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The European Green Deal: Determination of the Energy Parameters of the String Husking Device in Buckwheat Processing

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Abstract: The priority tasks of grain production sustainability are solving the problem of the significant total energy consumption of the full production cycle and adapting the existing equipment to use as part of equipment sets of low and medium productivity. A promising way to solve these problems is the development and implementation of a string husking device. Its use will significantly reduce the energy consumption of buckwheat groat production due to the use of an energy-efficient husking mechanism. In addition, the string device makes it possible to eliminate the operation of the preliminary sorting of grain into fractions from the technological line of grain production, which additionally reduces the energy consumption of the line and makes it possible to use the husker in lines of low, medium and high productivity. Reducing the specific energy consumption of buckwheat production corresponds to the "European Green Deal" concept and makes production more resource-efficient and competitive. This way, two out of the three pillars of sustainability are improved: environmental and economic. The design principle of carrying out the operation of removing the shell from the buckwheat grain in the developed string husking device is substantiated. Theoretical studies were carried out using an analysis and synthesis of the mechanics of destruction and the method of determining the moments of inertia of homogeneous bodies relative to their own central axes during the husking of buckwheat by impact. Experimental studies were carried out using an experimental string husking device. The conducted analytical studies made it possible to determine the dependence between the specific energy consumption of the husking process and the physical and mechanical characteristics of buckwheat, as well as the structural parameters of the string husking device and the kinematic indicators of its operation. As a result of experimental studies, it had been established that the specific energy consumption of the buckwheat husking process in the developed device is 44–47% lower than the equipment currently used for buckwheat husking, and is 0.491–0.498 Wh/kg.

Keywords: grain production sustainability; buckwheat husking; string husking device; shock husking; specific energy consumption of buckwheat husking

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1. Introduction

High-capacity enterprises are characterized by an expanded composition and branching operations of technological processes of buckwheat groat production. The sustainability of grain and cereal production technology, as well as prospects for its development, is closely related, first of all, to the improvement of the most energy- and material-intensive technological process—husking. The strategy of Ukraine's integration into the industrial environment of Europe includes a solution to the issue of increasing energy efficiency in all branches of production. Given that food production is the largest consumer of electricity, reducing energy consumption in this industry is an important part of the Green Deal strategy to achieve sustainability [1,2].

One of the ways to increase sustainability is to reduce energy consumption and use fewer machines and equipment for technological processes. The result is a reduction in the emissions of pollutants and greenhouse gases and, ultimately, an improvement in the ecology of our planet. In particular, for grain production, the known weak links of the technological process of grain processing are the need to accurately sort grain into fractions before shelling and an inefficient shelling process, where an excessive amount of energy is wasted. This way, two out of the three pillars of sustainability are improved: environmental and economic.

The problem of improving husking equipment and creating complex technological lines is gaining great importance and relevance, since modern methods and technological means of separating grain shells in agricultural production are not efficient enough. The reason for this is the high energy intensity index, which is related to the design feature of the existing equipment (the significant weight of working bodies and the high load on them). This equipment needs further research and improvement in terms of both the design as a whole and the modes of operation. Therefore, in order to reduce energy consumption, it is advisable to improve, first of all, husking systems and machines, the technological efficiency of which significantly affects the quality and yield of finished products, and the energy consumption of production as a whole [3].

Impact machines, which meet the requirements of resource-saving technologies to a greater extent than existing equipment and are suitable for husking buckwheat without preliminary sorting into fractions, are promising for use in grain processing lines at the dehusking stage.

In order to achieve the rational use and saving of electricity, it is appropriate to investigate the technical and technological factors of the husking process that affect energy consumption during the work. At the same time, the specific energy consumption factor was chosen as an indicator of the effectiveness of measures to rationalize energy consumption.

Thus, the study of the parameters and modes of operation of the string husking device is a promising direction for reducing the energy consumption of the husking process. The use of this equipment in buckwheat groat production lines will allow for a reduction in the total energy costs of production due to the possibility of removing the operation of pre-sorting into fractions from the technological scheme.

At the current development stage of grain production, the following conditions are required to be fulfilled: saving energy resources, improvements in quality and an expansion of the assortment of food products, and solving the problem of decentralizing the processing of grains in autonomous conditions on farms and in small processing enterprises. This can be achieved by providing such enterprises with technological equipment that should be versatile, ensure the processing of most regional crops [4,5], be based on compact energy and resource-saving technologies [6,7] and meet consumer requirements [8,9]. The development of research in the field of the anatomical structure and physico-mechanical and technological properties of grains of cereal crops was facilitated by Y.N. Kupritsia [10], E.M. Melnikov [11], M.E. Ginzburg [12] and E.N. Greenberg [13].

Depending on the method of separating husked grains from unhusked ones, technological schemes with and without the presence of an intermediate kernel removal operation are distinguished. V.V. Hortynskyi [14], A.Ya. Sokolov [15,16], Y.M. Zhislin [17] and R.R. Weisman [18] made a great contribution to the study of grain preparation for processing. In their works, both general and narrower issues of the theory and calculation of working bodies of equipment for processing and preparing grain were solved: problems of increasing productivity, technological efficiency and reducing energy consumption, optimizing the parameters of working bodies. They singled out buckwheat husking schemes with intermediate kernel removal and without intermediate grain removal. In both schemes, roller decking machines are most often used for the husking process.

In the case of using a scheme in which husking takes place through a conveyor method, i.e., without the intermediate selection of the kernel (Figure 1), the grain is shelled in three to four consecutive passes through husking machines with intermediate selection of the crushed kernel and flour followed by the winnowing of the husk. At the same time, there is no intermediate separation of the core, and only the husk (shell) is separated; the entire mixture obtained after the first passage through the machine is fed to the next husking machine. In this scheme, part of the already husked grains, again exposed to the influence of the working organs of the machines, is crushed, and the crushed grain is crushed to a greater extent, which leads to the loss of the kernel and a decrease in the grain yield. Such an irrational shelling scheme, despite a high shelling ratio, leads to the excessive loading of technological equipment and a sharp increase in product turnover.

