied by dividing it into fractions. And it did not refer to a separate head but to the harvest of the plot as a whole (from several dozen heads) (Tishkov & Borodin, 2009; Polyakov et al., 2011; Korkodola & Maklyak, 2021). At the same time, the main factor was the study of the peculiarities of growing conditions and their influence on several genotypes. These practical experiments do not make it possible to create mathematical models and corresponding forecasts necessary for breeding.

For the selection of lines and hybrids, simple selections used for varietal material turned out to be ineffective (Pérez-Vich et al., 2018). Different genotypes have different phenotypic characteristics of seeds. Still, due to the variability of the phenotype of seeds in one head, the opportunity to identify differences between each plant is often lost (Vedmedeva & Nosal′, 2020).

Therefore, there was an immediate need to determine the regularities of the distribution of phenotypic characteristics of sunflower seeds in the head and to develop methods and devices that allow detecting genetic differences of lines by seed phenotype and help make reliable predictions in plant selection.

The study aims to develop a methodology for measuring and determining the distribution patterns of phenotypic characteristics of sunflower seeds in a head.

A scientific hypothesis has been put forward: sunflower seeds and their phenotypic characteristics in the head are distributed according to specific patterns.

The study included the following steps:

– to develop methods for determining the mathematical model of the location of sunflower seeds in a head;

- to develop methods for determining the geometric dimensions of sunflower seeds based on a photo image;

- to investigate the distribution patterns of geometric (length, width, thickness) and mass (mass, kernel mass) parameters of seeds in a head of different sunflower samples;

- to develop a comprehensive set of demonstrative phenotypic characteristics of sunflower seeds and group them in the head area.

MATERIALS AND METHODS

The object of the study is the phenomenon of the formation of sunflower seeds in a head according to certain regularities of the distribution of their phenotypic characteristics.

As for phenotypic characteristics of sunflower seeds in the head, we used geometric dimensions (length L, width W, thickness T), seed mass (Ms), and seed kernel mass (Mk).

Samples from the collection of the Institute of Oil Crops of the National Academy of Sciences, contrasting in terms of seed morphology, were chosen as sunflower samples: 178ав, 174d, 165Вр1, КП1В, Bilochka.

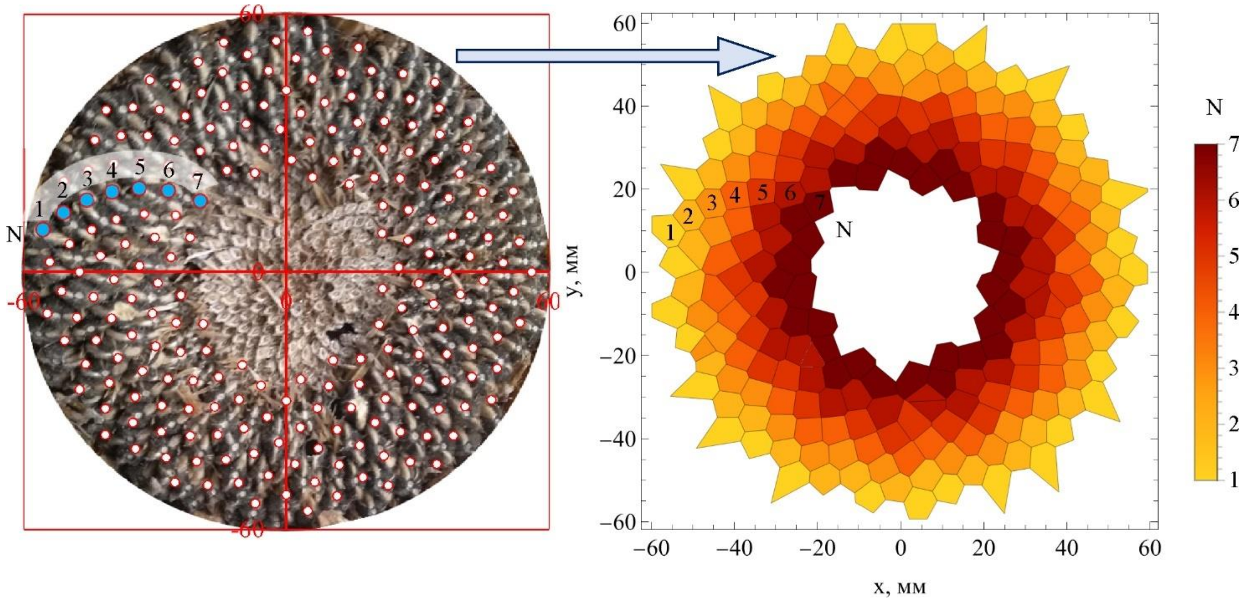


Figure 1. The selection of spirals for the distribution of sunflower seeds in a head (sample 165Bp1)

The samples were grown at the Institute of Oil Crops of the National Academy of Sciences research plots in 2022. The soil of the experimental site is ordinary chernozem, medium-strength low-humus, with humus content in the arable layer up to 30 cm - 3.5%, available nitrogen - 7.2-8.5, mobile phosphorus - 9.6-10.3, mobile potassium - 15.2–16.9 mg/100 g of soil, the pH of the soil solution is 6.5–7.0. The natural and climatic conditions corresponded to the zone of the southern Steppe of Ukraine. In general, the weather conditions of the growing season in 2022 were satisfactory for the development of sunflowers. The plot size for one sample is 14 m2, and repetition is three times. Planting and plant care was done manually.

After drying, the head is imperfectly flat and round. Therefore, the diameter of the head according to the photo was calculated using the JmageJ software package (Aliyev & Vedmedyeva, 2023) and further calculation using the formula:

$$D_{sh} = 2\sqrt{kS_{sh} / \pi} \quad (1)$$

where Dsh – is the diameter of the head; Ssh – head area in the image, pixel; k – area conversion factor, cm2/pixel.

The number of sunflower seeds in the head and their location on the photo were determined using a program developed in Wolfram Cloud (Aliyev & Vedmedyeva, 2023). The first step is to select the analysis area using the Image Crop function. The second step is to use the Color Convert function to convert the image to grayscale. After that, using Image Pad, masks were applied, and empty parts of the image were filled with black. In the third step, the Morphological Binarize function was used for the morphological binarization of the image. The coordinates of the white pixels of the image are obtained by the Component Measurements function. The fourth step is to plot points on the coordinate plane using List Plot and connect the nearest points to form spirals. The fifth stage calculates the number of obtained points (seeds) and spirals. Next, the obtained equations were approximated to the Fermat spiral equation with the golden section (Arakelyan, 2014; Aliyev & Vedmedyeva, 2023), i.e.

$$\varphi_0 = 137,5° = 2,399828$$

Considering the discrete nature of the variable n ϵ [0; 300]:

$$\begin{cases} \rho^2 = d^2\varphi, \\ \varphi = n\varphi_0, \end{cases} \Rightarrow \begin{cases} x = \operatorname{sgn}(d)|d|(n\varphi_0)^{1/2}\cos(n\varphi_0), \\ y = \operatorname{sgn}(d)|d|(n\varphi_0)^{1/2}\sin(n\varphi_0), \end{cases} \quad (2)$$

