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DETERMINATION OF THE INFLUENCE OF THE NUMBER OF PROFILE HOLES ON THE EFFICIENCY INDICATORS OF HEMP SEED DEHULLER IMPELLERS

The object of the research is technological processes, seeds and kernels of industrial hemp, centrifugal dehullers, dehuller impellers.

The research is aimed at increasing the efficiency of centrifugal dehulling of industrial hemp seeds by determining the influence of the number of profile holes in the impellers.

Two variants of the impeller design were developed and tested: with four and six profile holes. The research was conducted on seeds of the "Glesia" variety under stable processing conditions, including optimal humidity (8.4 %) and standardized wheel rotation parameters (6000±200 rpm).

According to the research results, it was established:

– an impeller with four profile holes in five dehulling cycles enabled a total kernel yield of 34.81 %. Under such conditions, the bulk of the seeds were dehulled in the first three cycles;

– the impeller with six profile holes made it possible to ensure a total kernel yield of 34.48 % in three dehulling cycles. Under these conditions, a significant part of the kernels was separated in the first two cycles.

According to the results of the analysis of the dehulling indicators, it was noted:

– in the first two cycles, the wheel with six holes separated up to 29.71 % of the kernels, and the wheel with four holes – up to 22.02 %;

– the use of the design of the wheel with six holes reduced the remains of undehulled seeds after the third cycle to 4.24 % of the initial mass, while the wheel with four holes – up to 16.23 %.

The advantages of the centrifugal dehulling method, which is based on the principle of converting kinetic energy into impact, were noted. This made it possible to separate the shells from the kernels without prior calibration of industrial hemp seeds.

The research results demonstrated the advantages of the improved design, which includes an impeller with six profile holes, and the prospects of its use to increase the productivity of industrial hemp seed dehulling.

Keywords: *hemp seeds, seed kernels, centrifugal dehulling, impeller, impeller profile holes, dehulling efficiency.*

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1. Introduction

Hemp seeds have historically been considered a by-product of the technical fiber industry. However, their unique nutritional properties have made them an extremely important and valuable food product [1]. Due to their biochemical composition, hemp seeds occupy a special place among food products. They contain 25–35 % oil with a balanced ratio of fatty acids, 20–25 % proteins with a full set of essential amino acids, and 20–30 % carbohydrates. They are especially valued for their rich complex of minerals, dietary fiber, vitamins, antioxidants, and biologically active substances [2]. Given the high content of beneficial components, hemp seeds are used in various forms: whole, as well as in the form of processed products such as kernels, oil, flour, protein concentrates, and fiber [3]. One of the most popular products is hulled hemp seeds, which are kernels separated from the hard outer shell. The seed shell creates discomfort during consumption. Its removal makes the product more convenient to use and digest [4]. Dehulled seeds have high nutritional value, rich protein composition, which makes them a complete source of vegetable protein. In addition, the product contains a significant amount of unsaturated omega-3 and omega-6 fatty acids, vitamins, antioxidants, minerals (magnesium, phosphorus, potassium, iron) and dietary fiber [5]. Dehulled hemp seeds are suitable for consumption in raw form, have a pleasant nutty flavor and are widely used in the food industry. Due to their ease of use, high nutritional value and balanced composition, dehulled hemp seeds are becoming increasingly popular among consumers and contribute to expanding the range of healthy food products on the market.

For dehulling seeds, machines with different working bodies are used, which implement the basic principles of separating the shell from the kernels. Depending on the physical and mechanical properties of the seeds, disk, roller, cylindrical and rotary working bodies are used. Each of the above types of working bodies creates optimal conditions for processing a specific type of material. Disk-type dehullers effectively combine impact and shear. Roller-type dehullers provide uniform

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compression. Machines with cylindrical dehullers usually implement the abrasive principle. Centrifugal dehullers generate high kinetic energy [6–8]. The correct choice of dehuller type is key to ensuring high quality of the final product and reducing processing losses.

Among the known methods of dehulling, centrifugal mechanisms are distinguished, which enable high productivity, low costs, and high ease of use. This method is used for dehulling spelt, emmer [7], tung tree fruits [9], sunflower seeds [10], rice grains [11], and walnuts [12]. The principle of converting the kinetic energy of rotational motion into impact is the basis of the effectiveness of the centrifugal method. This method quickly and efficiently separates the shell from the kernel. The method requires less energy, since the dehulling process is carried out quickly and without significant impact on the working surfaces of the machine. The disadvantages of the centrifugal method include high rotation speeds and intense impacts. This can lead to damage to the kernels, especially in cases where the impact angles and the speed of movement of the seeds exceed rational limits. This reduces the quality of the final product and increases the percentage of waste. The lack of precise control over the distribution of seeds in the working chamber can cause uneven dehulling. Under such conditions, some of the grains remain untreated, while others are subjected to excessive impact, which increases the level of losses.