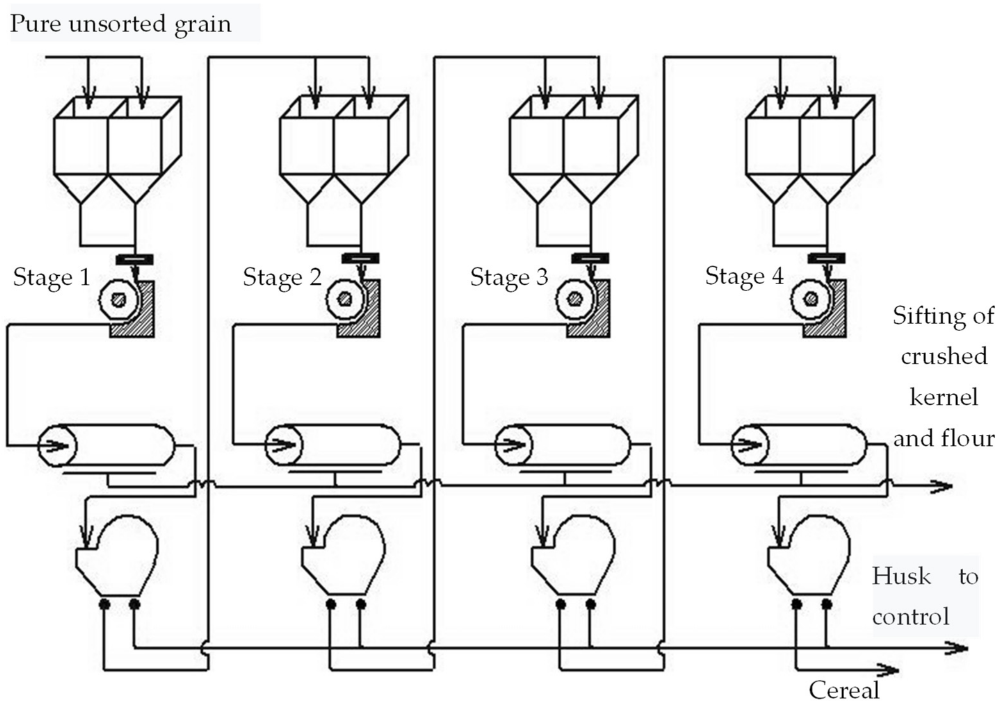

Figure 1. Schematic diagram of grain husking without intermediate kernel removal.

In schemes with intermediate selection of the kernel and the return of unhusked grains to the machine that performs the initial husking, groats are obtained as a result of the separation of the kernel (husked grains) in the sifting machines (Figure 2) after each pass through the husking machine.

In terms of kernel integrity, the most effective is the scheme with intermediate kernel selection and the use of a separate "ladder" system for reprocessing the remaining unhusked grains. According to this scheme, groats are obtained as a result of the separation of the kernel (in sorting machines, triers, etc.) after each passage through husking machines, returning unhusked grains to a specially allocated "ladder" system (husking machine) [19].

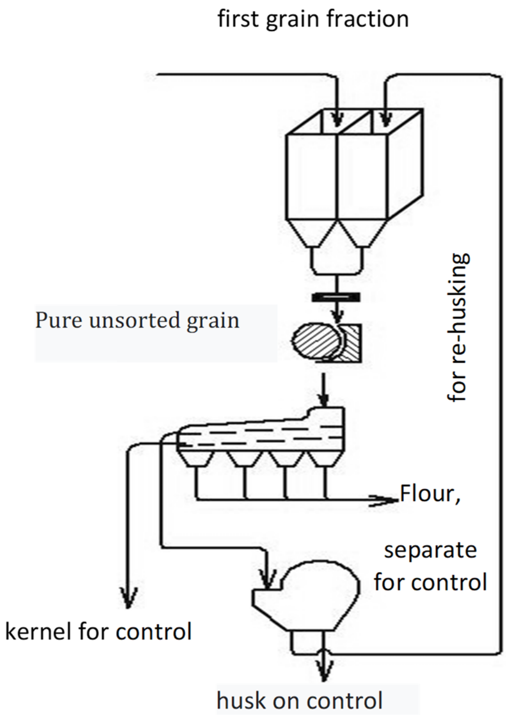

Figure 2. Schematic diagram of grain husking with intermediate kernel removal.

The analysis of the husking schemes showed that the most effective husking process is achieved if the system has an intermediate core removal system and a "ladder" system for re-husking the remaining (after the first pass) husked grains. This makes it possible to drastically reduce product turnover, reduce kernel crushing, increase the total yield of groats and reduce specific energy costs. If there is an intermediate selection of the core in the scheme, the turnover of the product decreases sharply.

Under the condition of using the scheme chosen by us, the total yield of groats, especially the whole kernel, increases dramatically, with a significant decrease in the output of crushed kernels and flour and a significant decrease in energy consumption for the groat production process as a whole.

The study of the influence patterns of the physical, mechanical and technological properties of cereal grains on the structural and technological schemes of husking machines and their modes of operation is reflected in the publications of I.N. Kovalenko, V.D. Kalininsky and V.L. Zlachevsky [20–22]. In the schemes discussed above, the husking process is carried out due to the influence of compressive and shear forces on the grain. Husking was carried out on a rolling machine. Currently, this is a classic scheme that is used in most buckwheat groat production enterprises (Table 1). The shell is removed when the grain passes through the gap between the roller and the tray. The main disadvantages of the equipment of this group include the need for preliminary sorting into fractions; the need to precisely adjust the gap between the roller and the deck; and significant energy consumption during operation (0.9–2.5 W·h/kg) [23].

This way, the use of the developed machine eliminates the need for the preliminary sorting of grain into fractions before husking and more efficiently concentrates energy on the destruction of grain. Therefore, the technology using it has a smaller amount of equipment and the specific energy consumption is reduced by 44–47%.

