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DETERMINING PATTERNS IN THE SEPARATION OF HEMP SEED HULLS

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The subject of this study is the technological processes of separation, the hull of industrial hemp seeds, an aspiration column, and whole kernels.

The problem solved was determining the technical and technological solutions that could enable the intensification of production processes for separating industrial hemp seeds.

The separation of hemp seed hull by linear dimensions on sieves with round and elongated holes has been investigated.

It was found that the percentage of seed hulls retained by sieves with circular holes was 25.98 % for ∅3.5 mm, 23.59 % for ∅3.0 mm, and 40.28 % for ∅2.0 mm, respectively. Sieves ∅3.5 mm and ∅2.0 mm made it possible to obtain seed hulls fractions with two components conditionally different in the «mass-size» ratio.

Using sieves with elongated holes enabled obtaining fractions consisting of at least three components. Sieves with elongated working holes of 3.0×20 mm, due to their low ability (1.76 %) to retain hemp seed hull components, were ineffective.

The clogging levels of kernels in seed hulls, separated by linear dimensions on combined sieves with round and elongated holes, were as follows: separation option No. 1 – 48.70 %, option No. 2 – 45.74 %, option No. 3 – 60.25 %, option No. 4 – 49.32 %, respectively.

It was established that the use of an aspiration column made it possible to remove up to 32.1 % of clogging in the form of a light fraction. The application of the aspiration column reduced the content of seed coating in separation option No. 1 by 3.0–5.7 times, option No. 2 by 1.35–3.7 times, option No. 3 by 1.9–11.2 times, and option No. 4 by 1.5–4.8 times, respectively.

The quantitative and component composition of seed hulls fractions obtained under conditions of using an aspiration column with set rational values of the air damper opening angle $\alpha=53°$ and the vertical tilt angle of the air channel $\beta=6°$, was as follows: Stage I – «heavy» fraction – 51.78 %, 27.56 % – waste, up to 20 % – «light» fraction of Stages II and III

Keywords: hemp seeds, seed hulling, seed kernel, seed hulls separation, division by size, cleaning, aspiration column

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1. Introduction

Hemp-derived products, in particular hemp seed kernel, are actively promoted in the food market. Due to the natural biochemical composition, hemp seeds are reasonably recognized as a source of the main functional food and biologically active substances, which has a positive effect on the general condition of the human body [1]. It is worth noting that, in addition to hemp oil, the kernels of hemp seeds, which are used both in their pure form and for the production of various cold meals and drinks, are of particular interest to humans [2]. Hemp seed kernels, as an independent product, do not contain non-digestible components, so they are a more valuable food product compared to hemp seeds covered with a coat.

The process of obtaining a seed kernel consists of two independent technological operations [3]. At the first stage, the seeds are crushed, and the seed hulls is obtained. At the second stage, the seed hulls is divided into fractions (seed hulls separation). The dehulling operation involves separating the seed kernels from the coat (seed hulls). The separation process involves dividing the seed hulls into fractions for the purpose of extracting the main product – seed kernels, as well as separating waste and whole and unhulled seeds. The technological performance of crushing and separation operations is quite complex. This is due to the heterogeneity of the properties of both individual seeds and the components of hulled seeds.

The choice of principles, equipment, and separation modes of seed hull depends on the properties of its components. Differences in the physical and mechanical properties of individual components of the seed hulls are used for separation [4]. These properties include shape, linear dimensions, mass, specific mass, aerodynamic properties and buoyancy, elasticity, coefficient of friction, surface condition, etc. [5, 6].

In the practical separation of seeds, the differences in their size, mass, and buoyancy are mainly used [7]. These features are the basis of air-sieve separation, which occupies the largest share in the volume of separation of seed-grain mixtures [8].

Sieving is the process of separating loose mixtures by size on sieving surfaces – sieves. The separation process occurs due to the difference in the sizes of the particles of the mixture and the sizes of the sieve openings. As a result, two factions are formed. The first includes particles that passed through the sieve. The second – particles that remained on the sieves and left them [9]. The parameters of the cross-section, length, and mass of the particles are the signs by which they are divided into fractions [10].

The orientation of the particles above the oblong holes is important. Particles will pass through oblong holes if their major axis coincides with the major axis of the holes, and the thickness of the particles is smaller than the width of the holes [11]. It should be noted that the speed of movement of particles determines both the performance of the separation process and its efficiency [12]. As speed increases, performance naturally increases and efficiency decreases. This is due to the fact that an increase in speed leads to a decrease in the probability of sieving individual particles [13].

Under the conditions of increasing the number of holes on the path of particles, the efficiency of separation of seed mixtures could be higher. That is, increasing the length of the sieves increases the efficiency of separation [14].

However, the separation of the mixture by only one of its properties does not ensure proper separation and does not allow the mixture to be qualitatively divided into fractions. A combination of several principles is used for qualitative separation.

That is why it is urgent to search for such technical and technological solutions, the implementation of which would provide for the necessary level of efficiency of the separation processes involving industrial hemp seeds.

2. Literature review and problem statement

The separation of seed-grain mixtures by air flow depends on many factors: the shape, size, and specific weight of the particle, the operating speed of the pneumatic separation, the concentration of the mixture flow in the channel. Under such conditions, the interaction of particles in the air stream in a suspended state is taken into account. Due to the noted factors, at the same working speed, complete separation of the seed-grain mixture at the same specific mass does not occur. Part of the heavy particles falls into the light fraction, and vice versa. Therefore, in advance, to increase the accuracy and clarity of aerodynamic separation, separation is carried out according to the linear dimensions of seed-grain mixtures on sieves [15].

Work [16] noted the use of aerodynamic properties for cleaning seeds of vegetable and medicinal crops. Vegetable crops belong to plants whose seeds are characterized by various structures, shapes, sizes, and chemical composition. The authors proposed an experimental module that uses the aerodynamic properties of seeds to separate impurities [16]. However, the method is difficult to apply for the separation of the hull of hemp seeds due to the above features of the content of its fractions.

Work [17] analyzed the influence of humidity of vegetable crop seeds under the conditions of aerodynamic separation of impurities. It was noted that with an increase in the moisture content of seeds (peas, beans), the speed increases, and the density and drag coefficient decrease. However, due to objective factors (differences in the characteristics of hemp seed hulls and vegetable seeds), applying the above results in the technological processes of hemp hull separation is not advisable for economic and technical reasons.

The authors of [18] investigated the problems and technical improvement of pneumatic centrifugal separators, which are used for grain cleaning on farms. It is noted that increasing the air flow speed increases the efficiency of separation. Under conditions of increased grain supply, its efficiency decreases. The maximum efficiency and purity of separation is achieved at an air flow speed of 7 m/s and a grain supply of 6 t/h, with a spreader rotation frequency from 100 to 130 rpm. The noted method and technical means for cleaning the components of hemp seeds are not suitable. The main obstacle is the differences in the physical and mechanical properties of seed hulls and cereals.

Study [19] substantiated the design parameters and the optimal position of the edge of the rotary valve during the sorting of wheat seeds. It was established that the vertical and horizontal position of the rotary valve affected the grain separation process and increased the cleaning efficiency to 98.4 %. However, the transfer of the noted technological settings to the conditions of separation of hemp hulls will not provide the required level of efficiency. The main obstacle is the differences in grain shapes and densities.

In [20], the effectiveness of a pneumatic conical separator on bean (spherical), wheat (elongated) and buckwheat (pyramidal) seeds was investigated. It was noted that the change in humidity (from 10.1 % to 17.3 %) and air flow speed (from 18.79 to 19.56 m/s) significantly affected the quality of separation. The authors noted that depending on the type of seed and its physical properties, the rational parameters of separation change significantly. Choosing the optimal conditions for each specific mixture is the key to improving the quality of separation and minimizing seed loss. Differences in the physical and mechanical properties of hemp seeds make it impossible to use the above methods for their separation.

The authors of paper [21] determined the factors affecting the process of separation of corn seeds. Among them are the size of the seeds and the speed of rotation of the sieves. It is noted that the smaller the seed size (less than 4.8 mm) and the lower the rotation frequency (33 rpm), the better the separation process. However, the adaptation of these parameters for the separation of hemp seeds is not technically and technologically expedient. Differences in the size and speed of effective separation are the main obstacles on this path.

