The Results of Studies on the Assessment of the Destruction of Soil Clods during Combine Harvesting of Potatoes

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Abstract: Existing potato harvesters cause damage to marketable products as a result of the interaction of potato tubers with each other, with working bodies and soil clods, given the wide variety of soil and climatic conditions in which the harvesting process takes place. In addition, under homogeneous soil and climatic conditions within the same accounting area, there is a large deviation from the average values of the main physical soil constants—moisture and hardness. Field studies were carried out to determine the fractional composition of soil clods, size-mass parameters, as well as their physical and mechanical properties with the identification of the greatest force for their destruction. The article presents a methodology for conducting research to assess the influence of working bodies on the magnitude of the force impact on potato tubers and soil clods during harvesting, a methodology for assessing the dynamic destruction of soil clods. The results of comparative studies of the force impact of the working bodies of modern potato harvesters, which affect the destruction of soil clods, causing damage to potato tubers as a result of their interaction with soil clods are presented.

Keywords: harvesting; force action; potato; working body; harvesting machines; device for assessing the suitability for harvesting

1. Introduction

The main factors that inflict damage to potato tubers during mechanized harvesting are the design of potato harvesters and the material [1–3] from which the working bodies of the machines and operating modes are made [4,5]. An important role is played by the physical and mechanical properties of tubers [6,7], which, in turn, depend on the variety, agricultural techniques of cultivation, soil structure, and climatic conditions. To determine the location and register the magnitude of the greatest force impact of the working bodies of potato harvesters on potato tubers, as well as recommendations for subsequent changes in the design and technological parameters of harvesting machines and the development of devices that ensure the stability of potato tubers to mechanized harvesting, experimental studies were conducted using the software tool “Electronic Potato Tuber Log” in the Moscow region of JSC “Ozery”. In addition, when conducting research on the assessment of the force impact of the working bodies of harvesting machines, it was found that despite the saturation of machines with separating working bodies of various designs and their intensification, the mass of soil impurities in the total volume of the tuberous heap reaches threshold values of 46–50% (Figure 2), depending on the fractional composition.
Therefore, studies aimed at establishing the patterns of interaction between tubers and working bodies, soil clods, and the establishment of physical and mechanical properties to determine the magnitude of the dynamic impact that contribute to the destruction of soil clods are relevant, so they will ensure the development of harvester devices, providing an exception, whether or not there is a decrease in the receipt of soil clods in the device for collecting marketable potato products.

2. Materials and Methods

The programmable tool “Electronic Potato Tuber Log” (Figure 3) includes: a data logger 1, made in shape, size, and density by a standard potato tuber, a personal 2 or tablet computer 3, with installed software for processing, registered root crop damage data and its subsequent analysis, as well as an auxiliary 4. Electronic potato equipment allows you to record the magnitude of the acquired acceleration, as well as the impulse of the impact force from its interaction with the working body. Studies to determine the places of damage on the web of the rod elevator of the potato harvesting machine were carried out at different values of the translational VEL of the speed of movement of the rod elevator [8,9]. To fix the location and time of damage to the data logger 1, an Inspector Tornado DVR with a screen resolution of 960 × 240 and a diagonal viewing angle of 150° mounted on a laboratory tripod was fixed on the rod elevator [7,10].
Figure 3. General view of the programmable tool “Electronic potato Tuber Log”: 1—data logger; 2—computer; 3—tablet computer; 4—auxiliary equipment.

The use of video recording of the movement of the data logger on the surface of the bar elevator is due to the need to compare the time intervals obtained from the DVR with the diagrams of the personal computer of the software tool “Electronic Potato Tuber Log”, followed by their superimposition to determine the location of the greatest force impact of the bar elevator on the data logger [11–14].