Positive results of the centrifugal method in the conditions of dehulling of industrial hemp seeds are known [13]. The use of the mechanism proposed by the authors makes it possible to shell seeds without prior calibration, normalization of humidity, which made it possible to obtain 28.0–38.0 % of finished kernels with a contamination of up to 1.0 %. However, despite the advantages, centrifugal mechanisms have a significant drawback. This drawback concerns the low coefficient of single dehulling. Five cycles are required to fully process a batch of seeds, since after each cycle, the undehulled parts require reprocessing. This feature requires further optimization of the design and operating parameters of the mechanism in order to increase productivity and minimize the number of required cycles. One of the key ways to achieve this goal can be to improve the design of the working body, because it is it that is responsible for ensuring the effective separation of the shell from the kernel.

In [11], the authors focus on the key problem of centrifugal dehullers – the low coefficient of single-time dehulling and the high level of grain damage. The researchers noted that these shortcomings are due to insufficient acceleration of grains, uneven speed distribution, and also an irrational angle of their impact on the working surface. This led to losses in the quality of the final product and an increase in the percentage of waste. To solve these problems, the main emphasis was placed on improving the design of the working body – in particular, its new shape. Thanks to this, it was possible to increase the dehulling coefficient by 8 % and reduce grain damage by 7.33 % [11].

There are known studies with improved design of working bodies of pneumomechanical dehuller, which became an important step to increase the efficiency of the process. The main emphasis was placed on finding rational directions of grain movement in the working area of the machine. The authors optimized the parameters of the working body, which provided more precise control of grain movement and improved conditions for their dehulling. These improvements contributed to the creation of a stable processing process, which made it possible to reduce the level of losses, improve the quality of the final product and increase the overall productivity of the machine [14]. However, this method is difficult to apply to dehulling hemp seeds due to the existing features of its physical and mechanical properties. In work [15], the influence of the geometry of the working body, in particular the shape of the sieve cross-section, on the efficiency of the vertical rice mill was considered. The main attention was focused on studying the mechanisms of turbulent particle motion in the working chamber, as well as their influence on the quality and productivity of the dehulling process. The authors noted that the shape of the sieve cross-section largely determines the distribution of particle speeds, their turbulent kinetic energy and collision frequency. This allowed to conclude that the optimization of the working body is one of the key areas for improving the mill's operation.

In [16] it was noted that the use of stiffer materials for the working rolls increases the rice dehulling coefficient by reducing deformation and improves the contact of the working bodies with the grains. Improving the working body, in particular the selection and modification of the materials of its components, increases the efficiency of the mechanism. Under such conditions, grain losses are reduced, surface wear is minimized and energy consumption is optimized.

There are well-known studies [17] on increasing the efficiency of pistachio nut dehulling. The authors investigated the influence of the geometry of the impeller blades and the materials of their manufacture on the dehulling efficiency indicators. It was noted that the use of aluminum blades with forward-curved ends made it possible to achieve the highest dehulling coefficient (92.77 %) with the minimum level of product damage (8.2 %). However, this method cannot be used for dehulling hemp seeds.

Improving the design of the working bodies of the dehullers looks like the most promising option for increasing the efficiency of the technological processes of dehulling industrial hemp seeds. Substantiation of rational geometric shapes, materials, parameters and operating modes of the working bodies will make it possible to increase the coefficient of one-time dehulling, reduce the high level of product damage, and ensure uniformity of processing.

The aim of research is to increase the efficiency of centrifugal dehulling of industrial hemp seeds by determining the influence of the number of profile holes in the impellers. This will make it possible to reduce energy consumption, reduce losses, and improve the quality of the finished product.

To achieve the aim, the following objectives were set:

– to establish the indicators of dehulling industrial hemp seeds with an impeller with four profile holes;
– to establish the indicators of dehulling industrial hemp seeds with an impeller with six profile holes.

2. Materials and Methods

The object of research is technological processes, seeds and kernels of industrial hemp, centrifugal dehullers, dehuller impellers.

The subject of research is the interaction of the dehuller working body with the seeds, the influence of the working body parameters on the process indicators.

The scientific hypothesis is that there are such technical and technological solutions, the implementation of which will enable the dehulling of industrial hemp seeds with a high level of efficiency.

The following assumptions were made in the research process:

– a constant value of seed moisture, which made it impossible for it to affect the effectiveness of the dehulling;
– laboratory conditions of all stages of the experiments are the same, without extraneous influences that could distort the results obtained;
– uniform flow of seeds to the impeller, which enabled a uniform dehulling process;
– the design of the impeller ensured a uniform distribution of the kinetic energy of the seeds, and the influence of random fluctuations in speed and direction of movement is insignificant.

In order to simplify the research, seeds were used without prior calibration in size, which corresponded to real production conditions. The influence of mechanical wear of the impeller was not taken into account, since the experiments were carried out in the short term. Determination of the efficiency of the dehulling process was based on the number of undehulled seeds and the yield of kernels without analyzing the morphological changes of the seeds after each cycle.