The authors of [22] investigated the separation of seeds of fruit crops, in particular, cherries, cherries, plums, apricots, and almonds using a vibrating sieve. It was noted that for all types of fruit crops, the best parameters of sieve oscillations are the frequency range from 200 to 500 rpm, the amplitude from 5 to 10 mm, and the angle of inclination from 0 to 20 degrees. These parameters vary depending on the type of crop, but usually provide an effective calibration of the pits. The physical-mechanical properties of hemp seed hull are significantly different from the characteristics of the above types of fruit crops. That is why it is not possible to use the above methods to separate the seed hulls.

Work [23] provides a comparative analysis of the indicators of a flat sieve oscillating in the horizontal plane on the efficiency of wheat grain cleaning. The impact of different sieve vibration modes on the quality of grain separation from impurities is considered. It was established that an increase in humidity by 1 % reduced the efficiency of cleaning machines by 2 %. Rational parameters to ensure effective separation include adjusting the vibration of the sieve taking into account the frequency and amplitude of oscillations affecting the uniform distribution of grain on the sieve. The variety of shapes and sizes of the components of the seed hulls impose objective obstacles to the standardization of the noted technical solutions for its separation. As a result of the specific physical and mechanical properties of hemp seed hulls, it is advisable to conduct more in-depth studies on the processes of their separation.

The authors of [24] evaluated the effectiveness of the rape seed separation process using a sieve with a conical separation surface that carries out a vibrating movement. It was noted that the physical properties of the components to be separated, the geometry of the separation surface, and the kinematic and functional parameters of the sieve significantly influenced the quality of separation. The specified method is difficult to apply for separation of hemp seed hull due to differences in the properties of components of hemp seed hull and rapeseed.

Sunflower seeds, among the seeds of oil crops, are the most identical in structure to hemp seeds, despite the fact that they are characterized by geometric differences in shape. Like hemp seeds, sunflower seeds are a coat (seed hulls) characterized by a fibrous structure, in the middle of which there is a seed core covered with a film [25].

Thus, the lack of defined laws of hemp seed hull separation is the main reason for the low technological and technical level of hemp production processing. The above problems are very important, their solutions will make it possible to transfer the hemp production industry to highly profitable technologies, which will ensure its competitiveness.

3. The aim and objectives of the study

The purpose of our study is to determine patterns in separating the seed hull of industrial hemp. The proposed technical-technological solutions for separating hulled hemp seed hull will make it possible to increase the selection of whole kernels from the hemp seed hull.

To achieve the goal, the following tasks were set:

– to establish the effectiveness of hemp seed hull separation according to linear dimensions on sieves with holes of round and oblong shapes;

– to establish the efficiency of hemp seed hull separation according to linear dimensions on combined sieves with holes of round and oblong shapes;

– for each degree of separation, analyze the component composition of seed hulls of four research options;

– to establish the efficiency indicators for the combined separation (by aerodynamic properties and sieves) of hemp seed hull;

– to establish the influence of the opening angle of the air damper and the angle of the vertical inclination of the air channel of the selection seed aspiration column on the component composition of seed hulls.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the technological processes of separation, the hull of industrial hemp seeds, the aspiration column, whole kernels.

The hypothesis of the research assumes that there are such technical and technological solutions, the implementation of which could provide for the necessary level of efficiency in the hull separation processes of industrial hemp seeds.

The following assumptions were accepted under the conditions of research on the hemp seed hull separation:

– all seeds have the same physical characteristics, owing to which the processes of collapsing and separation are simplified;

– seed moisture at all stages of research remains constant, which minimizes its influence on separation processes;

– all stages of separation are carried out under the same laboratory conditions without external influences, which could distort the research results;

– the efficiency of separation of dust and other small particles from the main mass of seed hulls by the aspiration column is maximum;

– feeding the seed hulls to the sieve is carried out uniformly, which ensures the uniformity of the process of separation into fractions;

– sieves for separation are characterized by perfectly precise sizes of working holes, which excludes the possibility of particles of inappropriate fractions entering.

Hemp seeds were used to obtain seed hulls without prior calibration to one size, which significantly simplified the technological chain of processing. The moisture content of the seeds was not normalized, i.e., the seeds that came from the storage warehouse of grain products were crushed.

The specified assumptions and simplifications provided the necessary accuracy and repeatability of experimental data, which made it possible to obtain reliable conclusions about the effectiveness of technical and technological solutions for the hull separation of industrial hemp seeds.

4. 2. Methodology for separating hemp seed hull according to linear dimensions

Industrial hemp seeds from the production crops at the Institute of Bask Crops were used for crushing. Seed moisture was determined in accordance with the DSTU 4138-2002 procedure using a laboratory drying cabinet. Seed moisture was W=8.8–9.2 %. The seeds were crushed without prior calibration on a centrifugal crusher [3].

The resulting seed hulls was divided into 6 components according to its component composition:

– whole kernel – a whole kernel separated from the seed coat;

– broken kernel – broken kernels separated from the seed coat (1/2, 1/4, 1/6 of the whole kernel), which in the process of separation can be separated from the main mass of the seed hulls;

– whole seeds – seeds without visible signs of crushing;

– unhulled seeds – seeds with a damaged seed coat;

– waste – seed coat, seed film, small parts of the seed kernel, which will inevitably end up in the waste during the separation process;

– dust – constituents of seeds in the form of dust.

In the process of reviewing the literature, it was established that at the first stage of the sieve-air separation technique, the separation of seed hulls is carried out using sieves. Therefore, a study was conducted to establish the nature of the behavior of the components of the hemp hull depending on the construction of the separation sieves.

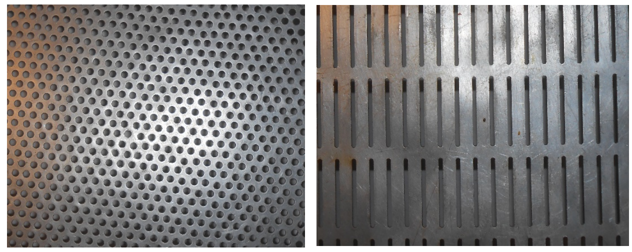
The ability of each sieve to retain and sift the components of seed hulls was evaluated owing to the ratio of the quantitative content of seed hulls at each stage separately to the initial mass of the sample.

To determine the capacity of each separate sieve, we divided the seed hulls into certain fractions. The sieves were mixed one above the other from the larger to the smaller size of the working opening. At the bottom, under the sieves, a closed vessel was installed for collecting the smallest particles of seed hulls. In this way, we got two separation modules of 7 stages, each with a different working opening.Research was carried out by disassembling a separate sample into components and determining the percentage content of each individual component. Sampling was carried out according to DSTU 4138-2002. The repeatability of experiments is fivefold. After separating the resulting seed hulls, the weight of individual components was measured and recorded. The main processing of experimental data results was performed according to [26] using the Microsoft Excel software environment. The following values were determined: mean value, standard error, variance, median, root mean square deviation, coefficients of kurtosis and asymmetry.

The test of the adequacy of the regression equations was performed first on the linear part using Fisher's test. In the case of inadequacy of the linear model, the adequacy of the incomplete quadratic equation, that is, the entire equation, was checked. It was taken into account that in order to find the variance of adequacy, the number of conducted experiments should be greater than the number of coefficients in the regression equation. The significance of the regression coefficients was assessed using the Student's test. The reproducibility of the experimental results was checked according to the Cochrane criterion.

The mean and standard error were used to assess the central tendency and precision of the outcome estimates. Variance and root mean square deviation helped determine the dispersion of the data. The median was used to estimate central tendency in the presence of possible outliers. The coefficients of kurtosis and asymmetry made it possible to estimate the shape of the data distribution and their deviation from the normal distribution. The results of the research were confirmed by the following statistical indicators. The mean and median were close, indicating no significant outliers. A small value of the standard error indicates high accuracy of the obtained data. The coefficients of kurtosis and skewness showed that the distribution of the data is close to normal.