Experiments to assess the force effect of working bodies on potato tubers were carried out on potato harvesting machines of the following brands: AVR-Spirit-6200 combine harvester (Belgium, Roeselare), Dewulf RA-3060 combine harvester (The Netherlands, Winsum), and Bolko combine harvester (Poland, Grudziądz). The methodology of conducting experimental studies is as follows. Before conducting experimental studies on the accounting plot, the physical and mechanical properties of the soil were determined: moisture and hardness, according to the method of STO AIST 8.7–2013 “Machines for harvesting vegetable and melon crops. Methods for assessing functional indicators” (STO AIST 8.7–2013, et al.). The technological parameters of the potato harvesting machine before the research were set to optimal operating modes, in which the depth $h_P$ of immersion of the digging ploughshare into the soil was set below the depth of potato tubers in a range of 0.12–0.18 m, which is due to the depth of planting tubers. The translational speed $V_M$ of the potato harvester movement in the course of experimental studies was set in a range of 3–5.2 km/h. The optimal values of the translational $V_{EL}$ of the speed of movement of the rod elevator of the potato harvesting machine under study were set in a range of values from 3.6 to 6.4 km/h, due to the prevention of unloading of the tuberous pile on the surface of the rod elevator. With the steady mode of movement of the web of the bar elevator, the DVR was turned on, and the data logger “Electronic Potato Tuber Log” was fed from container 2 for the preliminary placement of the pile. Consequently, after data logger 1 (Figure 1) passed the surface of the bar elevator, the logger was turned off, the studied factors were changed, and the experiment was repeated by the chosen research plan. In order to determine the destruction of soil clods under the dynamic action of the separating devices of the harvester, laboratory studies were carried out on a device (simulator of dynamic effects) that simulates the operation of the cleaning devices of the harvester (Figures 4 and 5). This specified device consists of a drum with rubberized rods 1, a blade 2 and an open window behind it for loading and unloading a batch of test tubers. Inside the drum, a finger slide 3 is installed above its axis, which allows you to change the angle of inclination. Fixed walls are installed at the ends of the drum, designed to keep tubers from rolling out of the drum and simulate the sides of the elevator and the sides of other working bodies of potato harvesters. The device consists of a drum with rubberized rods 1, with a blade 2 and an open window behind it for loading and unloading a batch of test tubers. Inside the drum, a finger slide 3 is installed above its axis, which allows you to
change the angle of inclination. Fixed walls are installed at the ends of the drum, designed to keep tubers from rolling out of the drum and simulate the sides of the elevator and the sides of other working bodies of potato harvesters.

![Diagram of the device](image)

**Figure 4.** Design and technological scheme of the device for assessing the suitability of varieties and hybrids for mechanized harvesting: 1—rod drum; 2—blade; 3—finger slide; 4—shaker.

![Laboratory installation](image)

**Figure 5.** A general view of the laboratory installation for assessing the force effect of a mock-up sample of a device for assessing the suitability of varieties and hybrids for mechanized harvesting: 1—a support platform; 2—a control cabinet; 3—a drum; 4—a personal computer; 5—a data recorder; 6—a finger slide.

The separating devices imitate the instantaneous impact that takes place in the field by changing the rotational speed of the bar drum 3 and the translational speed of the finger slide 6.

The estimated number of cycles is determined based on the correspondence between the number of drops and the path travelled by potato tubers along the elevator of the potato harvester and the simulator. The determinant of damage to tubers works as follows: A portion of the test potato tubers is placed in the rod drum 1 through the window. When the drum rotates clockwise, blade 2 captures the tubers and lifts them to a predetermined height, which is set by changing the angle of inclination of the blade. With further rotation of the drum, the tubers fall on finger slide 3, simulating the drops and movement of tubers along the combine’s hedgehog conveyors. From finger slide 3, the tubers roll down onto the rubberized rods of the drum (imitation of another drop) along which they roll until they return to blade 2, simulating the elevator of a potato harvester. When rolling over the inner surface of the drum, the tubers bump into rod 4, simulating the elevator shaker. Fixed sidewalls at the ends of the drum keep the tubers from rolling out of the drum and the finger slide while imitating the sidewalls of the elevator and the finger conveyors of potato harvesters. Then the cycle repeats. When the set number of cycles is counted, the drum is reversed and the tubers are poured out through the window into the receiving container and the movement of the drum is automatically turned off. The estimated number of cycles
is determined based on the correspondence between the number of drops and the path travelled by potato tubers along the elevator of the potato harvester and the simulator. Experimentally, the number of cycles for each type of potato harvester is specified by the calibration method when harvesting potatoes in the field. The height of the differences on the simulator is limited by the design dimensions of the drum and must correspond to the differences in potato harvesters. A greater fine-tuning of the damage simulator for a specific harvesting machine is achieved by changing the angle of rotation of blade 2 and the location of the finger slide 3 of the simulator.