These assumptions and simplifications were made to ensure the reproducibility of the experimental data. This allowed to obtain reliable conclusions regarding the efficiency of technical and technological solutions during the dehulling of industrial hemp seeds.

2.1. Methodology for determining the physical and mechanical properties of seeds

To study the physical and mechanical properties of seeds, generally accepted methods and existing techniques were used [18]. The studies used seeds of industrial hemp of the "Glesia" variety from production crops of the Institute of Bast Crops of the NAAS of Ukraine. The sizes of individual seeds were determined by measuring their parameters (length, width, thickness) using an electronic caliper. The separation of seeds by width into fractions was carried out on laboratory sieves with oblong holes measuring 3.0×20 mm and 2.5×20 mm. The separation was carried out by pouring the seeds onto the sieves with subsequent reciprocating oscillations of the latter. Under these conditions, three seed fractions were obtained: large (>3.0 mm), medium (2.5–3.0 mm), small (<2.5 mm). Each of the obtained seed fractions was separately examined. The mass of seeds and components of the hempseed cake was determined by weighing individual samples on electronic scales. Seed moisture was determined using a laboratory drying oven.

2.2. Methodology for determining the efficiency of the dehulling process

The dehulling of hemp seeds was carried out using a developed experimental centrifugal device [13]. Dehulling was carried out without prior seed calibration. The mass of a separate seed sample for each dehulling variant was 1000 g. The studies were carried out by conducting a series of experiments. The repeatability for each variant of the experiment was fivefold. The rotation frequency of the working body (impeller) in the experiments was within 6000±200 min^{-1}. The seeds were fed from above through a structural hole in a free flowing state into the loading hole of the impeller. The seeds dehulling freely from above during contact with the impeller, which had a certain rotation frequency, changed the direction of movement and hit the walls of the reflecting deck with some force.

For dehulling, each sample was passed separately through the device. After the seeds passed through the device, a hempseed cake was obtained. To separate it, a grain cleaning machine was used, which is an air-sieve separator. After passing through the separator, the following fractions were obtained: 1 – undehulled and damaged seeds; 2 – finished kernels; 3 – waste.

The dehulling process was as follows. A seed sample (weight 1000 g) was passed through the device (first cycle). After dehulling, the hempseed cake obtained from the sample was sent for separation in an air-sieve separator. The undehulled and damaged seeds isolated during the separation process were subjected to dehulling again (second cycle). Dehulling was repeated until 2–4 % of the seeds remained from the initial sample. The kernels obtained during all dehulling cycles of one sample were weighed and the total percentage content of the mass of the initial sample was determined. Thus, the total yield of kernels was obtained. The waste obtained after each cycle was not used in further studies.

The effectiveness of the dehulling process was determined after each cycle by analyzing the results obtained. The number of undehulled seeds, ready-made kernels and waste was determined. The main processing of the experimental data results was carried out according to [19] using the Microsoft Excel software environment.

A characteristic difference of the studied working body (Fig. 1) is its design. The working body is a wheel with a diameter of 162 mm, consisting of two disks with a thickness of 2 mm each. The upper disk in the center has a loading hole with a diameter of 74 mm. Between the disks there are sectors that together form radial profile channels measuring 20×20 mm with a hyperbolic shape of the side surfaces.

Increasing the number of channels in the working wheel to six is due to the need to maintain the stability of the dehulling process and the structural parameters of the mechanism. These include the distance between the working wheel and the reflecting deck. The dimensions of the profile holes and the loading hole affect the throughput and prevent seed clogging. The optimal gap between the reflecting deck and the wheel provides the necessary impact force. Increasing the number of channels beyond six would lead to a reduction in the size of the holes, which would impair the uniformity of seed movement and reduce the dehulling.

During the research, the number of profile holes of the impeller was the variable design parameter. To study the influence of the design of the working body on the efficiency of seed dehulling, two variants of it were developed (Fig. 2).

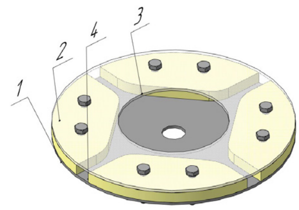

Fig. 1. Scheme of the impeller:
1 – lower disk; 2 – upper disk; 3 – loading hole; 4 – profile channel

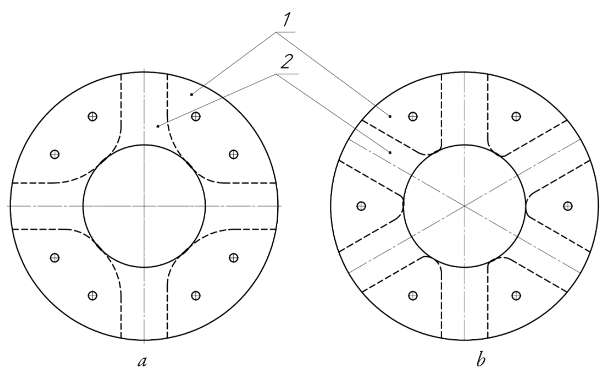

Fig. 2. Impeller: *a* – before improvement; *b* – after improvement;
1 – sectors; 2 – profile channels

Thus, increasing the number of channels to six is the most rational option for improvement without changing other design parameters.