Separation of the seed hulls according to linear dimensions was carried out on punching laboratory sieves with round holes (∅5.0; ∅4.5; ∅3.5; ∅3.0; ∅2.0; ∅1.0) and oblong holes (3.0×20; 2.5×20; 2.0×20; 1.2×20) (Fig. 1). Round sieves with offset holes and oblong sieves with straight rows of holes were used. Permissible deviations for holes of 1.0–3.0 mm were ±0.07 mm, and for holes 3.0–6.0 mm – ±0.09 mm. The sieve is manufactured in accordance with TU 23.2.2068-94 «Grain screen sieves for grain cleaning machines».



a *b*

Fig. 1. Sieves that were studied: *a* – with round holes; *b* – with oblong holes

To separate the seed hulls into fractions, sieves were placed one above the other, thus forming degrees of separation. The hemp seed hull was fed in a loose state on the top sieve. As a result of the reciprocating movement of the sieve, the seed mixture was evenly distributed over it. Such conditions contributed to the division of seed hulls into factions. The number of fractions obtained corresponded to the number of degrees of separation. The mass of a separate sample of seed hulls was 150 grams. The repeatability of experiments is fivefold. The number of oscillations for complete screening of the sample for each of the options was ≈70±10 oscillations.

The quality of sieving (1) was determined by the ratio between the number of substandard particles of the mixture (m_{ss}) to the volume of the main fraction (m_{mf}):

$$\eta = \frac{m_{ss}}{m_{mf}} \times 100\,\%. \quad (1)$$

The technological efficiency of sieving (2) was determined by the ratio of the number of impurities separated from the mixture (b) to the total number of impurities (a):

$$\varepsilon = \frac{a-b}{a} \times 100\,\%. \quad (2)$$

The choice of size and shape of the sieves was determined by the conditions of the passage of the mixture particles through their holes.

4. 3. Methodology for carrying out the separation according to the aerodynamic properties of hemp seed hulls

A Paul Polikeit (Halle/Saale) seed aspiration column was used to separate the seed hulls according to its aerodynamic properties (Fig. 2).

The aspiration column was a gravity air separator with an open vertical air cycle, which is designed to separate «light» impurities in the process of separating seed mixtures.

The aspiration column by Paul Polikeit (Halle/Saale) (Fig. 2) includes five stages of separation, which makes it possible to divide the hull of hemp seeds into fractions:

– Stage I – the whole, immobile seed hulls, the kernel;

– Stage II – kernel, coat;

– Stage III – kernel, coat, film;

– Stage IV – coat, finely ground seeds;

– Stage V – oil dust.

Note that the weight of the fraction components decreased with the increase in the stage number.

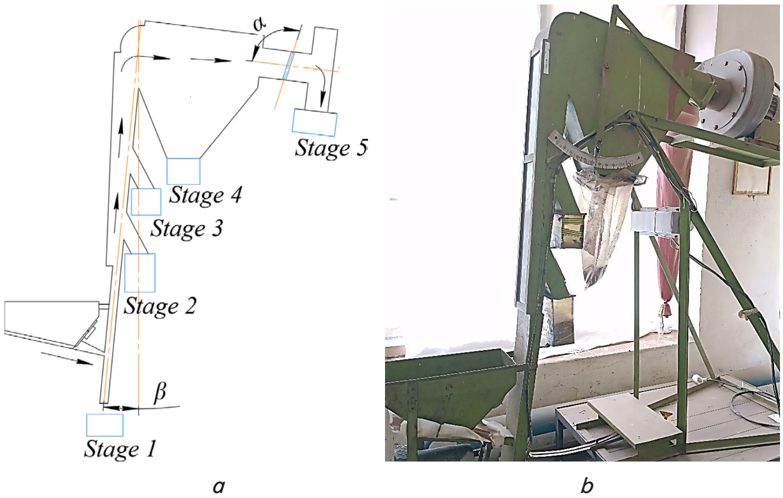


Fig. 2. Aspiration column Paul Polikeit (Halle/Saale): *a* – schematic; *b* – general appearance; α is the opening angle of the air damper; β is the angle of the vertical inclination of the air channel

In the course of research, the seed hulls was poured into a feed hopper and passed through an aspiration column. Each of the obtained fractions was analyzed by manual separation into components. The mass of a separate sample is 150 g. The repeatability of experiments is fivefold. Two fractions (IV and V) were not subjected to thorough analysis due to the fact that their components are by-products of processing.

The main processing of experimental data results was performed according to [26] using the Microsoft Excel software environment.

5. Results of experimental studies on the hemp seed hull separation

5. 1. Results of studies on the hemp seed hull separation according to their linear dimensions on sieves with round and oblong holes

The results of the distribution of fractions on the grids of the module with round holes are shown in Fig. 3, *a*.

Worth noting is the low efficiency of separation of hemp seed hull on sieves with working holes of ∅5.0 mm and ∅4.5 mm. Their ability to retain components was less than 1.0 %. Sieves with working holes of ∅1.0 mm for separating the hull of hemp seeds are also inefficient. Their ability to retain the components of the seed hulls was 7.95 %. In addition, the fraction retained on the sieve represented finely ground particles of seeds, which are difficult to separate with air flow.

Sieves with a working opening of ∅3.5, ∅3.0, and ∅2.0 mm are able to retain the largest percentage of seed hulls. Sieve ∅3.5 mm – 25.98 %, ∅3.0 mm – 23.59 %, ∅2.0 mm – 40.28 %, respectively. Sieves of ∅3.5 and ∅2.0 mm made it possible to obtain fractions of seed hulls with two components conditionally different in terms of the «mass-size» ratio, which had a positive effect on further separation by air flow.

The results of separating the seed hulls into fractions using a separation module with oblong working holes are shown in Fig. 3, *b*.

A complete separation of the hemp hull into individual components was not achieved by the separation module with oblong working holes. Unlike round sieves, where a two-component fraction was obtained, oblong holes made it possible to obtain fractions of at least three components. An exception is the 1.5×20 mm sieve, owing to which a fraction of two components conditionally different in terms of the «mass-size» ratio is obtained.

5. 2. Results of research on the separation of hemp seed hull on combined sieves

Four variants of the layout of separation sieves were studied (Table 1).

Owing to the installation of sieves one above the other, stage separation was studied. Option 1 consisted of a set of $n=5$ sieves, option 2 with $n=6$, option 3 with $n=4$ and option 4 with $n=4$ stages of separation, respectively.

It is worth noting that in the variant of separation No. 1, a fraction was obtained, which consisted of two conditionally different components (kernel and coat). Its amount was 46.56 % of the total weight of the sample. This fraction was obtained at separation Stage 4 with a working opening of ∅2.0 mm.

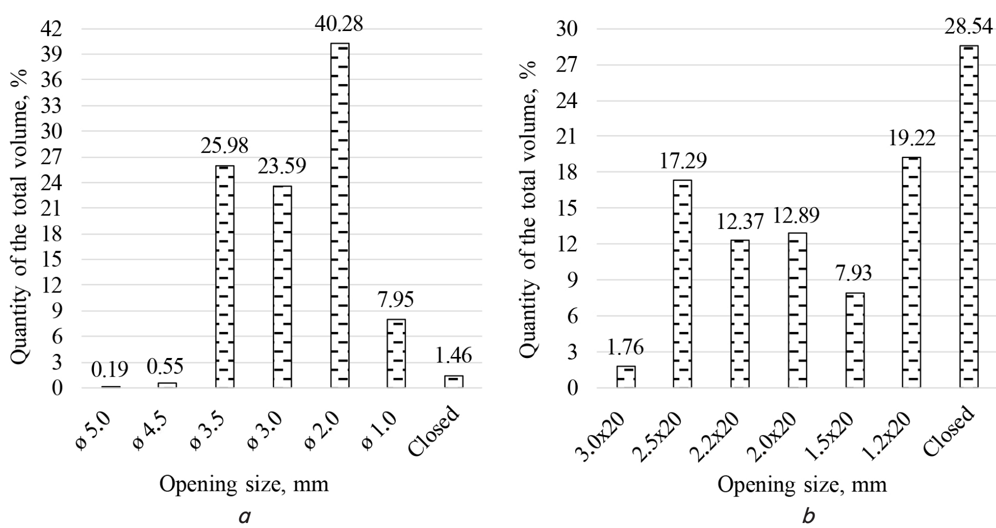


Fig. 3. Quantitative distribution of fractions of hemp hull: *a* – on sieves with working holes of round shape; *b* – on sieves with working holes of an oblong shape

Table 1

Variants to study the separation of hemp hull according to linear dimensions

Separation stage number	Size of sieves by layout options, mm			
	Variant No. 1	Variant No. 2	Variant No. 3	Variant No. 4
1	∅3.5	∅3.5	∅3.5	∅3.5
2	2.2×20	2.5×20	2.0×20	∅3.0
3	1.5×20	2.0×20	1.2×20	∅2.0
4	∅2.0	1.5×20	closed	closed
5	closed	∅2.0	–	–
6	–	closed	–	–

In the variant of separation No. 2 on Stage 5 of separation with a working opening of ∅2.0 mm, a two-component fraction (kernel and coat) was obtained in the amount of 35.16 %.