The second group of equipment for husking affects the grain with a single or multiple impacts [24]. The acceleration necessary to obtain the critical impact speed of the grain is obtained from the whips that rotate and throw the grain onto the tray, or with the help of blades installed on the rotor or tubes connected to the feeding hopper [25–27]. Otherwise, the grain freely slides off the guide cone and collides in free fall with the string rotating in the horizontal plane. Machines of this type can be used for husking buckwheat, which has a weak connection between the shell and the kernel. At present, most of the equipment of this group, except for bullocks, have almost no industrial use due to the insufficient research of the processes that take place in them. For further research, we chose the equipment from this group, namely the string husking device. The separation of grain into fractions and hydrothermal treatment significantly complicate and make more expensive the process of the production of cereals with intermediate kernel removal and the use of roller-deco machines. The use of a string husking device, due to its design, will make it possible to eliminate operations of preliminary sorting into fractions with a slight increase in the crushing ratio (a comparison was made with the production of groats using a preliminary hydrothermal treatment of buckwheat, with an increase of 1.1%) [28].

Table 1. Technology and list of equipment used in the traditional buckwheat groat production scheme and when using the developed string husking device.

Operation	Traditional Buckwheat Groats Production Scheme		Production Scheme When Using the Developed String Husking Device	
	Equipment Name	Specific Power W·h/kg	Equipment Name	Specific Power W·h/kg
Acceptance and quality control	Balance		Balance	
Separation	Grain separator	0.22	Grain separator	0.22
Hydrothermal treatment	Apparatus for hydrothermal treatment	0.12	—	
	Dryer	0.91	—	
Separation	Grain separator	0.22	—	
Husking	Rollers and deck machine	2.7	Developed string husking device	0.9
Separation	Grain separator	0.22	Grain separator	0.22
Packaging	Packing machine	1.94	Packing machine	1.94
Total		6.33		3.28

The technological process of husking cereal raw materials using a string husking device allows for a significant reduction in the number of passes, since with only a single pass of buckwheat, the efficiency of husking is 35% [29]. The design of the string dehusking device allows for a reduction in the energy consumption of the dehusking process, as it does not require additional movement of the grains, and the grain reaches the impact zone via self-flow thanks to the design of the guide cone. Therefore, conducting research on the husking process in a string husking device with the aim of developing the designs of energy-efficient husking machines is promising for the modern processing and food industry.

The purpose of this research is to reduce the specific energy consumption of the process of husking buckwheat by impact due to the use of a string husking device and the optimization of its technological and kinematic parameters.

In accordance with the set goal, the objectives of this research were as follows:

- To conduct analytical studies to establish mathematical dependencies between the energy and constructive–kinematic parameters of the operation of the string husking device;
- To conduct experimental studies to determine the specific energy consumption of a string husking device.

To solve the set problems, the technological process of buckwheat husking in a string husker was taken as the object of research, and the subject was the kinematic and structural parameters of husking.

2. Materials and Methods

Theoretical studies were carried out using the methods of an analysis and synthesis of the theories of elasticity and fracture mechanics, as well as a systematic analysis of the process of buckwheat husking by impact. The basis of this experimental research is the determination of the specific energy consumption of buckwheat grain husking.

This research was carried out on an experimental string husking device (Figure 3), created using the nodes of the husking and sorting complex of the APC—300M (Ukraine) in the laboratory of the Department of Equipment for Processing and Food Production, named after Professor F. Yu. Yalpachik, of the Tavri State University of Agricultural Technology, named after Dmytro Motorny (Ukraine) [30].

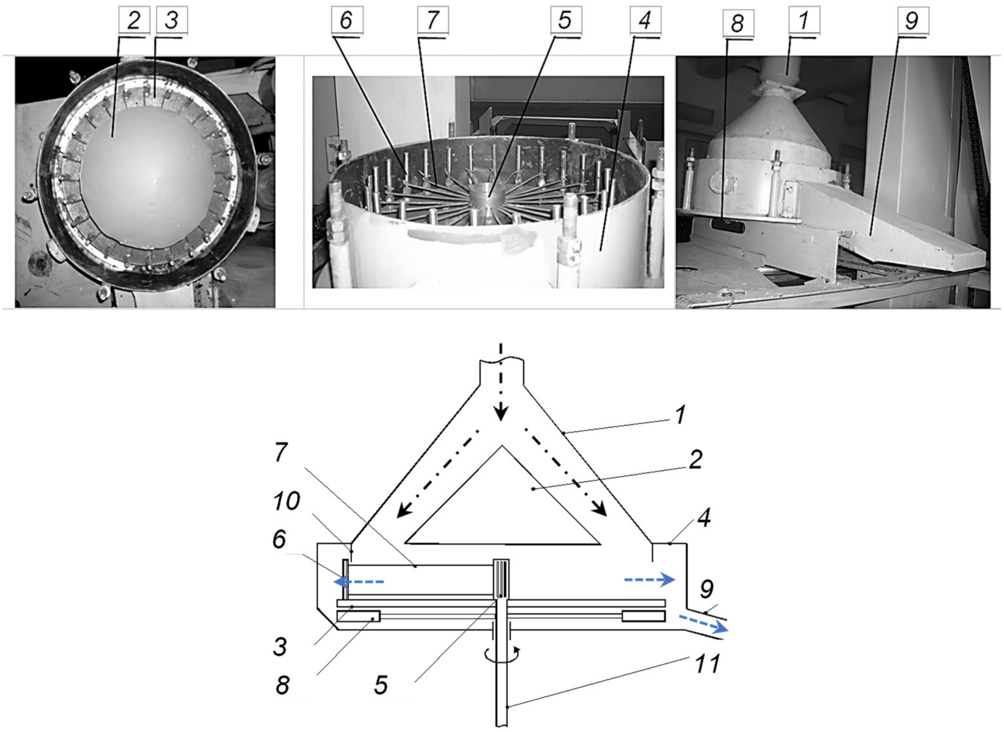

Figure 3. String husking device: 1—feed hopper; 2—guide cone, 3—disc; 4—body; 5—string distributor; 6—string holder; 7—string; 8—impeller; 9—outlet pipe; 10—partition;11—shaft. ‐·‐·‐➔ is the direction of movement of grain entering the husking zone. ‐‐‐‐‐➔ is the direction of movement of husked grain.