3. Results and Discussion

3.1. Study of physical and mechanical characteristics of seeds

The characteristics of the seed batch used in the experiments are given in Table 1.

Table 1

Characteristics of industrial hemp seeds

No.	Indicator	Value
1	Variety	Glesia
2	Moisture	8.4 %
3	Clogging	1.2 %
4	Mass of 1000 pcs.	17.46 g
5	Fractional composition of seeds, % large (>3.0 mm) medium (2.5–3.0 mm) small (<2.5 mm)	 11.52 % 63.73 % 24.75 %
6	Mass of 1000 pieces fraction large (>3.0 mm) medium (2.5–3.0 mm) fine (<2.5 mm)	 23.51 g 18.34 g 13.44 g

It should be noted (Table 1) that the seed moisture content in the experiments was 8.4 %. This indicator met the requirements of the State Standard of Ukraine (seed moisture should not exceed 11.0 %). The seed contamination was 1.2 %. The mass of 1000 seeds without division into fractions was 17.46 g, which corresponds to the average indicators for this variety.

Analysis of the fractional composition of the seeds showed that the main part is the medium fraction (2.5–3.0 mm) – 63.73 %. The fine fraction is 24.75 %, and the large fraction is 11.52 %.

It was noted that the mass of 1000 seeds varied depending on the size of the fraction. The large fraction was characterized by the highest indicator – 23.51 g, the medium fraction – 18.34 g, and the small fraction – 13.44 g. These indicators confirmed the relationship between seed size and 1000-piece weight. An increase in seed size leads to a corresponding increase in their weight. This distribution of weight and size was taken into account when setting up the processing equipment to ensure process efficiency and minimize seed damage.

3.2. Results of studies of the efficiency of a wheel with four profile holes

The change in the number of undehulled seeds for each cycle of dehulling by an impeller with four profile holes is shown in Fig. 3.

A regression equation for the change in the amount of undehulled seeds was established for calculation relative to the initial mass (1) and for calculation relative to the mass of undehulled seeds (2):

$$y = 4.9884x^2 - 47.026x + 112.87, \quad (1)$$

$$y = 2.1544x^2 - 22.66x + 91.614. \quad (2)$$

Table 2 shows the results of statistical processing of the obtained data for determining the number of undehulled seeds for each dehulling cycle (wheel with 4 profile holes).

It is noted (Table 2) that the variation between groups is significantly greater than the variation within groups. This confirms the presence of a significant influence of the factor distinguishing groups on the variable under study. The results of the treatment indicate the statistical significance of these differences.

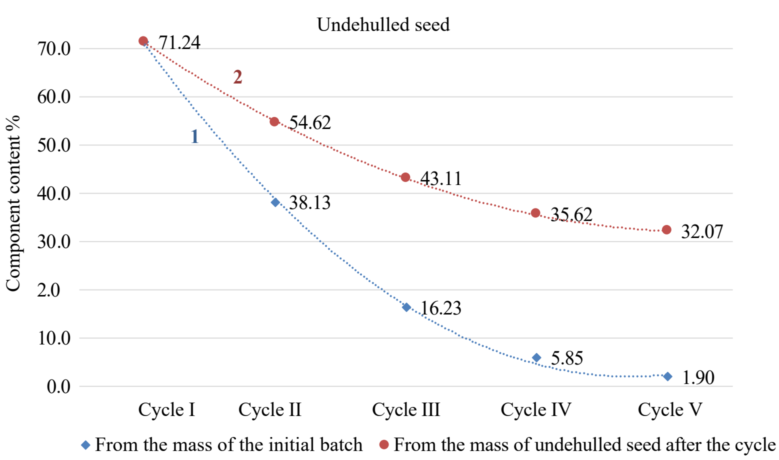

Fig. 3. Change in the amount of undehulled seeds for each cycle of the impeller dehulling into four profile holes

Table 2

Results of statistical processing of the results for determining the number of undehulled seeds for each dehulling cycle (wheel with 4 profile holes)

Source of variation	*SS*	*df*	*MS*	*F*	*P*-value	*F* critical
Between groups	16368.76	4	4092.19	205.2306	6.23E-16	2.866081
Within groups	398.7896	20	19.93948	–	–	–

Fig. 3 shows two curves that characterize the change in the number of undehulled seeds during dehulling for five cycles. From the mass of the initial batch (curve 1) and from the mass of the undehulled seeds after each dehulling cycle (curve 2). The data make it possible to assess both the overall efficiency of the process and the dynamics of the reduction of undehulled seed residues within each subsequent cycle. Curve 1 characterizes the overall dynamics of the process – almost complete dehulling of seeds after the fifth cycle. Under such conditions, the undehulled residues decreased to 1.90 % of the initial batch. Instead, curve 2 focuses on the change in the efficiency of each subsequent cycle, which indicates the gradual complication of the destruction of seed residues.