Experimental studies on the assessment of the force effect on potato tubers were carried out on a mock-up sample of a device for assessing the suitability of varieties and hybrids for mechanized harvesting, the design and operating principle of which were developed at the FSBI FSAC VIM (Figure 5).

The electronic potato allows you to record the magnitude of the acquired acceleration, as well as the momentum of the impact force from its interaction with the working elements of the laboratory installation.

In addition, using this device, experimental studies were carried out to determine the dynamic impact on the destruction of soil clods.

The mass of the lump was determined with an accuracy of 0.1 g on an electronic balance M-ER 122ACFJR-300.01 LCD (Figure 6).

![Figure 6](image6.png)

**Figure 6.** Weighing the soil clod: 1—soil clod; 2—electronic scales M-ER 122ACFJR-300.01 LCD.

The dimensions of the soil clods were determined with a caliper (Figure 7), which provides a measurement accuracy of 0.02 mm.

![Figure 7](image7.png)

**Figure 7.** Determination of the dimensional characteristics of soil clods.

To determine the energy of destruction of soil clods, it is necessary to conduct studies on the interaction of soil clods with the material of the separating surface of harvesting machines in identifying the critical height of the fall of the destruction of the clod. To conduct these studies, soil samples were prepared (Figure 8), corresponding to the moisture
content during harvesting and formation of a monolithic soil layer (Figure 9) with the appropriate dimensions: length \((L_k = 5\, \text{cm})\), height \((H_k = 5\, \text{cm})\), and thickness \((T_k = 5\, \text{cm})\).

Figure 8. Soil sample diagram.

Figure 9. General view of the destruction of soil clods on the bars of the separating surface: 1—the canvas of the rod elevator; 2—reference scale; 3—soil sample.

When carrying out studies on the energy of destruction of soil clods, the moisture content of the studied soil samples varied from 10 to 24% with an interval of variation towards an increase of 1% via the method of surface moistening and its determination by the thermostatic-weight method.

3. Results and Discussion

Therefore, an assessment of the graphical dependencies (Figure 2) obtained during experimental studies on the Bolko S combine harvester is distinguished by the most “gentle” force effect of the working bodies of the harvesting machine on the tuberous pile, where throughout the entire cleaning process, there is a minimal force effect on the separated
products in a range from 3 N to 6.5 N, which is 28–31% of the maximum force effect of the working bodies of the AVR-Spirit harvesting machines-6200 and “Dewulf RA-3060” (Figure 10) [14].

Figure 10. Structural and technological scheme of the Bolko combine harvester: 1—frame; 2—vertical discs; 3—digging ploughshare; 4—support wheel; 5—main elevator; 6—shaker; 7—transverse elevator; 8—bulkhead table; 9—hopper [15].

The conducted analysis of the experimental data presented in Figure 9 allows us to conclude that in the process of soil separation, tubers certainly interact with the active and passive working organs of the potato harvester. Therefore, tubers fall during the passage of the shaking section on the bars of the elevator and during the transition from one elevator to another, which is reflected in the graphical dependencies presented above.

At differences from one elevator to another, tubers fall from a height of no more than 0.2 m, which corresponds to a collision speed of 1.9 m/s and satisfies the permissible collision speed of tubers with working bodies (2.2 m/s). The speed of collision of tubers thrown by the bars of the elevator from the impact of the shaker, with the vertical component of the speed of the bars of the elevator 0.7 m/s or more, will be more than 2.6 m/s, which is higher than the permissible speed of collision of tubers with the working bodies of machines. As a result, tubers are damaged in this area.

Each parameter of the size/mass characteristics was measured in triplicate, after which the average values of mass measurements were used to estimate the variation series. At the same time, the concepts and elements generally accepted in variation statistics to characterize the variation series were used: average variation—$X$, standard deviation—$\sigma$, and coefficient of variation—$v$. Each of the main elements was determined according to the known formulas of variation statistics.