The technological parameters of the experimental string husking device are represented in Table 2.

Table 2. Technological parameters of the experimental string husking device.

Indicator	Value
Productivity, kg/h	700
Disc diameter, mm	340
Number of strings, pcs	24
Power, kW	0.65
Frequency of rotation of strings, s^{-1}	16
Length (taking into account the outlet nozzle) Width Height	590 380 550

Pre-cleaned grain, without sorting into fractions by size, entered the feeding hopper (1) (Figure 1). Passing through the channel created by the distribution cone and the housing, it enters the working zone, which is created by the disk, fixed rigidly in the horizontal plane on the shaft and body. Such feeding ensures the grain reaches the periphery of the disc. As a result, a single direct blow is realized, in which the same destructive force acts on the grain. Strings rotate in a plane perpendicular to the plane of grain fall, which ensures a constant direct impact. The proposed design of the string distributor and the string holder allows the number of strings necessary for the technological process at any level along the string holder to be set. To ensure the absence of grain crushing, the string holder is located on the periphery of the disk and is separated from the feed hopper partition. Next, due to the centrifugal acceleration that occurs during the rotation of the disk, kinetic energy is given to the husking products, which is directed to their removal from the husking zone. Then, the husking products are poured into the gap created by the disk and the housing, after which they fall into the cavity under the disk, and, reaching the output nozzle, are sent for further processing.

During the operation of the developed husking device, the stability of the direct impact of the working body on the grain was ensured, which is important for reducing the energy required for the destruction of the shell, while preserving the integrity of the kernel.

The purpose of experimental studies is to check the validity of theoretical studies. Here, we specify the mathematical description of the relationship between the specific energy intensity of the husking process and the technological indicators of the work.

The experimental program contains a study of the influence of the technological parameters of the buckwheat husking process on the specific consumption of electrical energy.

To perform the experiment, samples were selected in accordance with DSTU ISO 13690:2003, "Grains, legumes and products of their grinding. Sampling for analysis" [31]. Massive amounts of millet and buckwheat were obtained. The determined indicators of the buckwheat grain quality were the following: initial moisture content—12.4%; mass of 1000 grains—19.2 g; film density—19.3%; grain admixture content—1.8%; content of garbage admixture—2.4%; and the content of broken grains—0.8% [32,33].

The quality indicators of the buckwheat samples used for this experimental research correspond to DSTU 4524:2006, "Buckwheat. Technical conditions" [34].

To conduct experimental studies, a rotatable central composite plan was used, the advantages of which are the increased accuracy of obtaining the resulting equations. The values of the indicators obtained as a result of the experiments were processed using the Microsoft Excel and Matchcad-200 application programs, as well as a number of non-standard specialized programs [35–37].

In order to check the significance of the coefficients of the regression equation, the method of comparing the calculated value of the coefficient and its critical value was used [38,39]. The condition for the coefficients' significance can be seen in the following regression equation:

$$B_{0p}, B_{ip}, B_{ijp}, B_{iip} > t_T(q, f), \tag{1}$$

where B_{0p}, B_{ip}, B_{ijp}, B_{iip} are the calculated values of Student's criterion; $t_T(q,f)$ are the tabular value of Student's criterion for the level of significance (q) and the degree of freedom (f).

As a result of the calculations, a number of polynomial mathematical models describing the dependence of the response functions on the input parameters were obtained.

According to the research plan, a guide cone with a certain diameter of the lower base, which characterizes the beginning of the working zone, was installed. The drive of the string husking device is carried out by a direct current electric motor, which made it possible to adjust the frequency of rotation of the strings with the help of an autotransformer type 11-11 GOST 9532-67 (USSR); this method ensured the smooth adjustment of the rotation frequency of the shaft, and accordingly, of the strings, in the range from 5 to 20 s^{-1}. The engine of the string husking device was connected to the network through the measuring set K-541 GOST 11541-88 (Ukraine), with the help of cables and the control panel.

The shaft rotation frequency was determined by a mechanical centrifugal tachometer of the IO-10 time type (Ukraine), designed to measure the rotation frequency in the range of 25–10,000 rpm in five ranges. The error of device measurements is ±2% of the maximum limit in each range [40].

Studies of the influence of feeding on the effectiveness of the impact husking process were carried out by adjusting the diameter of the outlet opening of the feed hopper with a petal valve. The adjustment was made by turning the steering wheel, which caused the movement of the ring that regulates the position of the petals.

The energy index, namely the specific energy consumption for grain husking, was determined as follows [41]:

$$\Delta E = \frac{(I - I_{IM})U}{q}, \tag{2}$$

where I—the amperage in the stable mode of operation, A;

I_{IM}—the amperage in the idle mode of operation, A;

U—voltage, V;

q—productivity, kg/h.

In accordance with the above methodology, data had been obtained and processed regarding research on determining the energy intensity of the buckwheat husking process. Fisher's test and the standard method of determining the significance of factors were used to test the obtained models for adequacy.

3. Results

3.1. Analytical Determination of the Energetics of the Impact Husking Process

The impact of the string on the grain is quasi-elastic, since part of the energy generated during the impact is transferred to the residual deformation and heating of the bodies.

The kinetic energy lost when the string hits the grain is determined by the following known equation [42,43]:

$$E_0 - E_1 = \frac{1-k}{1+k} \cdot \left[\frac{1}{2} \cdot M_s \cdot (v_s - u_s)^2 + \frac{1}{2} \cdot m \cdot \left(v_g - u_g\right)^2\right], \tag{3}$$

where E_0—the kinetic energy of the system before impact, J;

E_1—kinetic energy of the system after impact, J;

k—recovery factor;

M_s—weight of the system, kg;

m—grain weight, kg;

v_s—speed of the system before impact, m/s;

u_s—speed of the system after impact, m/s;

v_g—grain speed before impact, m/s;

u_g—the velocity of the grain after impact, m/s.