Characterizing the features of the obtained dependencies, attention is drawn to the specific structure of hemp seeds. In the first cycles, mainly grains with a weak shell structure are subjected to dehulling. More stable fractions remain for processing in the following stages. The decrease in the number of undehulled seeds in each subsequent cycle indicates a decrease in the mass available for dehulling, which limits the efficiency of the process in the later stages. It should be noted that according to curve 1 (Fig. 3), which reflects the number of undehulled seeds as a percentage of the initial mass (1000 grams), a significant decrease in residues is observed after each cycle. After the first cycle, undehulled seeds amounted to 71.24 %. After the second cycle, this figure decreased to 38.13 %, after the third – to 16.23 %, after the fourth – to 5.85 %. And after the fifth cycle, only 1.90 % of the total mass of the batch remained untreated seeds. The indicated curve demonstrates the general tendency of the process of dehulling for a wheel with four profile holes. It is noted that the main part of the seeds fell in the first three cycles. In the later stages they remain more resistant to mechanical impact and grain destruction, which is probably due to their specific structure.

Curve 2 (Fig. 3), which displays the number of undehulled seeds as a percentage of the mass of the undehulled seeds after each cycle, details the change in efficiency taking into account each subsequent stage of processing. After the first cycle, the undehulled seeds were 71.24 % (from the initial mass of 100 %). After the second cycle, 54.62 % of the undehulled seeds remained (from the initial mass of 71.24 %). That is, half of the grains that did not fall in the first stage were not processed. After the third cycle, 43.11 % (from the initial mass of 54.62 %) remained undehulled, which corresponds to approximately a quarter of the previous mass. The fourth cycle left 35.62 %, which is about a third of the undehulled seed after the third cycle. After the fifth cycle, 32.07 % remained.

The change in the number of undehulled kernels after each cycle for the impeller with four profile holes is shown in Fig. 4.

Regression relationships were established, which determined the change in the number of dehulled kernels for calculation relative to the initial mass (3) and relative to the mass of the undehulled seed (4):

$$y = -0.764x^2 + 2.0868x + 9.1036, \quad (3)$$

$$y = -0.954x^2 + 9.2096x + 1.8024. \quad (4)$$

It is noted that thanks to the results shown in Fig. 4, both the overall dynamics of the kernel output and the efficiency of each dehulling stage are assessed.

Table 3 shows the results of statistical processing of the obtained data for determining the number of kernels for each dehulling cycle (wheel with 4 profile holes).

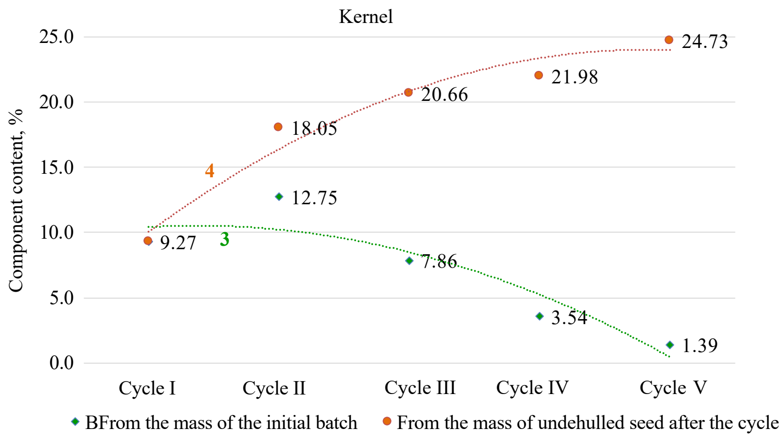

Fig. 4. Change in the number of kernels for each seed dehulling cycle (wheel with 4 profile holes)

Table 3

Results of statistical processing of the results for determining the number of kernels for each dehulling cycle (wheel with 4 profile holes)

Source of variation	*SS*	*df*	*MS*	*F*	*P*-value	*F* critical
Between groups	16368.76	4	4092.19	205.2306	6.23E-16	2.866081
Within groups	398.7896	20	19.93948	–	–	–

It should be noted that the results of the analysis of variance (Table 3) confirm the presence of statistically significant differences between the groups. The variation between the groups significantly exceeds the variation within the groups, which indicates a significant influence of the studied factor and its influence can be considered reliably confirmed.

Curve 3 (Fig. 4) displays the kernel yield as a percentage of the initial mass (1000 g) for an impeller with four profile holes. After the first cycle, up to 9.27 % of kernels were obtained. After the second – up to 12.75 %, the third – up to 7.86 %, the fourth – up to 3.54 %, and after the fifth cycle – 1.39 %, respectively. The total kernel yield for all five cycles was 34.81 % of the initial mass, which indicates a gradual decrease in the efficiency of kernel separation with each subsequent cycle.

Curve 4 (Fig. 4) shows the kernel yield as a percentage of the undehulled seed for each cycle for an impeller with four profile holes. For the first cycle, the number of kernels obtained was 9.27 % of the initial undehulled seed.