This made it possible to determine the accuracy of the experimental data and to establish the acceptable limits within which they were sufficiently reliable.
To determine the number of intervals (K) for varying the values of the parameters of the size/mass characteristics of tubers, we used the empirical relationship \[2,16]\n
\[K = \sqrt{n}\] (1)

where \(n\) is the number of tubers, pcs.

\[K = \sqrt{100} = 10\]

The sampling range can be expressed as:

\[R = \text{xmax} - \text{xmin},\] (2)

where \(\text{xmax}\) and \(\text{xmin}\) denote the maximum and minimum values of the investigated feature.

The interval of the investigated feature is calculated as follows:

\[D = \frac{R}{K}\] (3)

The size/mass characteristics of tubers combine the following features: the shape, size, and weight.

While planning a multifactorial experiment, it is necessary to analyze and determine the input parameters of the sorting process, which most significantly affect the quality indicators of the sorting. The selected factors should be controllable, unambiguous, compatible, independent, and the accuracy of measurements of the factor levels should be higher than the accuracy of the optimization parameter values.

When studying the process of separation of soil impurities and damage to potato tubers, factors were identified, the total number of which was initially 15, which covered the technological, design parameters of the separating devices, as well as the physical and mechanical properties of the soil.

As the results of studies of the fractional composition of soil clods show, one should take into account the fact that within one fractional group, there are also soil clods that differ in mass within one accounting plot (sampling in the harvester bunker was carried out every 15 m of movement). The mass of soil clods during the research is displayed in the diagrams in Figure 11.

![Figure 11](image-url)  
*Figure 11. Cont.*
2.1-10 10.1-15 15.1-22 22.1-30
2.1-10 10.1-15 15.1-22 22.1-30
2.1-10 10.1-15 15.1-22 22.1-30

Figure 11. Fractional composition and mass of soil clods.

Analysis of the diagrams presented in Figure 9 indicates that within one fractional group, the mass of soil clods differs by an average of 10–15.4%, which should be explained by the distinctive physical and mechanical properties of soil clods, even within the same sample taken and the pattern of mass change soil clods is probabilistic in nature.

At the same time, it should be noted that the strength properties of soil clods and the boundaries of their destruction, depending on the density and moisture content, were determined under a five-fold dynamic impact, based on the condition of destruction of at least 90% of soil clods.

At the same time, the allowable loads were limited by the condition of tuber damage: the maximum allowable fall height on the metal lattice surface is not more than 0.25 m; the value of static compression is within 200–250 N. The results of the studies of the destruction of the soil layer are presented in Table 1.

Conducting research on the dynamic destruction of soil clods was carried out when determining the mass of a soil sample of clods, the probability of the appearance of a fractional composition of which is the greatest, namely, 20, 25, and 30 mm.

The results of the studies on the force impact of the working bodies of harvesters on damage to potato tubers and the destruction of soil clods indicate that the implementation of the process of destruction of soil clods on the separating devices of modern machines for harvesting root crops is not possible, due to the limiting correlation—wearing the injury rate of tubers up to 18 N, which does not allow one to ensure the destruction of the soil clod, the minimum value of the dynamic impact of which is 243.6 N, which exceeds the maximum allowable force effect exerted on the potato tuber by 2.3-times.

The correlation dependence of the statistical destruction and density of soil clods on their moisture content is represented by a system of expressions:

\[
\begin{align*}
P_K(W) &= 326.14 - 9.54W + 0.27W^2 \\
\rho(W) &= 2293.5 + 327.6W - 6.39W^2
\end{align*}
\] (4)
Table 1. The results of studies on the dynamic destruction of soil clods.