Since the linear speed of the string at the moment of collision significantly exceeds the linear speed of the grain, it is reasonable to assume that $v_g = 0$.

Then,

$$E_1 = \frac{M_s}{M_s + m} \cdot E_0, \tag{4}$$

In our case, the weight of the grain is much smaller than the weight of the system that makes the impact, i.e., $M_s + m \approx M_s$, and, accordingly, $E_1 \approx E_0$. Based on this, although the impact is inelastic, there is practically no loss of energy during the impact, and the grain receives energy almost without loss [44].

The speed of points of a rigid body in spherical motion at each moment of time can be considered as rotation around the instantaneous axis of rotation. At the same time, the magnitude of the moment of inertia is not the same at different points of the system, since the distance from the axis of the system to the point under consideration also changes.

Therefore, the kinetic energy of a body performing spherical motion at the moment is determined by the following known equation [43]:

$$E_i = J_{zi} \cdot \frac{\omega_i^2}{2}, \tag{5}$$

where J_{zi}—the moment of inertia of the system at the i-th point, kg·m^2;

ω_i—the angular speed of rotation of the string at the i-th point, s^{-1}.

According to Euler's formula [45],

$$\omega_i = \frac{v_i}{R_i}, \tag{6}$$

where v_i—linear speed of rotation of the string at the i-th point of the working zone, m/s.

R_i is the i-th value of the distance from the axis of rotation of the string to the point of co-impact of the string with the grain, m (Figure 4).

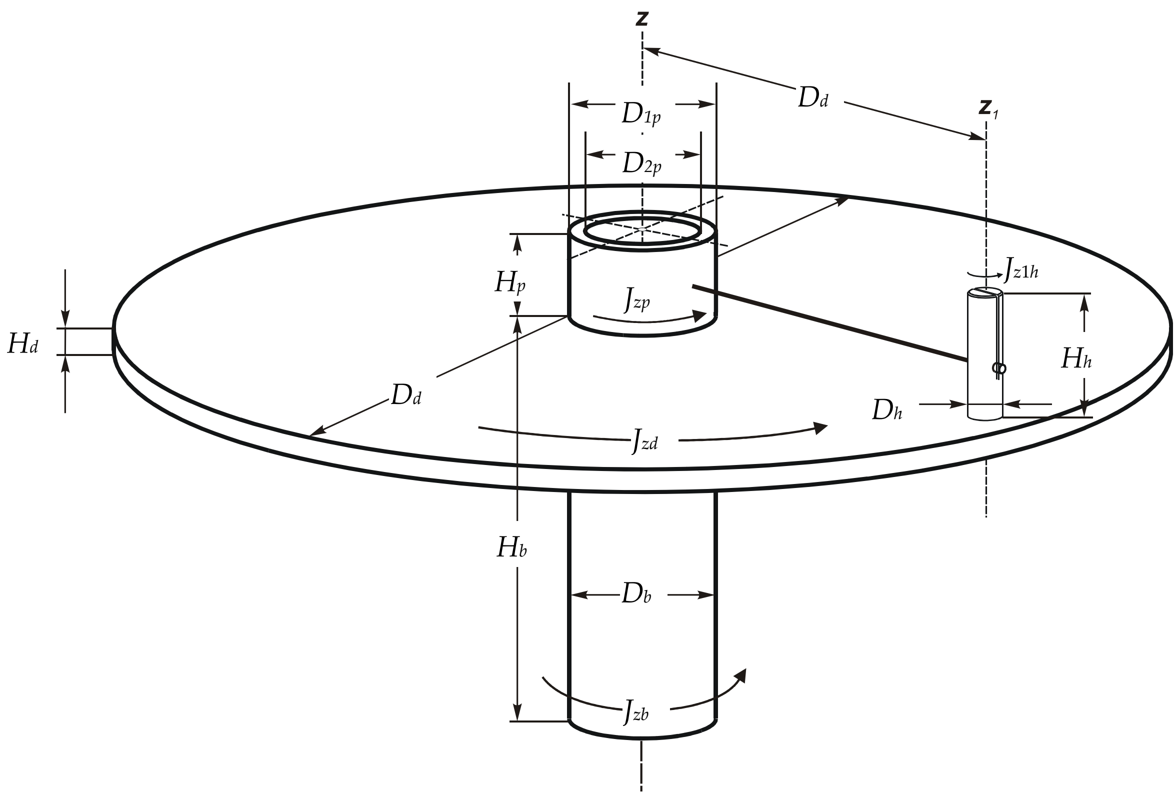

Figure 4. Scheme for calculating the moment of inertia of the system.

Based on Equations (5) and (6), we obtain the following expression:

$$E_i = J_z \cdot \frac{v_i^2}{2 \cdot R_i^2}, \tag{7}$$

The moment of inertia of the system at the ith point relative to the central axis of the system (z) consists of the sum of the moments of inertia of all components of this system at the same point relative to the z axis [42].

$$J_i = \sum J_j, \tag{8}$$

For our case, this concerns the shaft (the part of the shaft from the bearing unit and above is taken into account), string distributor, disc, strings and string holders (Figure 4).

$$J_z = J_{zb} + J_{zd} + J_{zp} + z \cdot (J_{zs} + J_{zh}), \quad (9)$$

where J_{zb}—the moment of inertia of the shaft, kg·m^2;

J_{zd}—the moment of inertia of the disk, kg·m^2;

J_{zp}—the moment of inertia of the string distributor, kg·m^2;

J_{zs}—the moment of inertia of the string, kg·m^2;

J_{zh}—the moment of inertia of the string holder, kg·m^2;

z—the number of strings, and, accordingly, string holders, pcs.

To determine the moments of inertia of parts of the system, we will use the method of determining the moments of inertia of homogeneous bodies relative to their own central axes [42]. The proper central axes of the shaft, disc and string distributor coincide with the central axis of the system, and the proper central axes of the string and string clamp are at some distance from it.