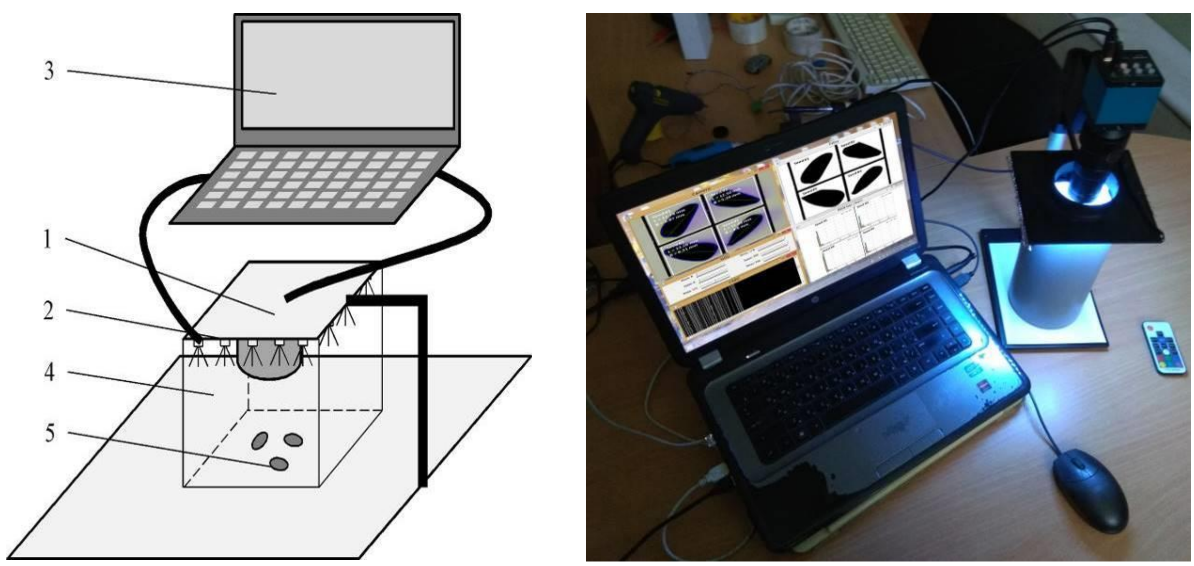
where ρ, φ – are polar coordinates, x, y – are Cartesian coordinates, n – is the number of the point (seeds in the head), φ0 – is the angle of rotation of the point (seeds in the head); d – is an empirical coefficient.

Seeds were selected from the head in a spiral, as shown in fig. 1 (Swinton & Ochu, 2016; Aliyev & Vedmedyeva, 2023). The number of spirals to be studied (repetition of measurement) was 5.

The main idea of determining the geometric dimensions of sunflower seeds consists of the obtained image of the seed and its further processing according to a particular algorithm.

The research was conducted on specially created laboratory equipment (Figure 2). It consisted of a video camera (Video Microscope Camera 1080P 16MP manufactured by Eakins), a set of LEDs (red, green, blue) and a personal computer (Aliyev, 2022). The principle of operation of the stand consists of the following stages: the operator takes out the seed from the head with tweezers, focuses the video camera, the video camera fixes the seed in a stationary position, and transfers the received data to a personal computer, where the operator saved the photo by assigning a folder and a name.

To analyze seed images, we used a program for measuring sizes and their configuration developed in Python (Vedmedyev & Tereshchenko, 2022). The first step is to convert the image of the selected rectangular area of the seed material from 24-bit (full color) to binary (black and white) using the segmentation method. This allows you to highlight the black seeds on a white background. Next, the program analyzes the photo and creates a database of the size of the seeds based on the photo image. The principle of operation of the program consists of converting a binary image into a matrix of ones and zeros



a b

1 – video camera Video Microscope Camera 1080P 16MP manufactured by Eakins; 2 – sets of LEDs of three types (red, green, blue); 3 – personal computer; 4 – protective screen; 5 - seeds

Figure 2. Scheme (a) and general view (b) of laboratory equipment for determining the geometric dimensions of seeds

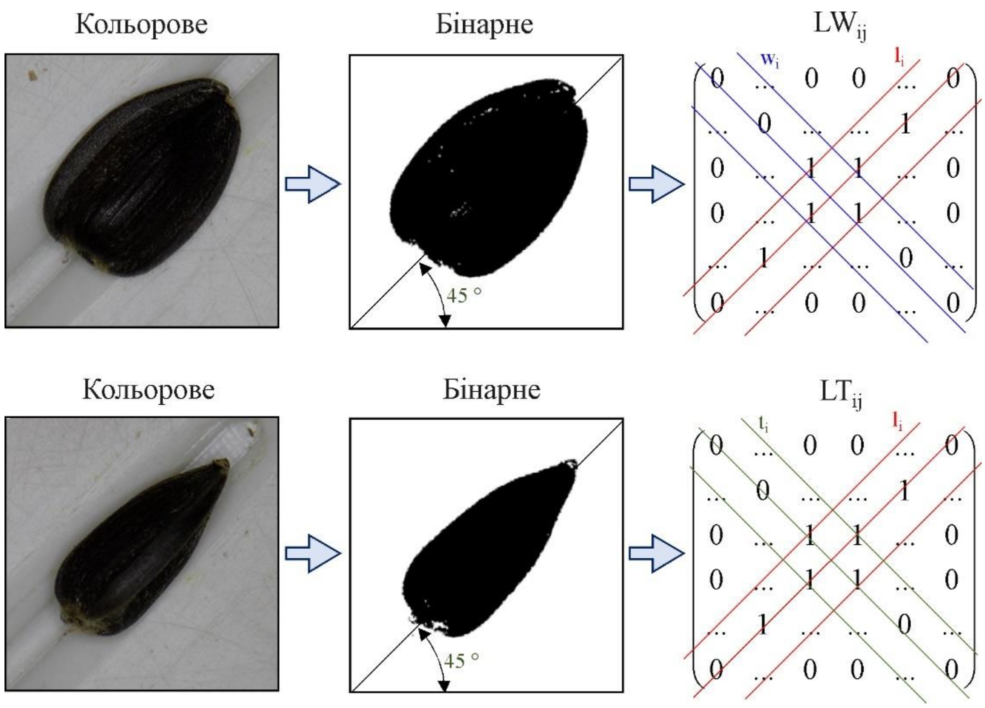


Figure 3. Stages of determining the geometric dimensions of seeds by photo

(Figure 3). Next, the matrix is transformed into a quadratic form. A data array is created to determine the length L of the seed, which stores the sum of the diagonal elements of the matrices LWij (LTij). To determine the seed's width L (thickness T), the procedure is similarly repeated for the main diagonal of the matrices LWij (LTij). Then, there is a sequential comparison of the received sums and determination of the maximum values corresponding to the seeds' geometric dimensions. The result of the work is a data table that can be processed in any table editor. For the final calculation of the geometric dimensions, it is necessary to multiply the obtained data by the calibration coefficient, which is determined using the reference sample.