For the second cycle, this figure increased to 18.05 %, for the third – to 20.66 %, for the fourth – to 21.98 %, and for the fifth – to 24.73 %. The increase in the proportion of kernels relative to the undehulled residue after each cycle indicates that the dehulling is concentrated on an ever smaller number of seeds, but more accessible for destruction.

3.3. Results of studies of the efficiency of a wheel with six profile holes

The change in the number of undehulled seeds after each dehulling cycle for an impeller with six profile holes is shown in Fig. 5.

Regression equations were established that describe the dynamics of the change in the number of undehulled seeds for calculation relative to the initial mass (5) and for calculation relative to the mass of undehulled seeds (6):

$$y=-0.344x^2-31.758x+100.74, \quad (5)$$

$$y=-3.664x^2-17.542x+89.846. \quad (6)$$

Table 4 shows the results of statistical processing of the data obtained to determine the number of undehulled seeds after each dehulling cycle (wheel with 6 profile holes).

The results of the analysis (Table 4) confirm the presence of significant statistically significant differences between the groups. The variation between the groups significantly exceeds the variation within the groups, which indicates a significant influence of the studied factor. These differences are not random, but are determined by the influence of this factor.

The presented calculation results (Fig. 5) using two methods indicate the high efficiency of the impeller design with six profile holes. Curve 5 demonstrates a rapid decrease in the amount of undehulled seeds to minimal residues after the third cycle (4.24 % of the initial weight). In contrast, curve 6 emphasizes the high efficiency of each subsequent cycle, indicating a gradual decrease in the residues of undehulled seeds to 6.23 % of the mass after the second cycle.

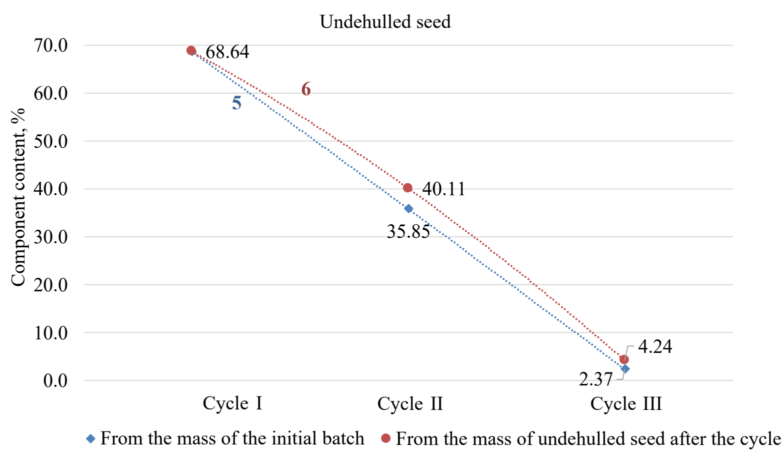

Fig. 5. Change in the number of undehulled seeds after each dehulling cycle (wheel with 6 profile holes)

Table 4

Results of statistical processing of the results to determine the number of undehulled seeds after each dehulling cycle (wheel with 6 profile holes)

Source of variation	*SS*	*df*	*MS*	*F*	*P*-value	*F* critical
Between groups	10979.01	2	5489.507	1696.75	1.91E-15	3.885294
Within groups	38.82368	12	3.235307	–	–	–

The features of the obtained dependencies indicate that the impeller design with six profile holes allows for more efficient seed processing compared to a wheel with four holes, especially at the initial stages. The reduction in the number of undehulled seeds in each cycle is explained by the improved interaction of seeds with working elements and the increase in the area of influence, which contributes to a more uniform and intensive dehulling.

It should be noted that according to curve 5 (Fig. 5), which reflects the number of undehulled seeds as a percentage of the initial mass (1000 g), a significant reduction in residues is observed after each cycle. After the first cycle, undehulled seeds amounted to 68.64 %. After the second cycle, this figure decreased to 40.11 %, and after the third – to 4.24 %. This curve demonstrates the general trend of effective dehulling in the first cycles, which allows a significant reduction in the number of undehulling seed residues.

Curve 6 (Fig. 5), which reflects the number of undehulled seeds as a percentage of the undehulled mass after each cycle, details the change in process efficiency for each subsequent processing stage. After the first cycle, the undehulled seeds were 68.64 % (from the initial mass of 100 %). In the second cycle, this figure decreased to 58.45 %, which indicates that almost half of the undehulled seeds remaining after the first cycle (68.64 %) were dehulled. In the third cycle, only 6.23 % of the undehulled seeds remained, which corresponds to a significant decrease in the volume of residues after each stage.

The change in the number of dehulled kernels after each cycle for the impeller with six profile holes is shown in Fig. 6.