The moment of inertia of the shaft relative to the central axis of the system is determined by the following formula:

$$J_{zb} = \frac{1}{2} \cdot \pi \cdot \rho_b \cdot H_b \cdot R_b^4, \quad (10)$$

where R_b—the radius of the shaft, m;

ρ_b—the density of the material from which the shaft is made, kg/m^3.

H_b is the height of the shaft from the center of the bearing unit to the disc, m.

The equation for determining the moment of inertia of the disk relative to the central axis of the system has the following form:

$$J_{zd} = \frac{1}{2} \cdot \pi \cdot \rho_d \cdot H_d \cdot R_d^4, \quad (11)$$

where R_d—the radius of the disk, m;

ρ_d—the density of the material from which the disc is made, kg/m^3;

H_d—the thickness of the disk, m.

The moment of inertia of the string distributor relative to the central axis will equal

$$J_{zp} = \frac{1}{2} \cdot \pi \cdot \rho_p \cdot H_p \cdot \left(R_{1p}^4 - R_{2p}^4\right), \quad (12)$$

where R_{1p}—the outer radius of the string distributor, m;

R_{2p}—the inner radius of the string distributor, m;

ρ_p—the density of the material from which the string distributor is made, kg/m^3;

H_p—the height of the string distributor, m.

Considering the geometric dimensions and weight of the strings, it is advisable to neglect its moment of inertia, that is, to assume that

$$J_{zs} = 0. \quad (13)$$

Since it is known that the moment of inertia of a rigid body relative to an axis is equal to the moment of inertia of a body relative to a parallel axis passing through its center of mass, added to the product of the mass of the body by the square of the distance between the axes, then the moment of inertia of the string holder relative to the main axis of the system is equal to

$$J_{zh} = J_{z_1 h} + m_h \cdot c^2, \quad (14)$$

where $J_{z_1 h}$—the moment of inertia relative to its own central axis z_1, kg·m^2;

m_h—the weight of the string holder, kg;

c—the distance from its own central axis (z_1) to the central axis of the system (z), *m*.

Relative to its own central axis, the moment of inertia of the string holder is determined by the following formula:

$$J_{z_1h} = \frac{1}{2} \cdot \pi \cdot \rho_h \cdot H_h \cdot R_h^4, \tag{15}$$

where R_h—the radius of the string holder, m;

ρ_h—the density of the material of which the string holder is made, kg/m^3;

H_h—the height of the string holder, m.

We obtain the equation for determining the moment of inertia of the string holder relative to the central axis of the system:

$$J_{z_1h} = \frac{1}{2} \cdot \pi \cdot \rho_h \cdot H_h \cdot R_h^4 + \pi \cdot \rho_h \cdot H_h \cdot R_h^2 \cdot c^2, \tag{16}$$

After transformations, we obtain the formula for determining the moment of inertia of the system relative to the central axis:

$$\begin{array}{l} J_z = \frac{1}{2} \cdot \pi \cdot \rho_b \cdot H_b \cdot R_b^4 + \frac{1}{2} \cdot \pi \cdot \rho_p \cdot H_p \cdot \left(R_{1p}^4 - R_{2p}^4\right) + \frac{1}{2} \cdot \pi \cdot \rho_d \cdot H_d \cdot R_d^4 \\ +\frac{1}{2} \cdot z \cdot \pi \cdot \rho_h \cdot H_h \cdot R_h^4 + z \cdot \pi \cdot \rho_h \cdot H_h \cdot R_h^2 \cdot c^2 \end{array}, \tag{17}$$

Taking expressions (7) and (17) into account, we obtain an equation that will allow us to determine the kinetic energy of the system at any of its points:

$$E_i = \frac{1}{4} \cdot \frac{\pi \cdot v_i^2}{R_i^2} \cdot \left(\begin{array}{l} \rho_b \cdot H_b \cdot R_b^4 + \rho_p \cdot H_p \cdot \left(R_{1p}^4 - R_{2p}^4\right) + \rho_d \cdot H_d \cdot R_d^4 \\ +z \cdot \rho_h \cdot H_h \cdot R_h^4 + \frac{1}{2} z \cdot \pi \cdot \rho_h \cdot H_h \cdot R_h^2 \cdot c^2 \end{array} \right) \tag{18}$$

The weight of the grain is much smaller than the weight of the system, and accordingly, the kinetic energy of the grain is much smaller than the kinetic energy of the system, which it has at any point in the working zone along the string. Taking into account the above, it is reasonable to assume that during the impact, the grain is given energy equal to the kinetic energy of the system at the point of impact. The accepted assumption allows us to neglect a part of the kinetic energy that will not be used for the destruction of the shell, but will go to move the grain [41].

Since the feed (q) determines the second loading of the dehusking device, then the number of kernels that collide with the strings will be

$$n_0 = \frac{1000 \cdot q}{M_{1000} \cdot n}, \tag{19}$$

where q—the feed of the husking device, kg/s;

M_{1000}—the weight of 1000 grains, kg;

n—the frequency of rotation of the strings, s^{-1}.

Taking into account the above equation for determining the energy spent by the drive motor on grain husking, it will have the following final form:

$$\Delta E_i = \frac{250 \cdot \pi \cdot V_i^2 q \cdot z}{R_i^2 \cdot M_{1000}} \left(\begin{array}{l} \rho_b \cdot H_b \cdot R_b^4 + \rho_p \cdot H_p \left(R_{1p}^4 - R_{2p}^4\right) + \rho_d \cdot H_d \cdot R_d^4 \\ +z \cdot \rho_h \cdot H_h \cdot R_h^4 + \frac{1}{2} z \cdot \pi \cdot \rho_h \cdot H_h \cdot R_h^2 \cdot c^2 \end{array} \right), \tag{20}$$

where z is the number of strings, pcs.