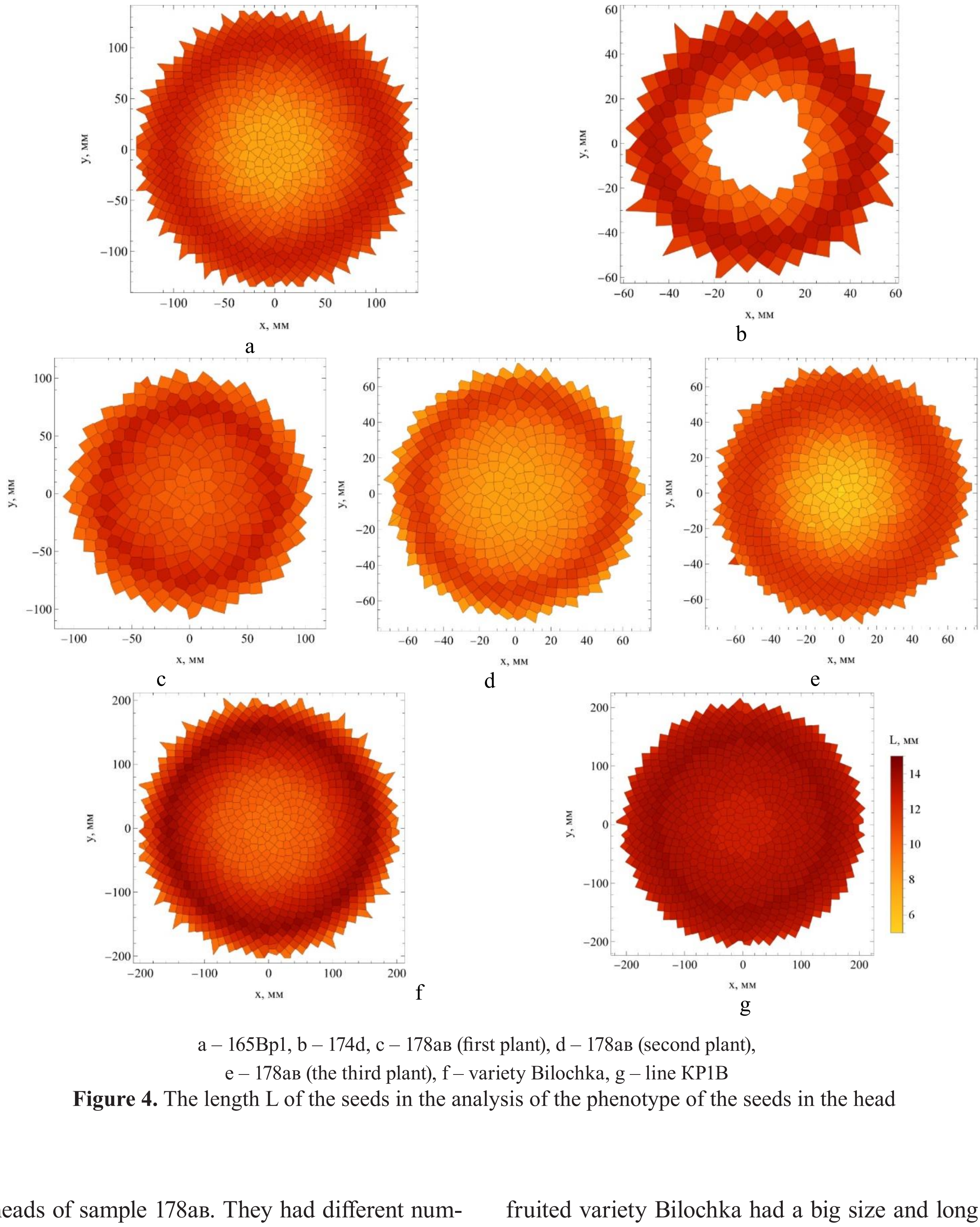
Seed mass Ms and seed kernel mass Mk were determined using JD-110/200-4 laboratory balances (Centroves, Ukraine).

Statistical processing of the obtained data in the Wolfram Cloud software package included the determination of the average, root mean square values, Student's test and coefficient of variation.

RESULTS AND DISCUSSION

The use of new methods and programs to analyze the head image showed the first visualized results. Some of them are presented in fig. 4–7. The program's capabilities allow you to separate visualize each of the characteristics of the seed: length L, width W, thickness T, seed mass Ms, kernel mass Mk. Our previous studies established that the trait of seed length is a more genetically stable component of high seed weight (Vedmedeva & Nosal, 2018). Therefore, let's start considering the results of research with the length of the seed L (Figure 4).

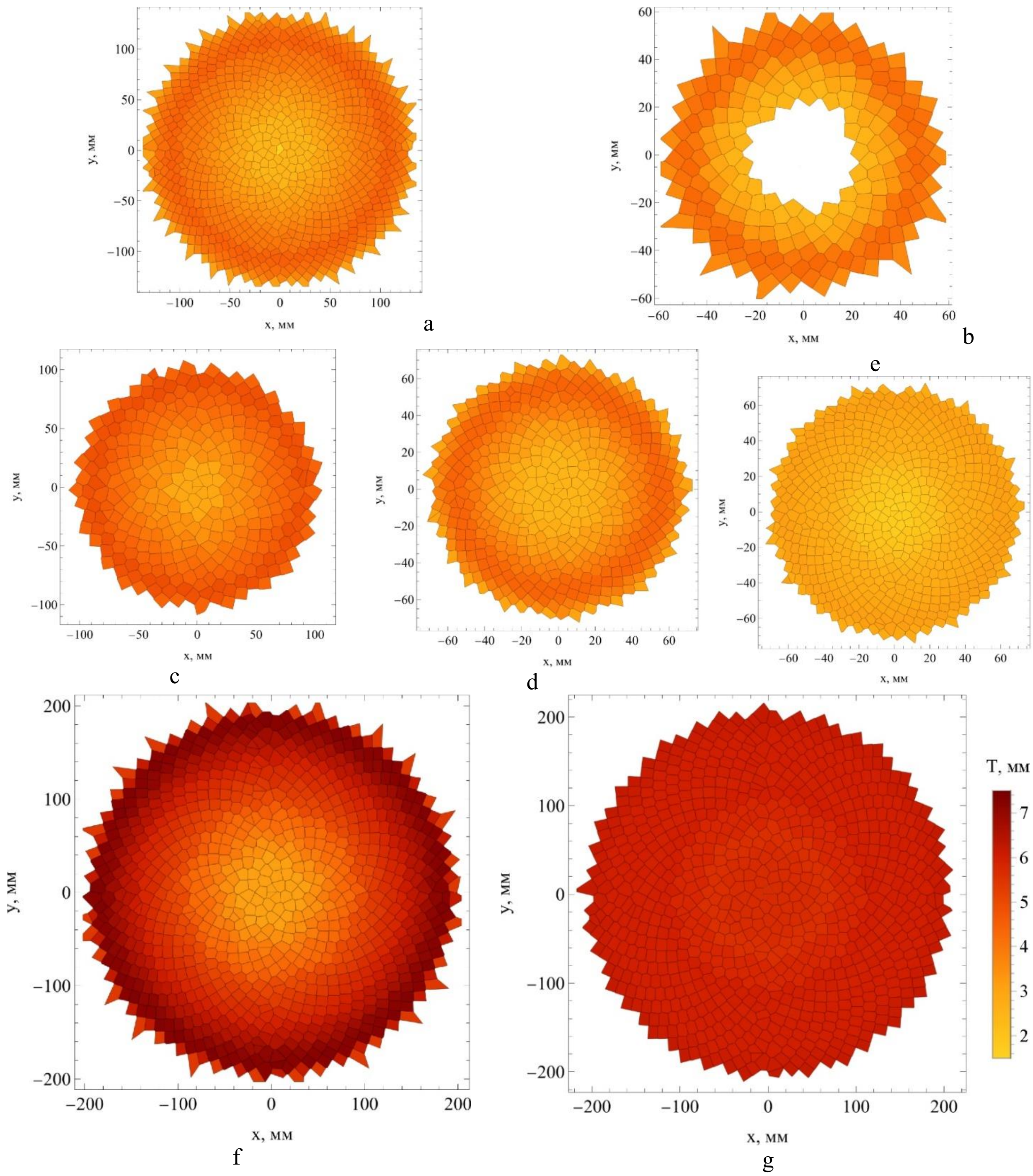
Lines 165Bp1, 174d, and 178ав measured and presented in the study are all parental and have upper branching and pollen fertility restoration genes. Line 174d differs from the others in the presence of an empty seed in the center of the head; in connection with this, a white spot appears in the middle of the head when visualized. The other two lines had almost a full head). To show the difference between individual sections and heads of the same line, figure shows 3