In the separation variant No. 3, fractions with three or more components were obtained at all stages of separation. Let's highlight Stage 4 of separation (harvesting container), which, in addition to the main component of separation (seed kernel), contained two components conditionally identical in terms of the «mass-size» ratio – the seed coat and finely ground seeds. Under such conditions, the finely ground seed belongs to the light fraction, which is removed by air separation.

In the variant of separation No. 4, we note Stage 3 with a working opening of ∅2.0 mm, which made it possible to obtain a two-component fraction in the amount of 35.21 %.

In the three investigated options, the two-component mixture was obtained at stage with a working opening of ∅2.0 mm.

5. 3. Results of studying the component composition of seed hulls in four research variants at each separation stage

At the next stage, an analysis of the quantitative composition of the components of seed hulls in a separate obtained fraction was carried out. Analysis of the components of the seed hulls was carried out for each separation stage for four research options. Seed hulls was divided into 6 components: whole kernel, destroyed kernels, whole seed (whole), and unhulled seed (undercut), seed coat and seed film (light fraction), waste (finely ground seed and dust).

The results of analyzing the quantitative composition of seed hulls components for separation options No. 1–4 are shown in Fig. 4–7; the results of statistical data processing are given in Tables 2–5.

Analyzing the given results (Fig. 4–7, Table 2), we note that most separation degrees are characterized by quantitative dominance in the composition of the fraction of one component of the seed coat (coats, unhulled seeds, seed kernels). The only exception is only Stage 4 of separation (option No. 1) and Stage 3 of separation (option No. 2), in which, in addition to the main component (kernels or unhulled seeds), the same number of coats are present. In all the obtained fractions, with the exception of the main component, other components are present, in different volumes, as well as other components.

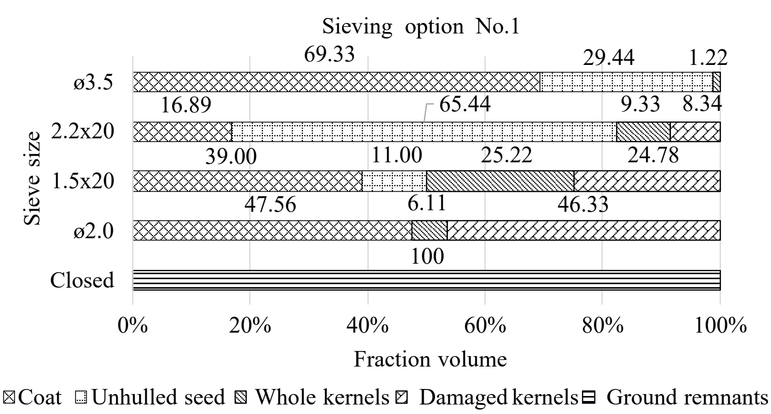


Fig. 4. The quantitative content of seed hulls components according to the stage of separation in separation option No. 1

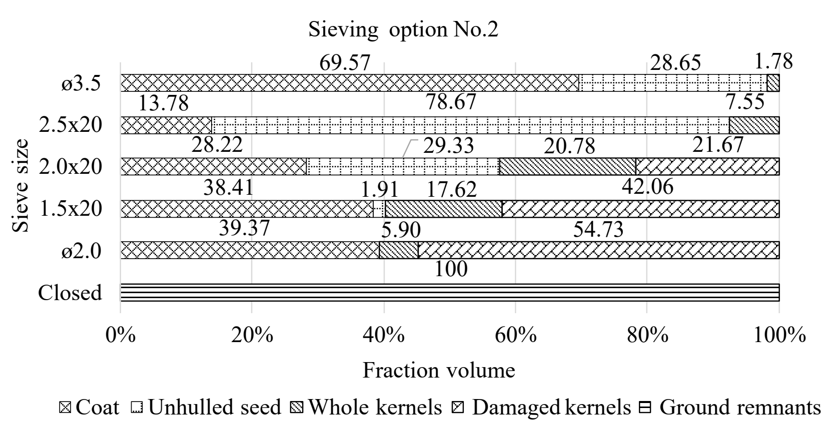


Fig. 5. The quantitative content of seed hulls components according to the stage of separation in separation option No. 2

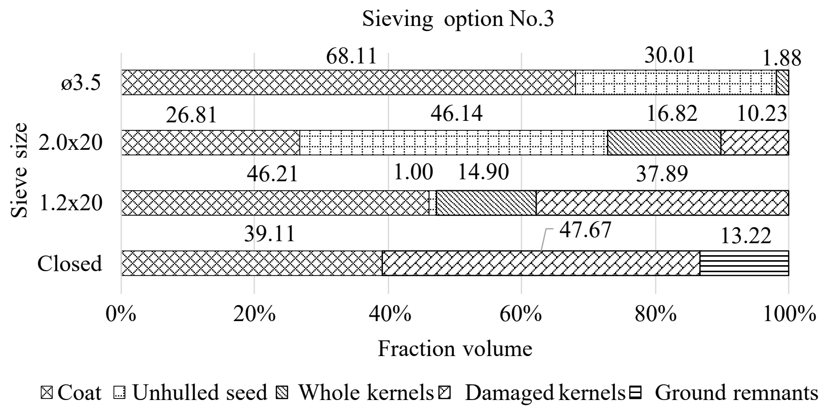


Fig. 6. The quantitative content of seed hulls components according to the stage of separation in separation option No. 3

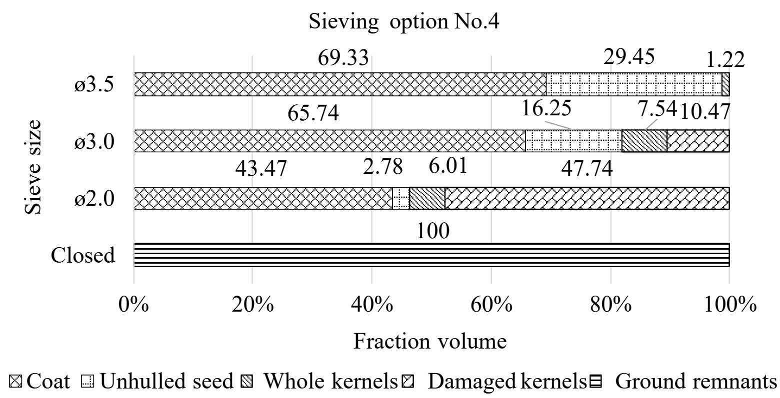


Fig. 7. The quantitative content of seed hulls components according to the stage of separation in separation option No. 4

Table 2

Results of statistical processing of the quantitative content of components of seed hulls by separation stages (separation option No. 1 without the use of air)

Indicator	Component ID				
	Coat	Unhulled seed	Whole kernels	Damaged kernels	Ground remnants
∅3.5 mm					
Average value	69.33	29.44	1.23	–	–
Mean square deviation	0.126	0.084	0.208	–	–
Dispersion	0.016	0.007	0.043	–	–
Median	69.330	29.443	1.223	–	–
The coefficient of kurtosis	–0.755	–1.147	–0.949	–	–
Asymmetry coefficient	–0.603	–0.291	0.567	–	–
2.2×20 mm					
Average value	16.89	65.44	9.33	8.34	–
Mean square deviation	0.074	0.086	0.102	0.254	–
Dispersion	0.006	0.007	0.010	0.065	–
Median	16.890	65.440	9.370	8.340	–
The coefficient of kurtosis	–1.157	–0.895	–0.252	–0.617	–
Asymmetry coefficient	–0.331	0.000	–1.057	0.567	–
1.5×20 mm					
Average value	39.00	11.00	25.22	24.79	–
Mean square deviation	0.068	0.093	0.124	0.148	–
Dispersion	0.005	0.009	0.015	0.022	–
Median	39.000	11.000	25.220	24.770	–
The coefficient of kurtosis	–0.530	–0.768	–0.699	–0.336	–
Asymmetry coefficient	–0.462	–0.434	–0.383	0.842	–
∅2.0 mm					
Average value	47.56	–	6.11	46.33	–
Mean square deviation	0.072	–	0.104	0.063	–
Dispersion	0.005	–	0.011	0.004	–
Median	47.560	–	6.110	46.300	–
The coefficient of kurtosis	–0.741	–	–1.608	–0.169	–
Asymmetry coefficient	0.725	–	–0.029	1.170	–

5. 4. Results of studying hemp seed hull separation by aerodynamic properties

As it was established, all the fractions obtained in the separation process for the four variants of the study contain a certain percentage of seed coats. The next stage of our research was to establish the clogging of the seed hulls with coats, depending on the layout of the separation techniques. A combination of air flow and screen separation methods was used. A selection seed aspiration column of the Paul Polikeit brand (Halle/Saale) was used to separate seed hulls according to its aerodynamic properties. After that, sieving was carried out on sieves for four separation options: No. 1 – n=5, No. 2 – n=6, No. 3 – n=4, and No. 4 – n=4. The program and methodology of research is similar to the above. For separation by linear dimensions, seed hulls of three fractions (I, II, and III) was used, which had previously been passed through an aspiration column. Before sieving, the seed hulls fractions were mixed to a homogeneous loose state.