<table>
<thead>
<tr>
<th>Absolute Humidity of Leached Chernozem, %</th>
<th>Dynamic Impact, H</th>
<th>Soil Density, kg/m³</th>
<th>Soil Clods Diameter, mm</th>
<th>Weight, g</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>243.6</td>
<td>1430</td>
<td>20.0</td>
<td>10.8</td>
</tr>
<tr>
<td>18</td>
<td>244.2</td>
<td>1540</td>
<td>25.0</td>
<td>46.6</td>
</tr>
<tr>
<td>18</td>
<td>242.8</td>
<td>1720</td>
<td>30.0</td>
<td>75.4</td>
</tr>
<tr>
<td>20</td>
<td>248.7</td>
<td>1530</td>
<td>20.0</td>
<td>12.4</td>
</tr>
<tr>
<td>20</td>
<td>246.2</td>
<td>1760</td>
<td>25.0</td>
<td>56.4</td>
</tr>
<tr>
<td>20</td>
<td>246.5</td>
<td>1840</td>
<td>30.0</td>
<td>78.7</td>
</tr>
<tr>
<td>22</td>
<td>253.4</td>
<td>1740</td>
<td>20.0</td>
<td>14.3</td>
</tr>
<tr>
<td>22</td>
<td>253.2</td>
<td>1850</td>
<td>25.0</td>
<td>58.7</td>
</tr>
<tr>
<td>22</td>
<td>253.6</td>
<td>1920</td>
<td>30.0</td>
<td>81.2</td>
</tr>
<tr>
<td>24</td>
<td>254.4</td>
<td>1830</td>
<td>20.0</td>
<td>16.2</td>
</tr>
<tr>
<td>24</td>
<td>254.8</td>
<td>1910</td>
<td>25.0</td>
<td>59.3</td>
</tr>
<tr>
<td>24</td>
<td>256.6</td>
<td>1950</td>
<td>30.0</td>
<td>81.7</td>
</tr>
<tr>
<td>26</td>
<td>261.5</td>
<td>1900</td>
<td>20.0</td>
<td>16.7</td>
</tr>
<tr>
<td>26</td>
<td>258.7</td>
<td>1930</td>
<td>25.0</td>
<td>61.2</td>
</tr>
<tr>
<td>26</td>
<td>262.6</td>
<td>1970</td>
<td>30.0</td>
<td>82.4</td>
</tr>
<tr>
<td>28</td>
<td>282.6</td>
<td>1920</td>
<td>20.0</td>
<td>17.1</td>
</tr>
<tr>
<td>28</td>
<td>283.8</td>
<td>1960</td>
<td>25.0</td>
<td>64.5</td>
</tr>
<tr>
<td>28</td>
<td>282.2</td>
<td>1980</td>
<td>30.0</td>
<td>83.2</td>
</tr>
<tr>
<td>30</td>
<td>287.4</td>
<td>1950</td>
<td>20.0</td>
<td>17.6</td>
</tr>
<tr>
<td>30</td>
<td>288.7</td>
<td>1970</td>
<td>25.0</td>
<td>67.2</td>
</tr>
<tr>
<td>30</td>
<td>287.6</td>
<td>1980</td>
<td>30.0</td>
<td>84.3</td>
</tr>
</tbody>
</table>

An analysis of the graphical dependence presented in Figure 12 allows us to state that the strength and density of soil clods increase, depending on the increase in the absolute moisture content of the soil, which is due to an increase in the plasticity and connectivity of soil particles among themselves and the impossibility of their destruction.

![Figure 12. Dependence of the static destruction of soil clods on their density and moisture content.](image-url)
The results of studies of the destruction energy of the soil layer depending on soil moisture and fall height are shown in Figure 13.

\[
\begin{align*}
H(W) &= -18.21 + 49.12 \log W \\
E(W) &= -2684.87 + 7755.31 \log W
\end{align*}
\] (5)

An analysis of the graphical dependence allows us to conclude that in a humidity range of 12–21%, the strength of the lumps does not change significantly; with a higher humidity, there is a sharp increase in the strength properties. With an increase in humidity from 21% to 25%, the destruction energy increases from 6848.21 to 8386.21 J/m³. With soil moisture above 25%, the height corresponding to the height of destruction was in a range of 50–60 cm. These circumstances are explained by the presence of moisture, which plays the role of a damper, which leads to swelling of soil particles and a decrease in the intercolloidal distance between them and the absence of a violation of bonds between them. The height corresponding to the destruction height and belonging to the central area of the graph, with an absolute soil moisture content of 18–24%, is minimal and amounts to 37–41 cm. This should be explained by the physical maturation of the soil and an increase in the connectivity between particles.