a – 165Bp1, b – 174d, c – 178ав (first plant), d – 178ав (second plant),
e – 178ав (the third plant), f – variety Bilochka, g – line KP1B

Figure 4. The length L of the seeds in the analysis of the phenotype of the seeds in the head

heads of sample 178ав. They had different numbers of seeds in the head and different diameters. Figure 4 shows, that the color of the head, that is, the length of the seeds in the head varies. You can observe the presence of a middle circle with the longest seed in each head. The head of the large-fruited variety Bilochka had a big size and long seeds (9.5–14.2 mm). The second zone, with the longest seeds of 13.0–14.2 mm (zone 8–16 seeds), also stands out in the Bilochka variety. The unique large-fruited maternal line of our own selection KP1B had the most giant seeds in terms of all parameters. The line's uniqueness is that there was no significant change in the length of the seeds in the head (12.2–14.0 mm). This characterizes the alignment of the seeds of one line. At the same time, it is also possible to visually distinguish the presence of head zones by the size of the seeds. The line has one more feature - during self-pollination - a lot of empty seeds are observed, which, accordingly, have only an empty husk and are smaller in size. Most likely, this is

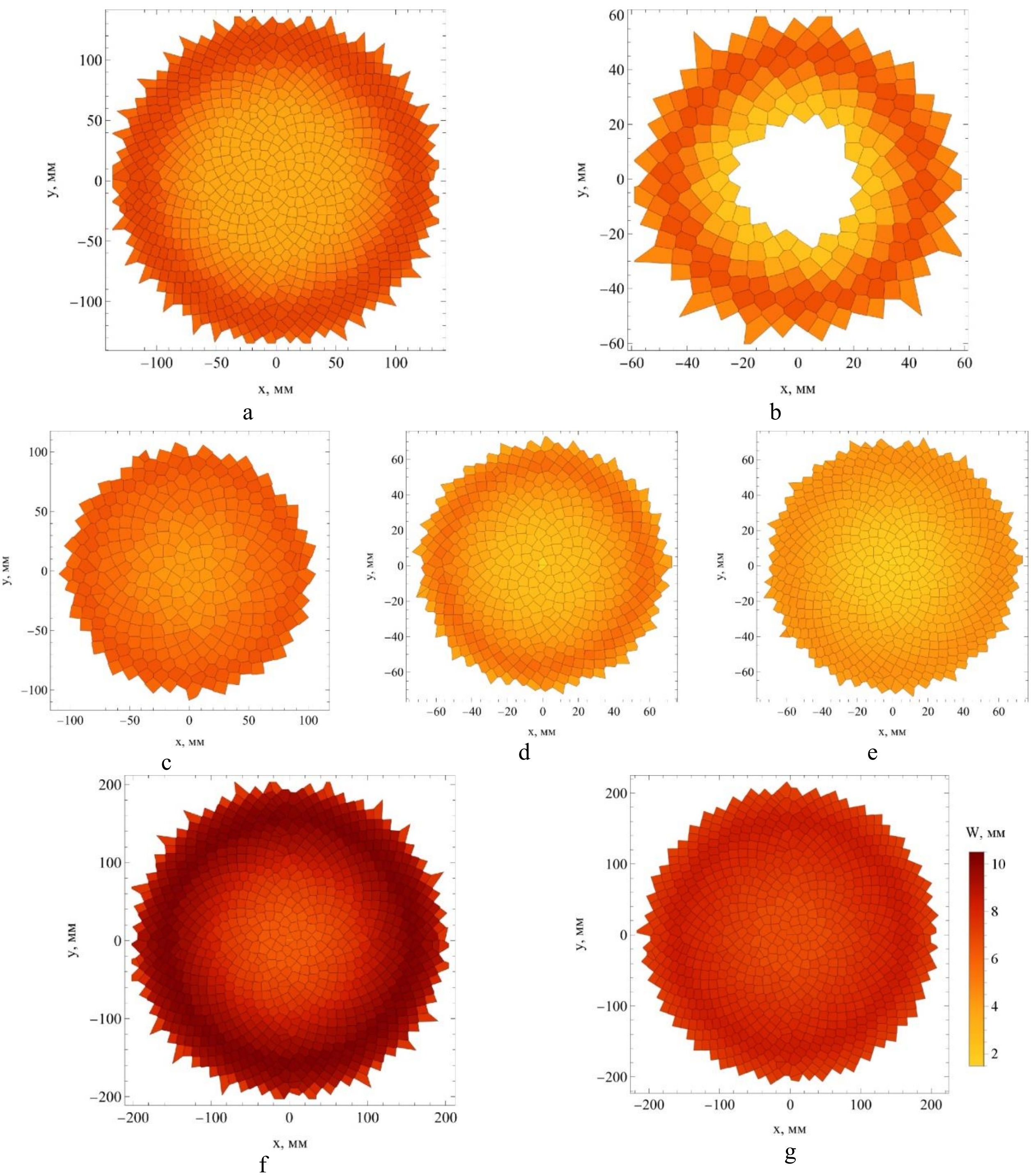


a – 165Вр1, b – 174d, c – 178ав (first plant), d – 178ав (second plant),
e – 178ав (the third plant), f – variety Bilochka, g – line KP1B

Figure 5. Seed thickness T when analyzing the phenotype of seeds in the head

an action of self-incompatibility. Measurements with obtaining completed circles can only be carried out on heads from free pollination which we used in the study.