The specific energy capacity is determined as

$$\Delta E = \frac{250 \cdot \pi \cdot V_i^2 \cdot z}{R_i^2 \cdot M_{1000}} \left(\begin{array}{l} \rho_b \cdot H_b \cdot R_b^4 + \rho_p \cdot H_p \left(R_{1p}^4 - R_{2p}^4\right) + \rho_d \cdot H_d \cdot R_d^4 \\ +z \cdot \rho_h \cdot H_h \cdot R_h^4 + \frac{1}{2} z \cdot \pi \cdot \rho_h \cdot H_h \cdot R_h^2 \cdot c^2 \end{array} \right) \tag{21}$$

The resulting equation for determining the specific energy intensity of the husking process in the string husking device allows us to determine this indicator, taking into account the main technological parameters of the device, the operating parameters and the physical and mechanical properties of the raw material.

3.2. Results of Experimental Studies of the Energetics of the Husking Process in a String Husking Device

As a result of conducting research according to the developed methodology for determining the specific energy intensity of the process of husking buckwheat by impact, an array of data were obtained.

During the processing of experimental data, the dispersion of observation errors (D_n) was determined, as well as the critical values of the coefficients of the regression equation (for groups of coefficients according to their interaction: free coefficient, single interaction, inter-factor interaction and quadratic interaction (B_0, B_i, B_{ij}, B_{i2}, respectively)), the dispersion series of errors (grouped similarly to coefficients) (S_0, S_i, S_{ij}, S_{i2}) the inadequacy error and Fisher's calculation criterion (F_r), which were calculated according to the methodology (Table 3) [46].

Table 3. Results of calculations and analysis of regression equations for determining the specific energy intensity of the buckwheat husking process.

Indicator Name	Symbol	Significance
The variance of observation errors	D_n	0.300
Critical value of free coefficient	B_0	0.574
Critical value of coefficient of single interaction	B_i	0.381
Critical value of coefficient of inter-factor interaction	B_{ij}	0.498
Critical value of coefficient of quadratic interaction	B_{ii}	0.371
Error variances of free coefficient	S_0	0.223
Error variances of coefficient of single interaction	S_i	0.148
Error variances of the inter-factor interaction coefficient	S_{ij}	0.194
Error variances of coefficient of quadratic interaction	$S_i{}^2$	0.144
Error of inadequacy	S_H	6.205
Fisher's calculation criterion	F_r	2.24

When processing the results of the experimental studies and removing factors with insignificant coefficients from the regression equations, the following functional relationship was established between the three factors mentioned above (the frequency of string rotation, n—X_1; the value of the distance from the axis of rotation of the string to the point of co-impact of the string with the grain, R—X_2; and the feed, q—X_3) and the specific energy intensity of the process:

$$\begin{aligned} Y = 0.504 + 0.033X_1 - 0.022X_2 + 0.029X_3 + 0.034X_1X_2 - 0.016X_2X_3 \\ -0.019X_1X_2X_3 + 0.013X_2^2 \end{aligned} \tag{22}$$

In the obtained equations, the coded factors X_1, X_2 and X_3 are related to independent variable indicators' (n (string rotation frequency), R_i (distance from the axis of rotation of the string to the point of collision of the string with the grain) and q (grain flow supply)) dependencies, as follows:

$$X_1 = \frac{n - 16.25}{2.05}, \tag{23}$$

$$X_2 = \frac{R_i - 0.1}{0.01}, \tag{24}$$

$$X_3 = \frac{q - 0.135}{0.045} \tag{25}$$

The analysis of the obtained analytical dependencies shows that with an increase in the frequency of rotation of the strings, an increase in the specific energy intensity of the process is observed (Figure 5).