It was established that the use of an aspiration column made it possible to remove up to 32.1 % of debris in the form of coats, seed films, finely ground seeds, and oil dust from the seed hulls. Given this, the component composition of the seed hulls has been significantly changed and the prerequisites for its further separation have been created.

Preliminary separation of seed hulls in the air flow in all four research options does not ensure its complete qualitative separation into separate components. By comparing the obtained results of the component composition of the fractions, the coincidence of the components of the seed hulls for the corresponding degree of separation was established. In the case of using preliminary air separation, a change in the percentage distribution of fractions at the corresponding stages was established. As in the first series of experiments, the largest number of seed kernels was obtained at the lower separation stages: Stage 4, 5, 4, and 3 for research variants No. 1, No. 2, No. 3, and No. 4, respectively. The largest number of fractions (39.33 %) was obtained for separation option No. 1, Stage 4. As in the first series of experiments, separation option No. 3 turned out to be less effective.

Fig. 8–11 show the results of component analysis of fractions for separation options No. 1, No. 2, No. 3, and No. 4; the results of statistical data processing are given in Table 3. The program and methodology of conducting research coincide with the above.

It should be noted that the use of an aspiration column increased the purity of the obtained fractions (Fig. 8–11, Table 3). As in the first series of experiments (Fig. 4–7), at most levels of separation, one specific component of the seed hulls was quantitatively predominant in the composition of the fraction. However, in our studies, not three predominant components (coats, seeds, kernels) were obtained but only two (seeds, kernels). In all the obtained fractions, in addition to the main component, other components are present, in varying amounts.

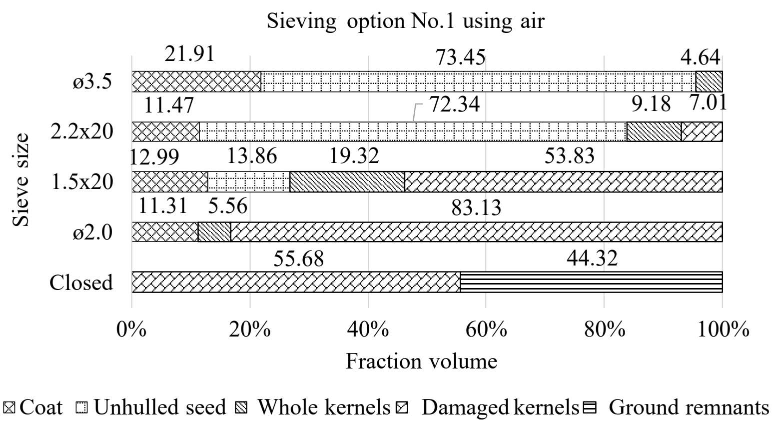


Fig. 8. Quantitative content of seed hulls components according to separation stages in separation option No. 1 with the previous use of an aspiration column

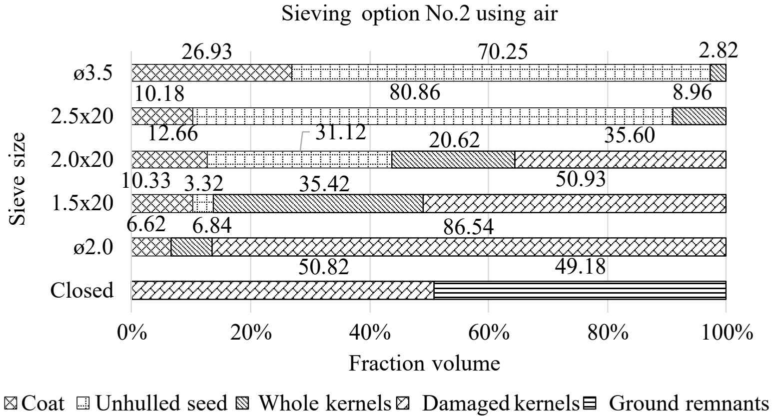


Fig. 9. Quantitative content of seed hulls components according to separation stages in separation option No. 2 with the previous use of an aspiration column

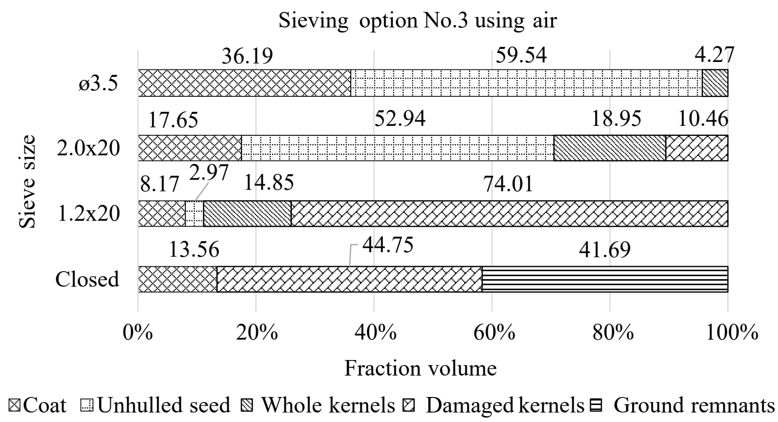


Fig. 10. Quantitative content of seed hulls components according to separation stages in separation option No. 3 with the previous use of an aspiration column

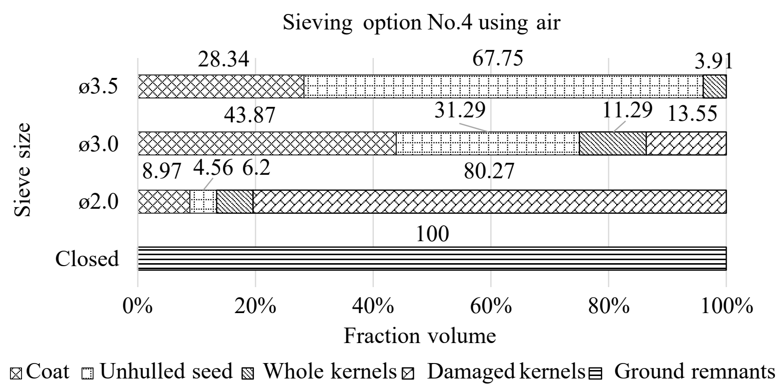


Fig. 11. Quantitative content of seed hulls components according to separation stages in separation option No. 4 with the previous use of an aspiration column

Table 3

Results of statistical data processing of the quantitative content of seed hulls components by separation stages (separation option No. 1 using air)