In our previous studies (Burenko et al., 2012; Nosal′ et al., 2017), the seed thickness parameter depended more on growing conditions. Visualization of its distribution on the same heads (Fig-



a – 165Bp1, b – 174d, c – 178ав (first plant), d – 178ав (second plant),
e – 178ав (the third plant), f – variety Bilochka, g – line КР1В

Figure 6. The width W of the seed in the analysis of the phenotype of the seed in the head

ure 5) showed uniformity of color in each head of sample 178av separately. The thickness of the seeds varied between 1.7–4.9 mm. While the heads of different samples differed quite significantly from each other, no bright circles are observed in the diagrams based on the thickness of the seeds in the lines. The most extensive variety (3.1–7.3 mm) and, at the same time, the thickest seeds can be seen on the head of the Bilochka variety used in confectionery. The KP1B line has large seeds, so the 5.6–6.2 mm thickness is expectedly large. However, there is a slight change in the seed thickness in the head, which indicates the different nature of this feature compared to the Bilochka variety - where the difference was quite bright and noticeable.

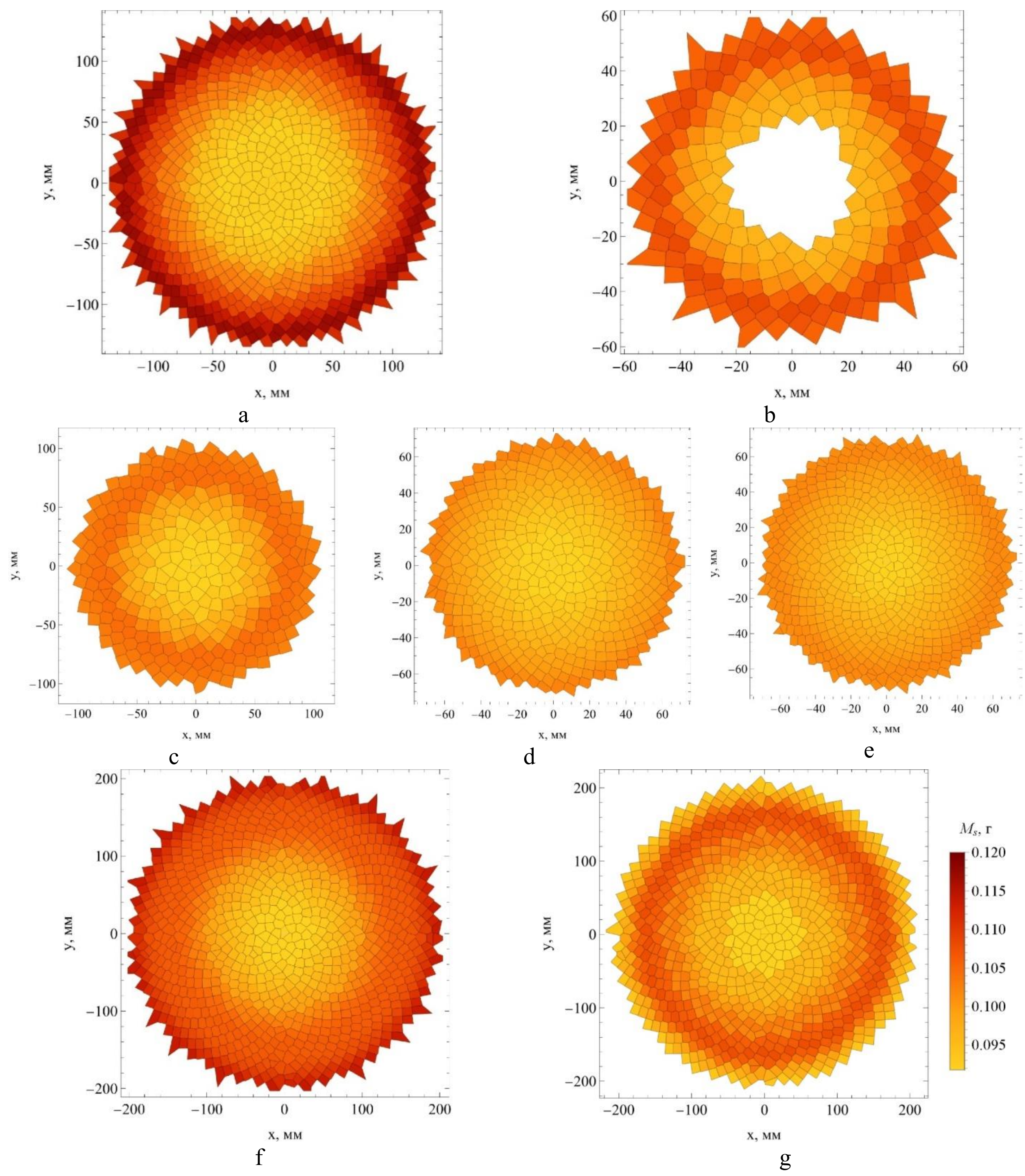
Similarly, the seeds are distributed in the head by width (Figure 6). The seed width for all samples ranged from 1.9 to 10.3 mm. Zones with a large width are observed. For example, for the Bilochka variety, this zone is located 3–17 seeds from the edge. The width of the seeds is 9.2–10.3 mm. For the KP1B line, there is a slight change in the width of the seeds in the head at a high value compared to other samples: 6.8–8.4 mm

The seed mass is the main commercial parameter of the seed phenotype, especially for confectionery use. Breeders usually use as an indicator mass of 1000 seeds. When considering the head and the individual seeds in it, we are talking about the measurements of the mass of one seed. Figure 7 visualizes this parameter in the heads of the studied samples. In the lines 165 Bp1, 174d and the variety Bilochka, we observe seeds with the largest mass on the outer edge of the inflorescence, forming a "crown". The gradient of decreasing seed mass is directed towards the center of the head. In line 178 ав, there is a decrease in seed weight from 0.069 to 0.013 g and the absence of a circle with larger seeds. The difference between the images of three heads of the same line shows that in the head with a smaller number of seeds (Figure 7, c), the seeds have a greater weight (up to 0.069 g). The mass of seeds in the center of all heads is noticeably smaller than in the outer circles. In the KP1B line, the mass change range is much smaller—0.092 g to 0.108 g. If you compare fig. 7, a–e, the circles are clearly visible only for the KP1B line (Figure 7, e). The size of the seed length in all other lines observed in this arrangement of circles.