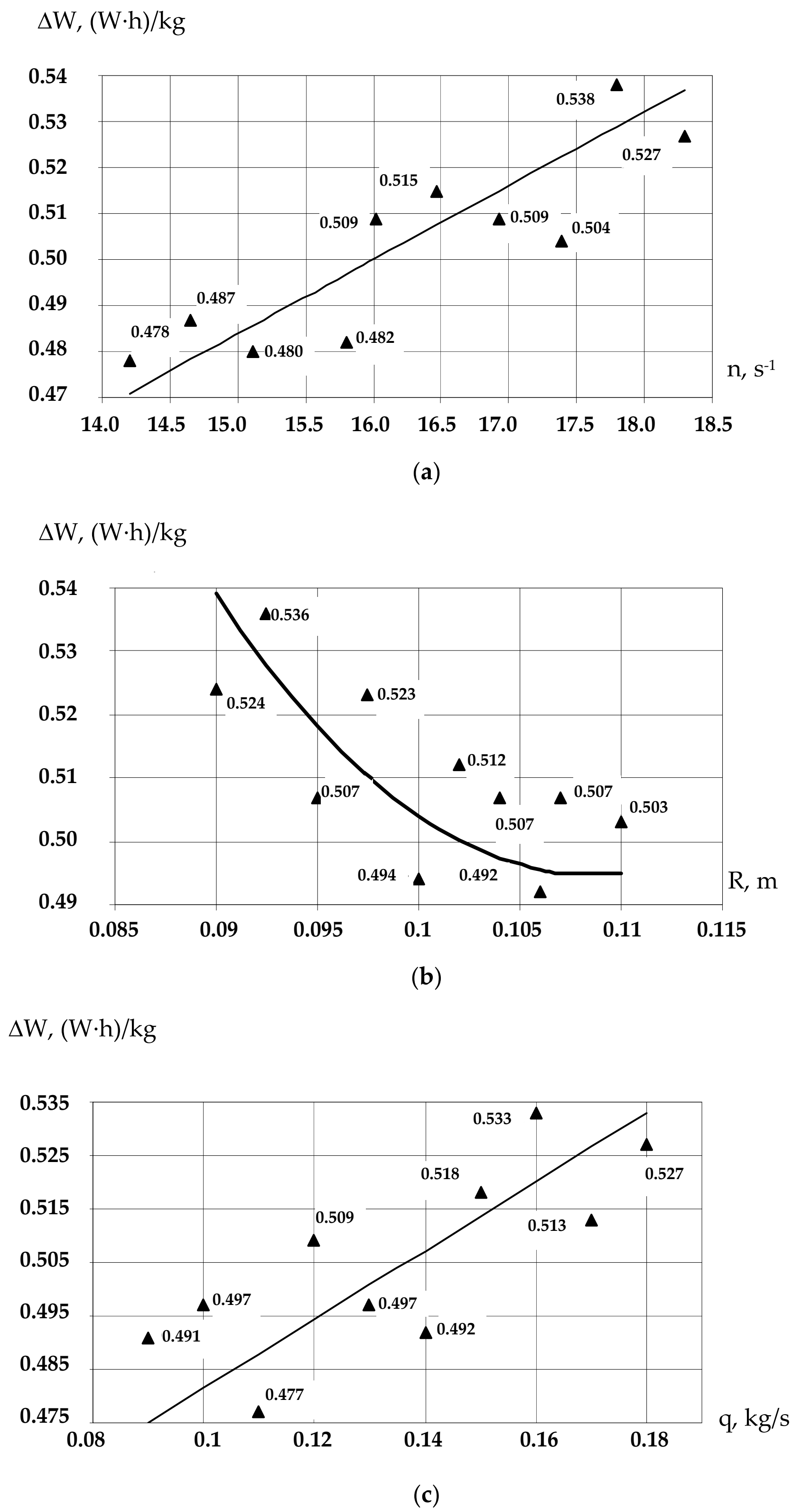

Figure 5. Experimental dependences of the specific energy of buckwheat husking on (**a**) the frequency of rotation of the string; (**b**) the distance from the axis of rotation of the string to the point of co-impact of the string with the grain; and (**c**) the grain supply.

In the studied range of rotation frequencies, the coefficient of the quadratic indicator of the considered factor is determined to be insignificant, according to the methodology discussed in the previous subsection. From the above, it can be concluded that despite the gradual nature of the factor's influence on the criteria, in the considered interval, the dependence takes on an almost linear character. The confirmation of the conclusion is the conduct of research regarding the recognition of the adequacy of the obtained models.

4. Discussion

The analysis of theoretical studies proves that the specific energy capacity is inversely proportional to the square of the *i*-th value of the distance from the axis of rotation of the string to the point of co-impact of the string with the grain, which determines the corresponding nature of the dependence.

Taking into account the minimization of energy consumption while maintaining high indicators of husking efficiency, the optimal research ranges were chosen: the distance from the axis of rotation of the string to the point of collision of the string with the grain (radius of the lower base of the guide cone): 0.102–0.108 m; the frequency of rotation of the strings: 15.8–16.9 s^{-1}; and the supply: 0.14–0.155 kg/s.

Despite the significant relationship between the frequency of rotation of the strings and the ith value of the distance from the axis of rotation of the string to the point of co-impact of the string with the grain, the influence of each of them was determined experimentally. As the distance at which the grain collides with the string increases, the specific energy intensity of the process after overcoming a certain gap begins to decrease significantly. However, at the same time, there comes a stage when the energy that the string can provide to the grain becomes insufficient to destroy the shell at the set values of the rotation frequency, or the rotation frequency becomes excessively high for optimal use.

Taking into account the minimization of energy consumption (Figure 5b), it was experimentally established that the most optimal value of the considered indicator is 0.106 m.

Similar to the effect of the frequency of rotation of the strings, the nature of the change in the specific energy intensity of the husking process is also observed when the supply of the product to the working area is increased (Figure 5c). Thus, an increase in the product supply to the buckwheat husking zone by 0.01 kg/s (from 0.12 to 0.13 kg/s) will cause an increase in the specific energy intensity of the process by 1.4% (from 0.495 to 0.502 Wh/kg).

Despite the identical nature of the effect of the frequency of rotation of the strings and the supply of the product to the working area on the specific energy intensity of the grain husking process, the above-mentioned factors are not interconnected and their ratio is not a constant value. Taking into account the above, it was decided to experimentally investigate the influence of both of these factors on the criterion of specific energy capacity.

From the graphic interpretation of the regression model (22), a rather obvious regularity of the following order follows: the degree of influence of the variable parameter (n) on the initial value (ΔW) increases as the value of the parameter (q) increases.

When increasing the feed, in order to increase the probability of the grain hitting the string, it is necessary to increase the rotation frequency. However, when the critical value of the critical linear speed is reached, a further increase in the rotation frequency is technologically unprofitable due to a sharp decrease in the core integrity coefficient and, accordingly, in the husking efficiency.

The experimental values of the specific energy capacity were compared with a similar indicator of the 2DShS rolling mill with two decks (2.7 Wh/kg), the SGR-600 rolling deck machine (2.5 h/kg) and the experimental equipment (0.9 W·h/kg) [27], and determined a reduction of the studied indicator by 44–47% for the equipment currently used for buckwheat husking.

5. Conclusions

1. The Green Deal strategy, to a large extent due to the reduction in energy consumption in all branches of production, provides for the creation of a resource-efficient and competitive economy. An important direction of this strategy is the grain production sustainability, which includes the need to reduce the amount of equipment and/or reduce energy costs for grain processing. This way, two out of the three pillars of sustainability are improved: environmental and economic. On the basis of theoretical and experimental studies, a simple and effective solution to these problems in the production of buckwheat groats is justified—the use of a string husking device. It eliminates the need to pre-sort the grain into fractions before shelling and more efficiently concentrates energy on the destruction of the grain. Therefore, the technology using it has a smaller amount of equipment, and specific energy consumption is reduced by 44–47%.

2. The result of this analytical research is the development of a mathematical model of buckwheat husking in a string husker. It helped to determine the functional relationship between the frequency of rotation of the string; the value of the distance from the axis of rotation of the string to the point of co-impact of the string with the grain and feed; and the specific energy intensity of the process.

3. The experimental studies resulted in determining the optimal ranges of the technological and kinematic parameters of the husking device: the distance from the axis of rotation of the string to the point of collision of the string with the grain (radius of the lower base of the guide cone)—0.102–0.108 m; the frequency of rotation of the strings—15.8–16.9s^{-1}; and the feed—0.14–0.155 kg/s. It has been proven that the specific energy intensity of the husking process in the developed device is 44–47% less than the equipment currently used for husking buckwheat, and is 0.491–0.498 Wh/kg.

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