When studying the process of mechanized harvesting of potatoes, factors were identified, the total number of which was initially 15, which covered the technological, design parameters of functioning elements, as well as the physical and mechanical properties of the soil.

In view of the fact that it is impossible to cover the influence of all factors and their interaction in studies, based on a priori information, as well as based on the specific objectives of the study, the most significant factors affecting the quality of potato harvesting were identified, which are presented in Table 2 and Figure 14.
Table 2. Factors affecting the quality of potato harvesting.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Name of Factors</th>
<th>Levels of Factor Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>Angle of inclination of the bar elevator $\beta$, hail</td>
<td>+1</td>
</tr>
<tr>
<td>$X_2$</td>
<td>Number of separators $z_2$, things</td>
<td>-1</td>
</tr>
<tr>
<td>$X_3$</td>
<td>Physical and mechanical properties of the soil $l_C$, things</td>
<td>+1</td>
</tr>
<tr>
<td>$X_4$</td>
<td>Forward speed of movement of separating devices $v_D$, m/s</td>
<td>-1</td>
</tr>
</tbody>
</table>

To conduct a screening experiment, an experiment planning matrix was compiled (Table 3) from a full factorial experiment, the formation of two half-replicas of the type $2^{4-1}$.

Table 3. Planning matrix and screening experiment results.

<table>
<thead>
<tr>
<th>Experience Number</th>
<th>Factors</th>
<th>Criterion Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X_1$</td>
<td>$X_2$</td>
</tr>
<tr>
<td>1</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>+</td>
<td>+</td>
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<tr>
<td>6</td>
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<td>+</td>
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<tr>
<td>7</td>
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<tr>
<td>8</td>
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<td>+</td>
</tr>
<tr>
<td>9</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>10</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
To evaluate the effects of factors, we construct a scatterplot. At the first stage, a selection of factors was chosen $X_1$ (angle of inclination of the bar elevator) and $X_2$ (number of separators).

The effects of the selected factors were assessed using a multi-entry table. The numerical values of the effects were (Table 4):

\[\begin{align*}
X_7 &= \frac{Y_1 + Y_3}{2} - \frac{Y_2 + Y_4}{2} = \frac{72.6 + 75.3}{2} - \frac{92.8 + 92.8}{2} = -18.85, \\
X_8 &= \frac{Y_1 + Y_2}{2} - \frac{Y_3 + Y_4}{2} = \frac{72.6 + 92.8}{2} - \frac{75.3 + 92.8}{2} = -1.35
\end{align*}\]

Table 4. Table for calculating the effects of factors.

<table>
<thead>
<tr>
<th>Factors Assessed</th>
<th>$X_7$</th>
<th>$-X_7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$+X_8$</td>
<td>73.8</td>
<td>90.4</td>
</tr>
<tr>
<td></td>
<td>71.4</td>
<td>92.8</td>
</tr>
<tr>
<td></td>
<td>95.2</td>
<td></td>
</tr>
<tr>
<td>$-X_8$</td>
<td>$\sum Y_1 = 145.2$</td>
<td>$\sum Y_2 = 278.4$</td>
</tr>
<tr>
<td></td>
<td>$\bar{Y}_1 = 72.6$</td>
<td>$\bar{Y}_2 = 92.8$</td>
</tr>
<tr>
<td></td>
<td>71.4</td>
<td>90.4</td>
</tr>
<tr>
<td></td>
<td>73.8</td>
<td>92.8</td>
</tr>
<tr>
<td></td>
<td>80.9</td>
<td>95.2</td>
</tr>
<tr>
<td></td>
<td>$\sum Y_3 = 226.1$</td>
<td>$\sum Y_4 = 278.4$</td>
</tr>
<tr>
<td></td>
<td>$\bar{Y}_3 = 75.3$</td>
<td>$\bar{Y}_4 = 92.8$</td>
</tr>
</tbody>
</table>

The significance of the effects of the selected factors was checked by the $t$-test, the calculation results of which are summarized in Table 5, and the numerical values were $t_{X_1} = 2.28$ and $t_{X_2} = 4.95$.

Table 5. Table for calculating $t$—criteria.