Indicator	Component ID				
	Coat	Unhulled seed	Whole kernels	Damaged kernels	Ground remnants
∅3.5 mm					
Average value	21.91	73.45	4.64	–	–
Mean square deviation	0.081	0.105	0.118	–	–
Dispersion	0.007	0.011	0.014	–	–
Median	21.910	73.450	4.640	–	–
The coefficient of kurtosis	–1.040	–1.535	–0.673	–	–
Asymmetry coefficient	0.051	0.000	0.724	–	–
2.2×20 mm					
Average value	11.47	72.34	9.18	7.01	–
Mean square deviation	0.109	0.060	0.107	0.162	–
Dispersion	0.012	0.004	0.011	0.026	–
Median	11.470	72.340	9.180	6.980	–
The coefficient of kurtosis	–1.419	–1.494	–1.242	–0.245	–
Asymmetry coefficient	–0.022	0.059	–0.340	1.126	–
1.5×20 mm					
Average value	12.99	13.86	19.32	53.84	–
Mean square deviation	0.068	0.077	0.080	0.075	–
Dispersion	0.005	0.006	0.006	0.006	–
Median	12.990	13.860	19.320	53.830	–
The coefficient of kurtosis	–1.379	–0.863	–1.147	–1.323	–
Asymmetry coefficient	0.224	0.282	0.173	0.192	–
∅2.0 mm					
Average value	11.31	–	5.56	83.13	–
Mean square deviation	0.087	–	0.140	0.100	–
Dispersion	0.008	–	0.020	0.010	–
Median	11.310	–	5.560	83.130	–
The coefficient of kurtosis	–1.535	–	–0.644	–1.218	–
Asymmetry coefficient	–0.069	–	–0.407	0.295	–

Analysis of the results of seed hulls separation (Fig. 8–11) established the following level of clogging of seed kernels: in the separation option No. 1 – 19.07 %, option No. 2 – 21.35 %, option No. 3 – 32.10 %, option No. 4 – 20.18 %, respectively. Note that all fractions obtained after separation contain seed coats in their composition in a much smaller amount than in the results of the first series of experiments (Fig. 9–12): in the separation option No. 1 – 3.0–5.7 times, in the option No. 2 – 1.35–3.7 times, variant No. 3 – 1.9–10.2 times, variant No. 4 – 1.5–4.8 times, respectively.

According to separation option No. 1 (Stage 4, ∅2.0 mm), hemp kernels with a clogging of 11.31 % were obtained. The clogging consisted of impurities in the form of seed coats, which belong to the «light» fraction. In separation variant No. 4 (Stage 3, ∅2.0 mm), hemp kernels with a clogging of up to 13.53 % were obtained. Under such conditions, 4.56 % of the mixture consisted of the «heavy» fraction (whole and unhulled seeds), the rest – the «light» fraction in the form of seed coats.

5. 5. Results of research on the influence of parameters of the aspiration column on the hemp seed hull separation

Aerodynamic separation was carried out in the pneumatic channel of a selection seed aspiration column by Paul Polikeit (Halle/Saale) with vertically directed air flow. The separation of the components occurred as a result of the difference in the buoyancy of individual components and their floating speeds. The amount of air flow was adjusted by changing the value of angle α – the opening angle of the air damper (Fig. 2). The angle α was varied within 0–100°. For the convenience of research, the indicator «valve opening angle» was used, which was set in natural values on the aspiration column. The research range of the air damper opening angle was 40°, 45°, 48°, 50°, 53°, 55°, 60°, respectively.

The results of studies on hull separation according to aerodynamic properties are shown in Fig. 12.

Changing the opening angle of the damper led to a corresponding change in the component composition of fractions (Fig. 12). As the angle increases, the separation efficiency decreases. A decrease in the value of the angle (α=40°) led to an increase in kernel losses.

Based on the component composition, rational values of the opening angle of the air damper were established for each obtained stage. For Stage I, the rational angle is defined as α=48°. Under such conditions, a two-component mixture (kernels and whole grains) was obtained, which created the prerequisites for simplified processes of further separation of the mixture according to linear dimensions. For Stage II, the rational angle is defined as α=50°. Under these conditions, a two-component mixture with the maximum content of kernels was obtained. Such indicators made it possible to simplify the following processes of aerodynamic separation. For Stage III, the rational angle is defined as α=50°, for which a two-component mixture (coats and kernels) was obtained. For Stage IV, the rational angle is defined as α=53°. At this value of the angle, no removal of kernels into the waste was observed.

The minimum necessary value of the angle is taken at the level of α=53°. Under such conditions, the air separation of hemp hull was carried out with the selection of «light» fractions without loss of the main product – kernels. It should be noted that at the above value of the angle, there was no significant change in the indicators of separation efficiency at all stages. Only at Stage 1, the number of coats increased by 1.65 %, and at Stages 2 and 3, the component composition of the fractions changed only in percentage.

The main factors affecting the quality and efficiency of separation include the angle of the vertical inclination of the air channel β (Fig. 2). The value of the angle depends on the strength of resistance of the particles of seed hulls, which affects the final composition of the fraction. The ranges of changing the angle of the vertical inclination of the air duct under investigation were 0°, 3°, 6°, 9°, respectively. The research was carried out at the value of the opening angle of the air damper α=53°. Under such conditions, the feasibility of analyzing separation Stage IV (waste) was ruled out. The results of the research are shown in Fig. 13.

Analyzing the research results (Fig. 12, 13), we note the high value of the correlation coefficients, which indicates a strong correlation dependence of the values that unite them.

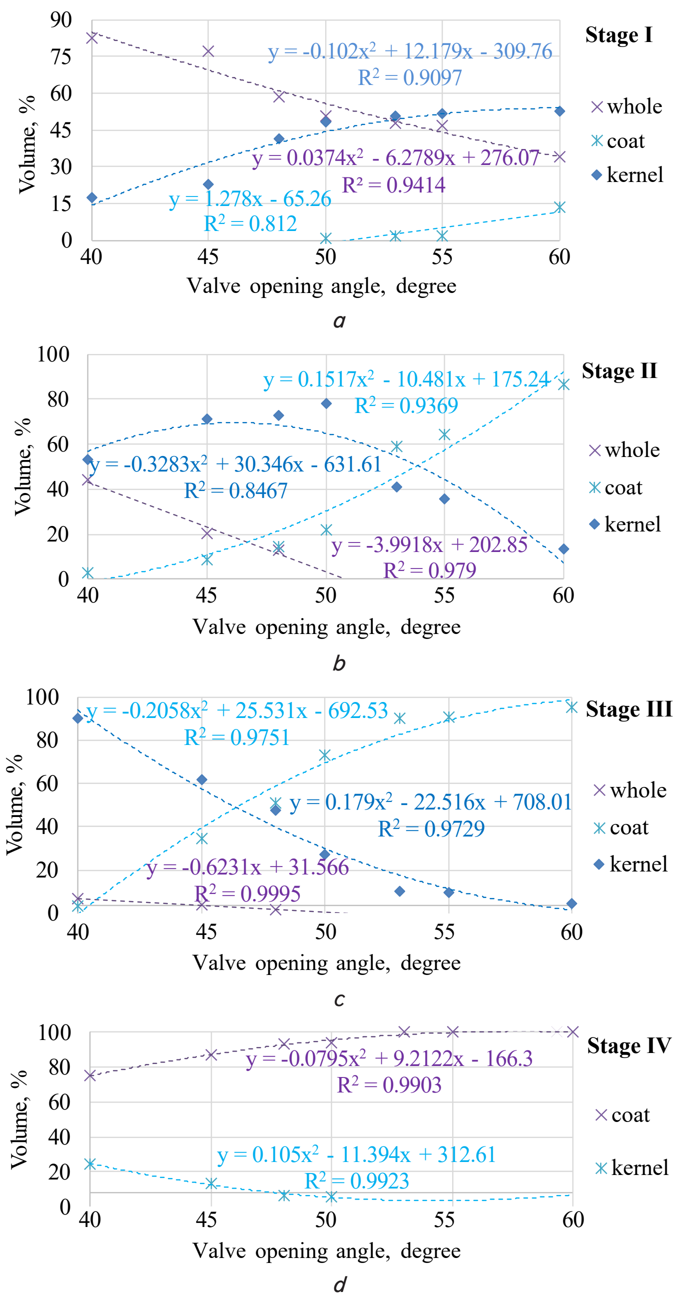


Fig. 12. Component composition of seed hulls at the stages of separation in the aspiration column: *a* — Stage I; *b* — Stage II; *c* — Stage III; *d* — Stage IV