Equations have been established that describe the dynamics of the change in the number of collapsed kernels for calculation relative to the initial mass (7) and for calculation relative to the mass of the undehulled seeds (8):

$$y = -10.12x^2 + 37.13x - 15.54, \quad (7)$$

$$y = -0.364x^2 + 7.402x + 4.432. \quad (8)$$

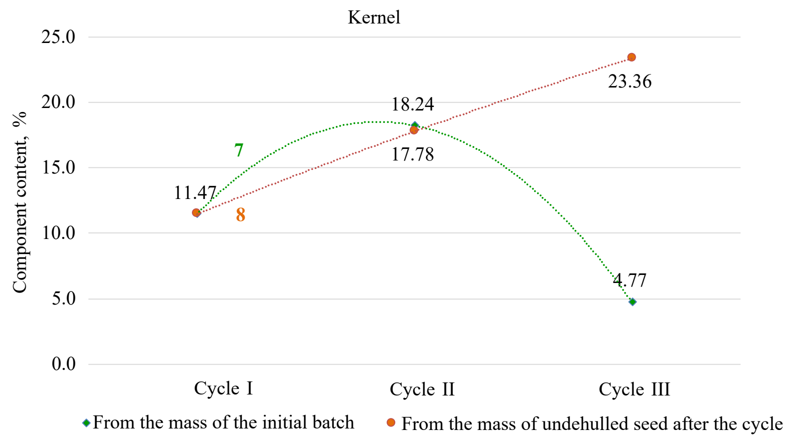

Fig. 6. Change in the number of kernels after each dehulling cycle (wheel with 6 profile holes)

Table 5

Results of statistical processing of the results from determining the number of kernels after each dehulling cycle (wheel with 6 profile holes)

Source of variation	*SS*	*df*	*MS*	*F*	*P*-value	*F* critical
Between groups	453.6063	2	226.8032	143.71	4.14E-09	3.885294
Within groups	18.9384	12	1.5782	–	–	–

Table 5 shows the results of statistical processing of the data obtained from determining the number of kernels after each dehulling cycle (wheel with 6 profile holes).

The results of the analysis of variance (Table 5) confirm the presence of statistically significant differences between the groups, which indicates a significant influence of the studied factor and its influence can be considered reliably confirmed.

According to curve 7, which reflects the number of kernels as a percentage of the initial mass (1000 g), 11.47 % of kernel were obtained in the first cycle. In the second cycle, this figure increased to 18.24 %, and in the third cycle, an additional 4.77 % of kernel were obtained. The total yield of kernels for three cycles was 34.48 % of the initial mass. Such dynamics indicate that the main part of the kernels was isolated in the first two cycles, while in the third dehulling cycle their number significantly decreased.

Curve 8 (Fig. 6), which reflects the number of kernels as a percentage of the mass of the undehulled material after each cycle, details the efficiency of the process at each subsequent stage. In the first cycle, 11.47 % of the kernels were obtained from the initial mass of undehulled seeds. In the second cycle, this figure increased to 17.78 %, and in the third cycle it reached 23.36 %. The increase in the percentage of kernels relative to the undehulled seed indicates that with each subsequent cycle, the dehulling process becomes more focused on separating kernels from the residues. Comparing the dynamics of obtaining kernels (Fig. 4) and obtaining undehulled seed residues (Fig. 3) for an impeller with four profile holes, it is possible to note the relationship between the efficiency of dehulling and the yield of the finished product at different stages of the process. In the first cycle, 100 % of the initial mass of seeds (1000 g) was directed to dehulling. As a result, the undehulled residues amounted to 71.24 % (Fig. 3, curve 1), and the kernel yield was 9.27 % (Fig. 4, curve 3). The remaining 19.49 % became waste. Of the total collapsed mass, kernels accounted for 9.27 %, or about 32.2 % of the dehulled material.

In the second cycle, 71.24 % of the undehulled seeds obtained after the first cycle were sent for dehulling. As a result, the undehulled residues were reduced to 38.13 % (Fig. 3, curve 1), and the kernel yield was an additional 12.75 % (Fig. 4, curve 3). The remaining 20.36 % were sent to waste. Of the total dehulled mass in the second cycle, the kernels accounted for 12.75 %, or 38.5 % of the dehulled material. In the third cycle, 38.13 % of the undehulled seeds obtained after the second cycle were sent for dehulling. As a result, the undehulled residues were reduced to 16.23 % (Fig. 3, curve 1), and the kernel yield was an additional 7.86 % (Fig. 4, curve 3). The remaining 14.04 % were sent to waste. Of the total dehulled mass in the third cycle, the kernels accounted for 7.86 %, or 35.9 % of the collapsed material.

In the fourth cycle, 16.23 % of the undehulled seeds was sent for collapse. As a result, the undehulled residue was reduced to 5.85 % (Fig. 3, curve 1), and the kernel yield was an additional 3.54 % (Fig. 4, curve 3). Waste was 6.84 %. Of the total dehulled mass in the fourth cycle, the kernels accounted for 3.54 %, or 34.1 % of the dehulled material.