<table>
<thead>
<tr>
<th>№ Cells</th>
<th>$\sum Y_i$</th>
<th>$(\sum Y_i)^2$</th>
<th>$\sum Y_i^2$</th>
<th>$n_i$</th>
<th>$S_R^2 = \frac{\sum Y_i^2}{n_i}$</th>
<th>$\frac{\sum Y_i^2}{n_i} - 1$</th>
<th>$S_{R/n_i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>145.2</td>
<td>21,083.04</td>
<td>10,544.36</td>
<td>2</td>
<td>2.84</td>
<td>1.42</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>278.4</td>
<td>77,506.56</td>
<td>25,847.04</td>
<td>3</td>
<td>5.76</td>
<td>1.92</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>226.1</td>
<td>51,121.21</td>
<td>17,089.17</td>
<td>3</td>
<td>24.38</td>
<td>8.12</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>278.4</td>
<td>77,506.56</td>
<td>25,847.04</td>
<td>3</td>
<td>5.76</td>
<td>1.92</td>
<td></td>
</tr>
</tbody>
</table>

If the selected factor is significant, the tabular value of the $t$-test should be less than the calculated one. Tabular value of $t$ (criterion) for the number of degrees of freedom $f = 7$ at 5%th level of significance $t_{0.05} = 2.365$, at 10% om significance level $t_{0.1} = 1.895$.

Based on the calculation $t$ (criterion), it can be concluded that the factor $X_1$ and $X_2$ is significant, with a confidence probability 0.95.

After highlighting the effects of $X_1$ and $X_2$, the results of the experiment were corrected.

Based on the adjusted results of the optimization parameter, scatterplots were again built, according to which the factors were visually identified $X_3$ and $X_4$. The numerical values of the effects were:

\[\begin{align*}
X_3 &= -12.23, \quad t_{X_3} = -1.05, \\
X_4 &= -6.45, \quad t_{X_4} = 2.82
\end{align*}\]

Based on the calculation of the $t$-test, it can be concluded that the factor $X_4$ is significant with confidence probability 0.95, and the factor $X_1$ significant for 5%, significant for 10% the significance level of Student’s tabular test, respectively $t_{0.05} = 2.447$ and $t_{0.1} = 1.943$ with the number of degrees of freedom $f = 6$.

The results of the quantitative assessment of the selected factors are displayed in Table 6.
Table 6. The results of the quantitative assessment of the identified factors.

<table>
<thead>
<tr>
<th>Selection Stage</th>
<th>Factors</th>
<th>Importance of Factors</th>
<th>Estimated Value of ( t )—Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>According to initial data</td>
<td>( X_1 )</td>
<td>-18.85</td>
<td>( 2.28 ) ( X )</td>
</tr>
<tr>
<td></td>
<td>( X_2 )</td>
<td>-1.35</td>
<td>( 4.95 ) ( XX )</td>
</tr>
<tr>
<td>After adjustment</td>
<td>( X_3 )</td>
<td>-12.23</td>
<td>( -1.05 ) ( XXX )</td>
</tr>
<tr>
<td></td>
<td>( X_4 )</td>
<td>-6.45</td>
<td>( 2.82 ) ( X )</td>
</tr>
</tbody>
</table>

\( X \)—significant to the level 0.05(\( t_{0.05} \)); \( XX \)—significant to the level 0.1(\( t_{0.1} \)); \( XXX \)—significant to a level less than 0.1.

Insignificant factors as a result of the screening experiment were eliminated and we began to produce the search for the equation of the surface and the description of this surface. As a result of calculating the regression coefficients, we obtained a linear equation for the factors of the screening experiment:

\[
Y = 98.65 - 0.007x_1 - 0.015x_2 - 0.085x_3
\]  
(8)

Fisher’s calculated \( F_p \) (criterion) was obtained when determining the adequacy of the presentation of the results of the experiment using a polynomial of the first degree:

\[
F_p = \frac{S^2_{LF}}{S^2_y} = \frac{0.0698}{0.022} = 3.17
\]  
(9)

Tabular value of the Fisher criterion \( F_T \) at 95% probability for degrees of freedom of the denominator \( f_y = N-(k - 1) = 10-(3 - 1) = 20 \) and numerator \( f_{LF} = N - n - 1 = 10 - 4 - 1 = 5 \) makes up \( F_{0.05} = 3.84 \).