The mass makes the main contribution to the actual value of the sunflower of the seed kernel since the husk has only a protective function. And in the field of confectionery production, only the fallen seed - its core - is used. Figure 8 presents a visualization of the heads by the mass of the seed kernel Mk. A significant difference from the visualization of seed weight and thickness is the presence of a clearly defined middle circle with the heaviest seed core on all heads. The widest circle is in the variety and line 165Vr1 (3–11 seeds, Mk = 0.044–0.064 g). A similar pattern was observed for the trait of seed length. The calculated Pearson correlation coefficient (0.84–0.95) of the traits of seed length and seed kernel mass confirms the existence of a relationship. Another trend is noted for the KP1B line: the seed kernel's mass is practically unaffected by the placement of seeds in the head. Its range of change is 0.071–0.080 g. This indicator is the largest for all heads of the studied samples.

It can be stated that observations of several samples revealed a very significant difference in some samples, in particular, the KP11B line and the Bilochka variety. They stand out with high seed kernel mass and high seed mass. However, the regularity of the location and changes in the qualities of the seeds in their heads are very different. Line KP11B has circles of change only in the length and weight of seeds and their absence in other parameters. The Bilochka variety has clearly defined circles according to most indicators

A comprehensive assessment of seeds in a head based on its visual representation and mathematical description makes it possible to group and rank sunflower samples according to their agricultural value. Thus, in previous papers on the study of the collection of large-fruited sunflower lines, the following coefficients were used: volume coefficient ($K_O = L \times T \times W$) and nature coefficient ($K_N = M_s \times 1000 \times K_O$). The coefficient of nature reflects the mass of the seed per unit volume, which illustrates the degree of its filling with the cores (Burenko et al., 2012; Nosal′ et al., 2017). Since the studies were conducted in years that differed greatly in the amount of precipitation, the corresponding coefficients of the influence of weather conditions were introduced. However, their use in the future turned out to be quite difficult, which primarily did not meet the requirements of immediate breeding selections.

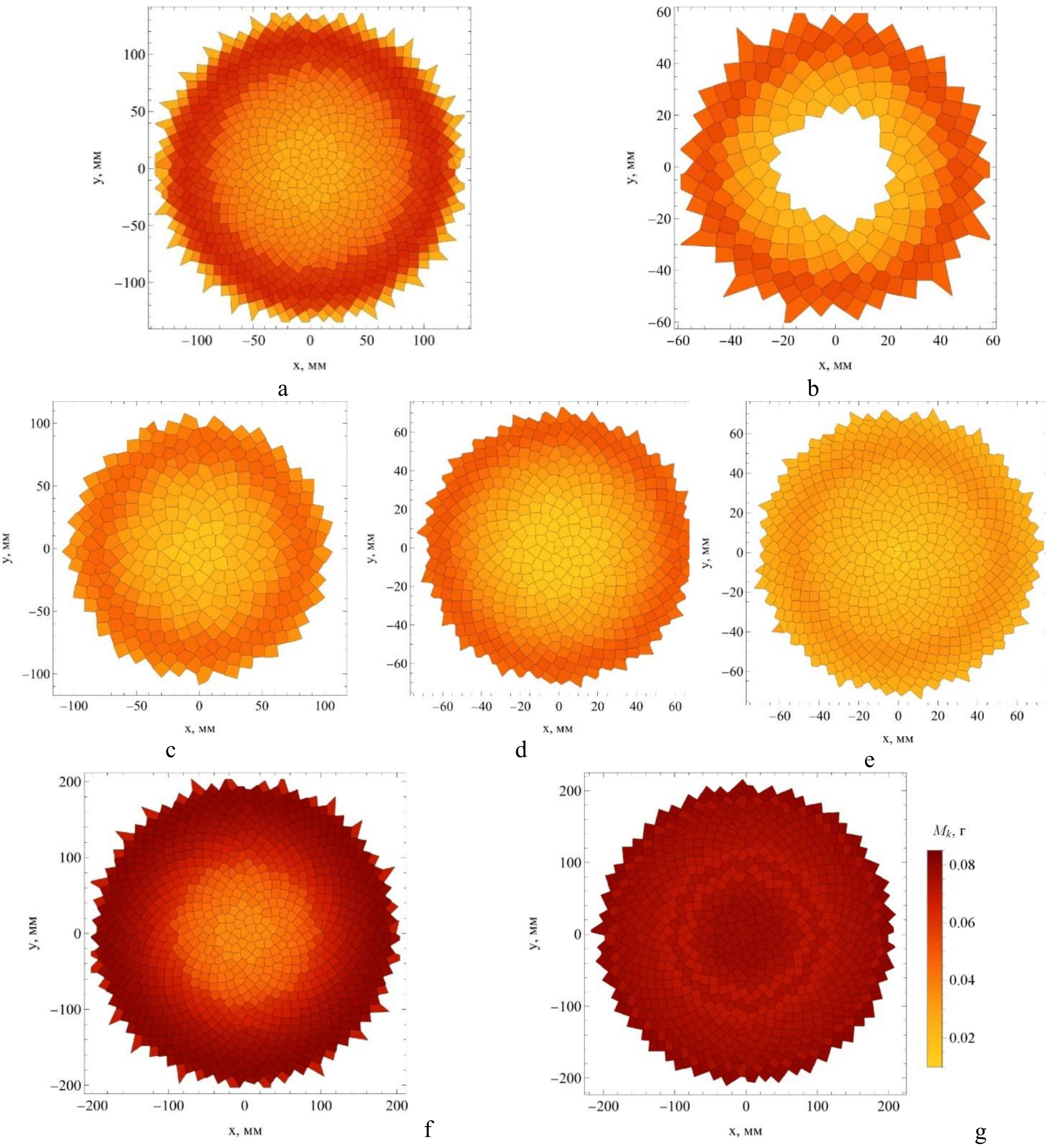


a – 165Bp1, b – 174d, c – 178ав (first plant), d – 178ав (second plant),
e – 178ав (the third plant), f – variety Bilochka, g – line КР1В

Figure 7. Seed mass Ms when analyzing the phenotype of seeds in the head

The selection of lines and varieties revealed a great variety of sizes and number of seeds in one head. Therefore, in this study, we offer a new version of a comprehensive solution for assessing the phenotypic parameters of samples.

For this, the obtained data were summarized, considering all the measured seeds of the head.



a – 165Вр1, b – 174d, c – 178ав (first plant), d – 178ав (second plant), e – 178ав (the third plant), f – variety Bilochka, g – line КР1В

Figure 8. Seed kernel mass Mk in head seed phenotype analysis

First, each parameter was ranked within a separate sample using the following formula:

$$I_x = \frac{X - \min(X)}{\max(X) - \min(X)}, \qquad (9)$$

where X is a phenotypic parameter (L, W, T, Ms, Mk); max, min – the maximum and minimum value of the parameter X within a separate sample; Ix – a coded value of parameter X (changes from 0 to 1).

Next, the complex indicator of the phenotype of seeds in head I was calculated according to the formula:

$$I = I_L I_T I_W I_{M_s} I_{M_k}, \qquad (10)$$

After the calculation, a graph of this indicator's change in the head's area was constructed. Three distinct areas were identified in which a change in the phenotype of seeds in head I was observed.