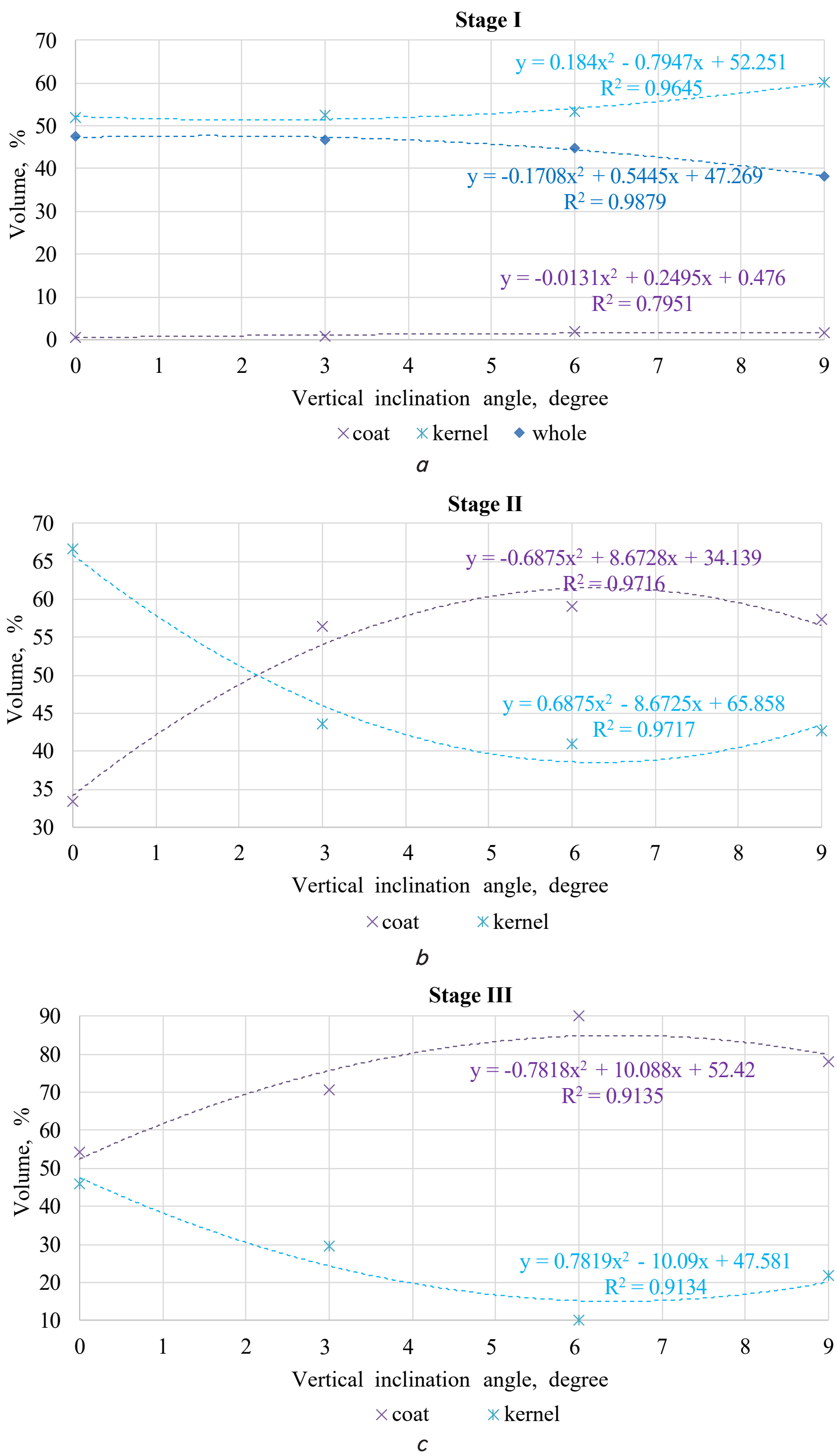


Fig. 13. Component composition of seed hulls at the stages of separation in the aspiration column: *a* – Stage I; *b* – Stage II; *c* – Stage III

Worth noting is the lack of influence of changing the value of the angle of vertical inclination β on the final result (Fig. 13) of the first stage («heavy» fraction). The fluctuation of the number of kernels in the experiment was within 10 %. An increase in the angle β led to a corresponding increase in the number of kernels. Under such conditions, the number of whole and unhulled seeds decreased. The angle β=9° is a rational value for which a mixture with the maximum content of kernels is obtained. The achieved indicators made it possible to separate the mixture according to linear dimensions under the conditions of further research.

Analysis of the composition of the fraction, which was obtained at Stage II, revealed that the angle β=6° is rational. Under such conditions, a two-component mixture with the lowest content of kernels was obtained.

Based on the results of analyzing our findings at Stage III, the content of the mixture, which included coats and a certain number of kernels, was established. We note that the mixture containing the smallest number of kernels for β=6° was considered the most rational.

At the second and third stages of separation, we received the «rehulling» fraction. This fraction represented a seed mixture that could not be separated in one pass. Under such conditions, it was sent for re-separation. Achieving the minimum content of hemp kernels in the mixture of «rehulling» simplified further technological operations of separation on sieves. Under such conditions, the angle β=6° is accepted for Stages II and III. The component composition of the fraction of the first stage did not change significantly, which did not affect the final result of the separation.

The results of our studies on the quantitative and component composition of the mixture at each separation stage in the aspiration column at the rational values of the opening angle of the air damper α=53° and the angle of vertical inclination of the air channel β=6° are given in Table 4.

Table 4

Quantitative and component composition of fractions obtained in the aspiration column

Stage No.	Fraction ID	Characteristics of the components of seed hulls remaining at the separation stage	Amount of mixture per stage of the total mass, %
1	«heavy»	Whole and unhulled seeds, whole kernels, destroyed kernels, seed coat	51.78
2	«light»	Kernels destroyed, kernels intact, seed coat	10.23
3	«light»	Seed coat, destroyed kernels, seed film	9.37
4	waste	Seed coat, finely ground parts of seeds	27.56
5	dust	Particles of seeds of the dust fraction	1.06

Analyzing separation results according to separation stages in Table 2, we note that 51.78 % was Stage I – the «heavy» fraction, 27.56 % was waste, and up to 20 % was the «light» fraction of Stages II and III.

6. Discussion of results of research on the hemp seed hull separation

Separation of hulled kernels of hemp seeds by separation methods is a complex, multi-functional process. The technological operations of separation of seed hulls belong to the determining systems in technologies for the production of hemp products. The complexity of the processes of seed hulls separation, as a mixture of a number of components that fill it, is due to certain factors. The most decisive are the coincidence of the physical and mechanical characteristics of the components in the mixture. That is, components with different purposes are characterized by similar ranges of properties. This significantly complicates the process of separating hemp seed hulls. Under such conditions, the separation factor at the level of 55–60 %, which is achieved under the conditions of separation of sunflower seed hull, for hemp seed hull is a desirable indicator in the near future.

It is worth noting that a combination of two operations is used to separate sunflower hulls. First, the seed hulls are divided according to linear dimensions with the help of sieves. Five sieves (∅7.0 mm, ∅6.0 mm, ∅5.0 mm, ∅4.5 mm, ∅3.0 mm) make it possible to obtain six fractions. At the second stage, all fractions are separated in the inclined air flow, using the factor of difference in their aerodynamic properties [25].

With the help of round sieves, a complete separation of hemp hulls into individual components was not achieved. Seed hulls fractions were obtained, which consisted of at least two components. These components can be both conditionally the same in terms of the «mass-size» ratio (whole kernels and whole and unhulled seeds), and different (damaged kernels and coats). At all sieving stages, the fraction included the seed coat in varying amounts. Similar results were obtained by separating sunflower seed hulls.

Under the conditions of linear size seed hulls separation, the fractions tend to obtain fractions of a maximum of two components, which conditionally differ in terms of the «mass-size» ratio. For example, a kernel-coat, or a seed-coat. This facilitates the separation of the fraction into components during subsequent air separation.

It is worth noting (Fig. 3, *b*) that the nature of the distribution of the components of the seed hulls on separate sieves differs from the distribution on sieves with round working holes (Fig. 3, *a*). With the exception of the first and fifth stages, the seed hulls were more or less evenly distributed over the sieves of the separation module. Sieves with working holes of 3.0×20 mm, due to low (1.76 %) ability to retain components (Fig. 3, *b*), are ineffective for separating hemp seed hulls.

Worth noting is the different total capacity of the studied separation modules. Sieves with round working holes, in contrast to oblong sieves, separated mixtures more accurately. For example, the fraction (collection tare) under the conditions of using round sieves consisted of waste that was not subject to further processing. Under the conditions of using oblong sieves, the last fraction (collection tare) contained, in addition to waste, the main product of separation – the seed kernel.