The tabular value of the Fisher criterion \( F_T \) is greater than the calculated value \( F_p \); therefore, the adequacy hypothesis can be accepted.

Therefore, it is necessary to ensure the development of separating working bodies of potato harvesters with fundamentally new principles of influencing the material being cleaned, the implementation of which will ensure not only the separation of potato tubers from soil clods but also reduce damage to marketable products from interaction with soil clods. The results of the studies obtained are consistent with the previously known data on the development and testing of machines in terms of cleaning marketable products of root and tuber crops. Further, the design of the separating rod elevator, which is a separation intensifier, contains within it a passive two-shoulder shaker 4 located under the upper branch of the web of the rod elevator 3 [14].

The disadvantages of the well-known design of the rod elevator include increased damage to root crops during the transition from one cascade to another, as well as the inability to disperse the pile of root crops over the entire width of the conveyor [15].

4. Conclusions

The results of the experimental studies carried out indicate the prospects of the work performed in the direction of obtaining knowledge of the physical and mechanical properties of the tuberous heap in order to create devices that ensure the separation of marketable potato products from soil clods in the development of modern machines for harvesting potatoes.

It has been established that in a humidity range of 12–21%, the strength of the lumps does not change significantly; at higher humidity, a sharp increase in strength properties occurs.

With an increase in humidity from 21% to 25%, the destruction energy increases from 270 to 288 N. With soil moisture above 25%, the height corresponding to the destruction height was in a range of 50–60 cm. These circumstances are explained by the presence of moisture, which is the role damper, which leads to swelling of soil particles and a decrease in the intercolloidal distance between them and the absence of a violation of the bonds between them.
The height corresponding to the destruction height and belonging to the central area of the graph, with an absolute soil moisture content of 21–27%, is minimal and amounts to 37–41 cm. This should be explained by the physical maturation of the soil and an increase in the connectivity between particles. In addition, the results of the studies obtained made it possible to establish that, regardless of the types of loads, the influence of density and moisture content on the strength properties of soil clods can be traced significantly.

The greatest destruction of soil clods is provided at a moisture content of 22–24%, which should be explained by the formation of the physical ripeness of the leached chernozem. In addition, a decrease in soil moisture leads to a more intensive gluing of soil particles among them and, consequently, an increase in the force effect on the soil lump for its destruction. Under dynamic impact, soil clods with a density of 1600–1700 kg/m$^3$ are destroyed and under static compression—1300–1400 kg/m$^3$ at a moisture content of soil clods of 22–24%.

This, in our opinion, is explained by the fact that vibration provides a more targeted development of cracks due to the constancy of the impact of external forces in a certain (limited) clod zone, which will ensure more efficient removal of soil clods and an increase in the purity of the tuberous heap. On heavy soils with high humidity, the use of destructive devices using the static compression method is also impractical.

The novelty of this study lies in obtaining empirical dependences of the physical and mechanical properties of soil clods on their size and mass parameters, with the possibility of changing the size of soil clods as a result of force action to the passage values of fractions through the separating devices of the harvesting machine.

The results of the research carried out will ensure the development of automated separating devices with an adaptive force effect of the cleaning executive elements on soil clods, with their physical and mechanical properties changing during the technological process of potato harvesting.

Author Contributions: Conceptualization, O.D., A.D. and A.S.; methodology, A.S. and M.G.; software, N.S., A.A. and M.M.; validation, A.D. and A.S.; investigation, A.S.; resources, A.S.; writing—original draft preparation, N.S.; writing—review and editing, A.S.; project administration, A.A.; funding acquisition, A.S. and A.D. All authors have read and agreed to the published version of the manuscript.

Funding: The study was supported by the Russian Science Foundation grant No. 22-76-10002.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

References
5. Dorokhov, A.S.; Sibirev, A.V.; Aksenov, A.G. Results of field studies on the separation of a heap of onion sets on a bar elevator with asymmetrically installed shakers. Eng. Technol. Syst. 2020, 1, 133–149. [CrossRef]