As an example of calculation, we will consider the Bilochka variety and the KP1B line. The histogram of the change in the phenotype indicator is shown in fig. 9, a–b. From the diagram, you can clearly distinguish three areas in which the phenotype of the seeds in head I is clearly different. For comparison, the distribution of phenotypic parameters of seeds is presented (in Fig. 9, a–b, marked with lines). For each parameter, performing a similar ranking by zone is visually and statistically impossible. This is evidenced by the low coefficient of variation for each parameter separately (Table 1). For the seed phenotype indicator in head I, the coefficient of variation exceeds or is close to 1.

This is more clearly observed for the KP1B line, in which the seeds have the highest level of alignment in the head (the coefficient of variation is 0.026–0.064). That is, the indicator of the phenotype of the seeds in the head I is correct (coefficient of variation – 1.014). In the future, the specified zones will be called tiers. To confirm this observation, we will superimpose Figs. 4–8 for the Bilochka variety and the KP1B line. The result of the specified action is shown in fig. 9, v–g. We also observe the separation of three tiers.

Figure 10 presents generalized information for all studied samples in the form of the fate of spiral seeds belonging to each of the selected three tiers. This information shows the presence of a clearly expressed ratio of the number of seeds in tiered heads, which is 1:1:2. This ratio is preserved, both when considering one sample 178av (by population) and for different samples, including the KP11 line and the Bilochka variety.

The results show that to reduce labor costs in future studies, the seeds from the head should be separated by tiers.

The developed method and a defined mathematical model of the location of sunflower seeds in the head make it possible to approximate the natural location of the seeds to the equation of the Fermat spiral with the golden section (2). Comparison of the obtained data with the results of world studies (Swinton, 2004; Swinton & Ochu, 2016; Borda & Bowen, 2020) emphasizes their importance and complements them.

The given method of determining the geometric dimensions of sunflower seeds based on a

Table 1. Coefficient of variation of changes in the phenotypic parameters of the seeds in the head

Samples	L	T	W	Ms	Mk	I
178ав (first plant)	0,091	0,154	0,131	0,285	0,297	1,182
178ав (second plant)	0,179	0,152	0,241	0,319	0,194	0,894
178ав (the third plant)	0,141	0,176	0,235	0,285	0,345	1,151
165Вр1	0,123	0,130	0,228	0,286	0,273	1,148
174d	0,112	0,188	0,321	0,335	0,303	1,203
variety Bilochka	0,123	0,208	0,135	0,206	0,198	0,902
КР1В	0,036	0,064	0,027	0,050	0,033	1,014

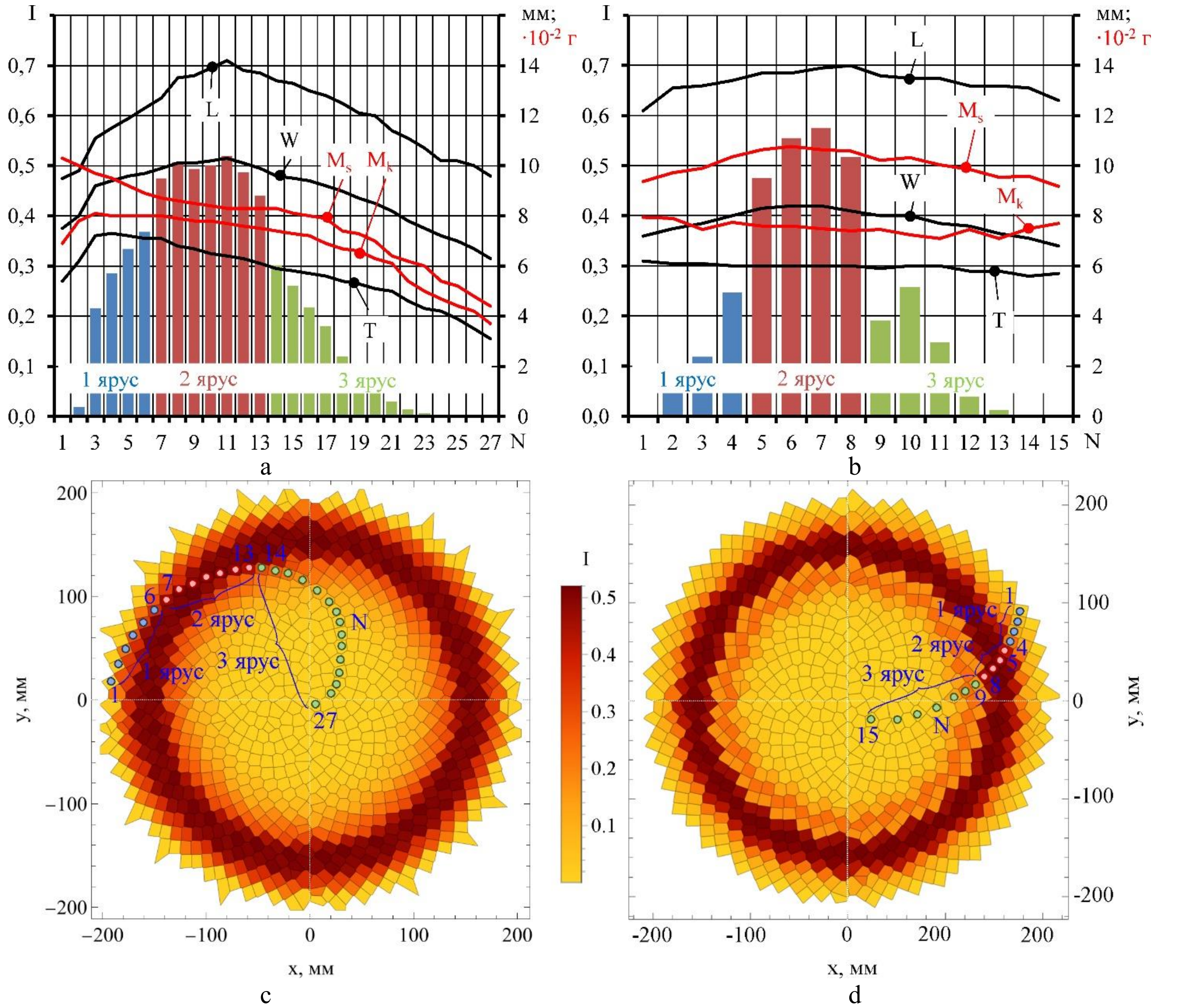


Figure 9. Distribution of the seed phenotype indicator in the head I of the Bilochka variety (a, c) and the KP1B line (b, d)