In the fifth cycle, 5.85 % of the undehulled seeds was sent for dehulling. The undehulled residue was reduced to 1.90 % (Fig. 3, curve 1), and the kernel yield was an additional 1.39 % (Fig. 4, curve 3). Waste was 2.56 %. Of the total dehulled mass in the fifth cycle, the kernels accounted for 1.39 %, or 35.2 % of the dehulled material.

For the impeller with six profile holes (Fig. 5, Fig. 6), 100 % of the initial seed mass (1000 g) was directed to dehulling in the first cycle. As a dehulling result, 68.64 % remained as undehulled seeds (Fig. 5, curve 5), and 11.47 % turned into kernels (Fig. 6, curve 7). Of the total dehulled material, the kernels accounted for 11.47 %, i. e. about 36.6 % of the dehulled seeds, while the remaining 63.4 % of the dehulled material was transferred to the waste fraction. This result indicates that the first cycle ensures the destruction of the shells of mainly weak grains, which only partially pass into the finished product.

In the second cycle, 68.64 % of the undehulled seeds obtained after the first cycle were sent for dehulling. As a result of dehulling, the residuals of the undehulled seeds were reduced to 35.85 % (Fig. 5, curve 5), and the kernel yield was an additional 18.24 % (Fig. 6, curve 7). Thus, the kernels accounted for 18.24 % of the dehulled material, or 55.6 % of the dehulled seeds. This indicates a significant improvement in the efficiency of the process, since at this stage, seeds with a more stable shell, which contains a larger number of kernels, are dehulled.

In the third cycle, 35.85 % of the undehulled seeds obtained after the second cycle were sent for dehulling. As a result, the residuals of the undehulled seeds were reduced to 2.37 % (Fig. 5, curve 5), and the kernel yield was 4.77 % (Fig. 6, curve 7). Thus, the kernels accounted for 4.77 % of the dehulled material, or about 14.3 % of the dehulled seeds. This indicates a significant decrease in the efficiency of kernel extraction at the final stage, since the remains of seeds with the strongest shell, which is only partially susceptible to destruction, were processed.

3.4. Discussion of results

The established patterns of changes in the number of dehulled kernels relative to the initial mass and relative to the mass of the undehulled material by the impellers of centrifugal dehullers with different numbers (four and six) of profile holes made it possible to reduce the number of dehulling cycles and increase the efficiency of the process.

It was noted that the efficiency of kernel extraction by the impeller with four profile holes decreased with each subsequent processing cycle. This is due to the peculiarities of the physical and mechanical properties of the seeds, which were not destroyed under the given process parameters. The seeds may contain a kernel that is difficult to separate due to incomplete destruction of the shell. Under such conditions, the highest yield of kernels was achieved in the first three cycles, where the bulk of the seeds were dehulled In the following cycles, the tendency to reduce the yield of kernels relative to the dehulled material prevailed.

The design of the wheel with six profile holes made it possible to effectively separate kernels mainly in the first two cycles. The third cycle completed the processing, but its efficiency is limited by the physical properties of the remaining seeds.

It was noted that increasing the number of profile holes in the impellers from four to six increased the efficiency of kernel extraction, especially at the initial stages of dehulling. These results coincided with the results of studies [11, 14–17].

Increasing the number of profile holes made it possible to reduce the amount of residual undehulled seed and increase the yield of the finished product in a shorter processing period.

Objective difficulties caused by the war in Ukraine, the psychological state of the performers, significantly affected the implementation of all stages of the research. Obtaining raw materials (hemp seeds), developing, manufacturing the installation and directly experimental research were carried out in a region with extremely high risks. These risks are due to the unstable military situation, not always defined schedules of electricity and heat supplies, strict adherence to safety measures.

Under the conditions of industrial use of the research results, it is advisable to minimize the impact of humidity fluctuations, both atmospheric and raw materials, abrasive wear of working elements on the process quality indicators. The list of priority tasks includes establishing the stability of efficiency indicators under the conditions of seed dehulling of other hemp varieties, as well as determining the influence of the material of the working elements on the quality and efficiency indicators of the process.

4. Conclusions

1. According to the results of studies on determining the influence of the number of profile holes in the impellers on the efficiency of the centrifugal dehuller process of industrial hemp seeds, the following were established:

– the advantages of the centrifugal dehuller method, which is based on the principle of converting kinetic energy into impact – this made it possible to separate the shells from the kernels without prior seed calibration;

– an impeller with four profile holes in five dehuller cycles enabled a total kernel yield of 34.81 %. Under such conditions, the bulk of the seeds were dehulled in the first three cycles.

2. An impeller with six profile holes in three dehuller cycles enabled a total kernel yield of 34.48 %:

– in the first two cycles, a wheel with six holes separated up to 29.71 % of the kernels, and a wheel with four holes – up to 22.02 %;

– the use of a six-hole design reduced the remaining undehulled seeds after the third cycle to 4.24 % of the initial mass, while the four-hole wheel reduced it to 16.23 %.

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Conflict of interest

The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship or other, which could affect the research and its results presented in this article.

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Data availability

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 presented work.

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