The use of each separation option (Fig. 4–7) made it possible to obtain seed kernels of the following clogging: option No. 1 – 48.70 %, option No. 2 – 45.74 %, option No. 3 – 60.25 %, option No. 4 – 49.32 %, respectively. Impurities in the form of coats in all the studied variants prevailed over other components of the clogging products. The smallest clogging was obtained with the number of separation stages $n=6$, the largest – with the number of separations $n=4$. It is worth noting that option No. 2 was characterized by the largest number of separation stages (6), which naturally led to a corresponding increase in metal capacity and the size of the separating mechanism.

At the first separation stage, it is suggested to carry out aspiration of seed hulls. Given this, the volume of seed hulls is significantly reduced, and it is divided into five fractions.

The first fraction («heavy»), consisting of hemp kernels and unhulled seeds, is separated according to linear dimensions on sieves. Under such conditions, a ready-made hemp kernel, undisturbed seeds, which are sent for repeated hulling, and a mixture are obtained.

The second and third fractions («light») are united. The resulting mixture is separated on sieves. Owing to this, impurities in the form of seed coats and finely ground seeds (chunks) are removed from the mixture. The mixture is then sent for aspiration. We receive waste, finished kernel, and «rehulling» – a fraction of the hemp kernel clogged with seed coat, which is sent for repeated aspiration.

The fourth and fifth fractions, which do not contain kernels, are not subjected to further processing.

It is advisable to separate seed hulls according to linear dimensions with the following set of sieves: ∅3.5–∅3.0–1.5×20–∅2.0–closed. It is advisable to separate seed hulls according to aerodynamic properties using an aspiration column with angles $\alpha=53°$, $\beta=6°$.

Analysis of the results of aspiration established that the main part of kernels (up to 53.31 %) was obtained during the first passage of the mixture through the aspiration channel. The second and third passing of the «rehulling» fraction made it possible to obtain 15.16 % and 2.12 % of kernels, respectively. Each subsequent pass reduced the number of discharged kernels.

Hulling hemp seeds according to the devised technological scheme has made it possible to obtain five products:

– kernel – a ready-to-use product with up to 1.0 % impurity content (shredded coats), consisting of crushed (85.0 %) and whole (14.0 %) seed kernels. It is worth noting that according to DSTU 4843:2007, the clogging of ready sunflower kernels should be 2.5 %;

– a mixture – a product with an increased content of whole seed kernels, consisting of whole seed kernels (75.0 %) and whole and unhulled seeds (25.0 %). It can be used for the production of hemp milk, germination, in the preparation of meals, for consumption in its pure form;

– ground mix – a product with an increased content of ground seed kernel, consisting of finely ground seed kernel (60.0 %) and coat (40.0 %). It is used in the preparation of meals and drinks;

– unhulled seeds – whole and damaged hemp seeds, used for re-hulling or obtaining oil;

– waste – seed coat, seed film, finely ground seed particles, seed dust, organic impurities. It can be used in animal husbandry and poultry farming, for heating non-residential premises.

It is worth noting that the following indicators of separation are implied for sunflower seed hulls [27]: kernel 45 %, whole grain and unhulled seeds 25 %, ground mix 15 %, oil dust 15 %.

Each specified product has a series of convincing properties and occupies an appropriate niche among connoisseurs of hemp products. However, the most promising are whole kernels of hulled (shelled) hemp seeds. The fields of use of the noted product are developing rapidly. The most well-known is the effective use of hulled hemp seeds in a variety of food products, meals, and drinks. Hulled seeds are characterized by an increased content of plant protein (35 %) and fat (49 %). Extracts of hulled seeds have the best antibacterial properties.

Hulling improves seed quality. The content of protein and the content of macro and microelements (phosphorus by 1.5 times, zinc and cobalt by 2 times) increases in hulled seeds by 1.5 times. Hulled seeds are characterized by a high content of essential amino acids and lysine.

The specificity of the mechanical-technological properties of the components of seed hulls, as well as the hulling process itself, significantly complicate the regulations for obtaining hemp seed kernels. Until recently, the above was not adequately reflected in the publications reporting completed scientific studies.

The lack of a detailed analysis of the influence of external factors (environmental temperature and humidity) on the processes of hulling and separation is attributed to the shortcomings of our studies. In addition, the research was conducted under laboratory conditions, which naturally did not take into account all possible variations and complexities of the real production process. In this context, worth noting is a number of studies aimed at determining the chemical composition and biological activity of hulled seeds [2], analyzing their nutritional value [28], and impact on human health [29]. Of particular interest are the results of hemp seed research from an engineering point of view [30] and the study of its physical and mechanical properties [31, 32]. However, there are still not enough systematic studies of evaluation of the processes of hulling and hemp seed hull separation as the basic components of modern technologies for hemp production. Therefore, it looks promising to expand the program of experimental research and clarify the laws of seed hulls separation, owing to which the varietal differences of industrial hemp and the regions of their cultivation will be taken into account. Such activities could also make it possible to establish the influence of environmental factors on the effectiveness of the hulling and separation processes. It is expedient to determine the ranges of increasing the efficiency of the separation of different fractions of seed hulls through the expansion of technical capabilities of the aspiration column and other equipment elements.

The above areas of research are very important. Addressing them could make it possible to modernize the technical and technological processes for treating hemp products at the required level of efficiency, including the hulling and separation of hemp seeds.

7. Conclusions

1. Based on the results of research into hemp seed hull separation according to their linear dimensions on sieves with round and oblong holes, it was established:

– the percentage of the retained seed hulls at sieves with round holes was: ∅3.5 mm – 25.98 %, ∅3.0 mm – 23.59 %, ∅2.0 mm – 40.28 %, respectively. For sieves of ∅5.0 mm and ∅4.5 mm, the percentage of retained seed hulls was less than 1.0 %. Sieves of ∅3.5 mm and ∅2.0 mm made it possible to obtain fractions of seed hulls with two components conditionally different in terms of the «mass-size» ratio, which had a positive effect on further separation by air flow;

– the use of sieves with holes of an oblong shape made it possible to obtain fractions consisting of at least three components. The exception was a 1.5×20 mm sieve, owing to which a fraction of two components conditionally different in terms of the «mass-size» ratio was obtained. Sieves with working openings of an oblong shape of 3.0×20 mm are ineffective because of their low (1.76 %) ability to retain the constituents of hemp seed hulls.

2. The separation modules based on the linear dimensions of the combined sieves with holes of round and oblong shapes did not enable a complete high-quality separation of seed hulls into individual components. Separation options No. 1 (Stage 4), No. 2 (Stage 5), and No. 4 (Stage 3) made it possible to isolate fractions of seed hulls, which consisted of two conditionally different components of the «kernel-coat». These fractions were obtained at a separation stage with a working opening of ∅2.0 mm.

3. Clogging of the kernels of seed hulls separated by linear dimensions on combined sieves with holes of round and oblong shapes was: separation option No. 1 – 48.70 %, option No. 2 – 45.74 %, option No. 3 – 60.25 %, option No. 4 – 49.32 %, respectively. In all variants of research, the share of impurities in the form of coats was dominant in clogging.

4. It was established that the use of an aspiration column made it possible to remove up to 32.1 % of debris in the form of coats, seed films, finely ground seeds, and oil dust from seed hulls. The largest amounts of fractions (39.33 %) was obtained for separation option No. 1, Stage 4. According to the results of the separation of the seed hulls, the following level of clogging of the seed kernels was established: separation option No. 1 – 19.07 %, option No. 2 – 21.35 %, option No. 3 – 32.10 %, option No. 4 – 20.18 %, respectively. The use of an aspiration column made it possible to reduce the content of seed coat in separation variant No. 1 – by 3.0–5.7 times, variant No. 2 – 1.35–3.7 times, variant No. 3 – 1.9–11.2 times, variant No. 4 – 1.5–4.8 times, respectively.

5. Rational values of the opening angle of the air damper $\alpha=53°$ and the angle of vertical inclination of the air channel $\beta=6°$ of the aspiration column were established. The quantitative and component composition of seed hulls fractions, obtained under the conditions of using an aspiration column with the above rational values of the angles $\alpha=53°$ and $\beta=6°$, is as follows: Stage I – «heavy» fraction – 51.78 %, 27.56 % – waste, up to 20 % – «light» fraction of Stages II and III, respectively.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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