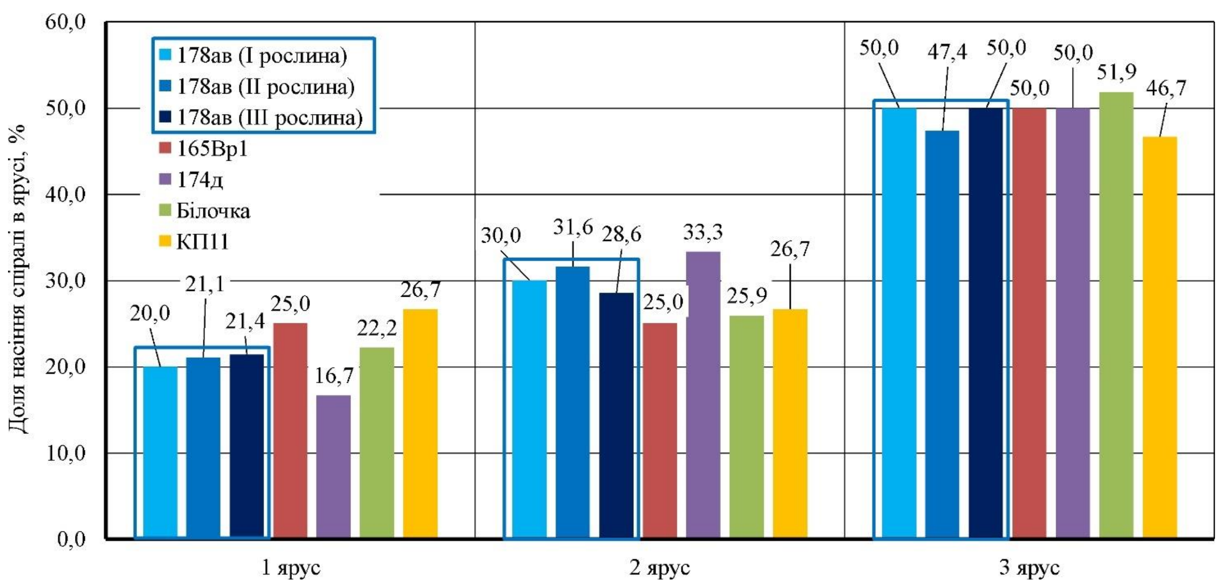


Figure 10. The ratio of spiral seeds in head tiers of different samples

photo image complements modern visualization methods (Li et al., 2014; Afonnikov et al., 2016; Lei & Sun, 2023). The matrix calculation of the geometric dimensions of seeds presented in this article (Figs. 2–3) is a fairly simple mathematical method. It ensures high accuracy in measuring the length L, width W and thickness T of the seed in a sufficiently short period of time. This allows you to automate manual work and increase the information received.

Applying the analytical-mathematical image of the head (Fig. 4–8) shows the difference in the seed according to its location on the plant. Further research, considering the growing conditions, will reveal the genetic features of the lines. But now, based on the results of the first experiments, it is clear that these genetic features exist and can be used in sunflower selection for seed size and weight. These results were partially confirmed in works (Tigay & Tereshchenko, 2017; Pérez-Vich et al., 2018). However, the presented results provide a broader picture of the head's phenotypic diversity and distributions of sunflower seeds.

As a result of the analysis of the presented research and work (Vasil'yeva et al., 2012), a hypothesis was put forward that the reason for the decrease in the size of the seeds in the center of the heads is the number of substances that come from the plant and are distributed among all the seeds of the head. Edge seedlings start growing 5–8 days earlier and are stronger competitors for assimilates. Calculations of the complex indicator of the seed phenotype in the head I (10) identified three tiers (Figure 9). Valuable large and full seeds are in the second tier, not the very first. This indicates the presence of other factors that affect the phenotype of seeds according to their location in the head. However, practical observations (Vedmedeva et al., 2023) did not make it possible to distinguish the boundaries of these tiers clearly. The proposed new approach to calculating the complex indicator of the phenotype of seeds in the head I will make it possible to establish the boundaries of the tiers in the head when applied to a larger amount of material. Separation by visual observation of the seed phenotype showed that large seeds' fate (by number) differed in different lines and hybrids. This is influenced by the fact that different samples have a different number of seeds in the head and different sizes. But in most of the previously measured samples, there was a third zone with incomplete or shallow seeds. Only the Zaporizhzhia confectionery variety (Vedmedeva et al., 2023) had greater seed uniformity, even in the central part of the head. It study took place without visualization of the head and spirals. Also, the KP11B line in this study had an almost uniform distribution (the coefficient of variation is within 0.026–0.064) of seeds in the head according to various phenotypic parameters. But even in it, according to the comprehensive indicator of the seed phenotype (I), there is a clear separation of three tiers. What is confirmed by the graph of Figure 9, a, c. These three zones have a general pattern, but the breeder's task is to find and create material that will have larger and more uniform seeds in all zones of the head.

Another interesting observation is the presence of an empty or partially empty 3rd tier, as in sample 174d. It is formed in unfavorable growing conditions and a lack of sufficient pollination. In this tier, some samples have no seeds or the presence of only a husk without a formed core. In this case, it is very difficult to determine the complete spiral of seeds in the head. As a result, we have an incomplete picture of the sample head. Therefore, in fig. 10, the histogram of sample 174d was constructed considering seeds' presence in the 3-rd tier according to the mathematical model (2), but with a zero value of the phenotypic parameters. To solve this problem in further studies, it is necessary to photograph the head at all stages of its formation. This will make it possible to investigate the dynamics of head formation and, secondly, to find out the specific reasons for the degradation of the 3-rd tier of seeds.

CONCLUSIONS

A method of determining the mathematical model of the location of sunflower seeds in a head) based on its photo image has been developed. The technique includes the following stages: converting the photo image into black and white, constructing points (seeds) on the coordinate plane and connecting the nearest ones to form spirals, counting the number of obtained seeds, spirals and approximating the resulting equations to the Fermat spiral with the golden section.

A technique for determining the geometric dimensions of sunflower seeds based on a photo image has been developed. The technique includes the transformation of the image of the seed from full color to black and white by the segmentation method, transformation of the binary image into a matrix of ones and zeros LWij (LTij), determination of the geometric dimensions of the seed using mathematical transformations of the matrix.

The distribution patterns of geometric (length L, width W, thickness T) and mass (mass Ms, kernel mass Mk) parameters of seeds in a head of different sunflower samples were studied. The variability of the phenotype of the seeds in the head, depending on its location, was established.

A set of demonstrative phenotypic characteristics of sunflower seeds I is introduced. It is defined as the product of the ranks of individual phenotypic parameters of seeds (L, W, T, Ms, Mk). The grouping of seeds in the area of the head was carried out according to indicator I. The general regularity was determined - three tiers with different phenotypic characteristics in each head. A hypothesis was put forward regarding a ratio of the number of seeds in tiered heads, which is 1:1:2 (from the edge of the head to its center).

The possibilities of visualizing the phenotype of seeds by their location in the head have been revealed. With the help of a new technique, the differences in the phenotypic characteristics of sunflower seeds in the heads of the next samples: 178ав, 174d, 165Вр1, КП1В and the Bilochka variety are shown.

The established problems of a mathematical and selection nature are related to the presence of an empty or partially empty 3-rd tier of the sunflower head, which must be solved in further research.

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