

UDC 658.562.2:635.11:633.63
DOI: 10.31548/machinery/3.2023.21

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Experimental studies of the quality of root crop heads residue cleaning using a new cleaner

Abstract. Given the high technical requirements for cleaning root crop heads from residues, the development of new, more advanced cleaners is an important and urgent issue. The research aims to improve the quality of the cleaning process by determining the optimal kinematic, structural, and operational parameters of a new root crop head cleaner from root residues. A new design of the root crop head cleaner was created, which allowed the use of cleaning elements with different mechanical properties and sizes, and changing its kinematic parameters depending on the crop it processes. A new experimental setup was also made to install this cleaner and change its operational parameters. A new mathematical model of a multifactorial experiment was developed for the study. Based on the results of the field experimental study, correlation analysis, and statistical numerical calculations using a computer, the optimal design, kinematic, and operational parameters of the improved cleaner were determined, at which the highest quality of cleaning (the lowest amount of stover residues per linear metre) is observed. Based on the results of the correlation analysis, the following optimal parameters of the improved root crop head cleaner were obtained: the location of the ends of the rubber cleaning blades relative to the soil surface, i.e., the parameter h should not exceed 1.5 cm. The angular velocity ω of the counter-rotating movements of the cleaning shafts should correspond to the following range of values – 36.4...76.6 rpm. The translational speed V of the cleaner should not exceed 2.0 m·s⁻¹. The obtained structural, kinematic, and operational parameters can be successfully used in design bureaus when designing advanced machines for harvesting various root crops, and in research institutions and universities when conducting modern research in the field of agricultural engineering

Keywords: stubble; residues; plan matrix; optimal parameters; rubber blades

INTRODUCTION

For harvesting commercially grown root crops, which include sugar beet, fodder and table beet, carrots, etc., the most common technology is separate harvesting, i.e., when a separate unit harvests the tops on the root and then uses a root harvester to dig the roots out of the soil. Previously, the technology for harvesting the tops of the heads involved preliminary continuous cutting at an elevated height and then mechanical cutting of the upper parts of the heads together with the residues. In this case, the cut parts of the heads were not collected, but rather scattered over the surface of the field, and later ploughed into the soil as fertiliser. V. Bulgakov *et al.* (2021a) thor-

oughly investigated and found that the useful parts of root crops are irretrievably lost along with the cut-off parts of the heads. This is especially noticeable when harvesting sugar beet when up to 14% of sugar can be lost along with the cut-off root heads. In addition, mechanical cutting of root crop heads almost immediately causes the loss of juice from their bodies, and the cut part becomes a place through which microbes and viruses begin to penetrate the body, causing further decay and loss. In general, it is impossible to store such root crops, even for a short period, and they must be processed immediately. In this case, short-term storage results in an intensive loss of their presentation.

Article's History: Received: 20.03.2023; Revised: 28.06.2023; Accepted: 11.08.2023.

Suggested Citation:

Budzanivskyi, M. (2023). Experimental studies of the quality of root crop heads residue cleaning using a new cleaner. *Machinery & Energetics*, 14(3), 21–33. doi: 10.31548/machinery/3.2023.21.

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Modern foreign-made topsy-turvy harvesting machines are designed not only to cut but also to grind the entire array of cut green topsy-turvy and spread it over the field as a plant fertiliser.

As such, the technology of harvesting the tops was further improved and included a preliminary continuous cut of the green mass of tops, and then a separate operation was performed to clean the heads of root crops from the remains of tops on the root without damage and to knock the bodies of root crops out of the soil. Almost everywhere, root crop tops are now collected, removed from the fields, and used effectively for biogas production. Sugar beetroots themselves, even with uncut heads, are widely used in many countries for bioethanol production.

L. Pogorely (1983), L. Pogorely & M. Tatyanko (2004) not only present different types of peelers (sickle, chain, impact, etc.) but also investigate the principles of operation used in machines for cutting tops and peeling root heads from residues by the world's leading manufacturers. However, in most designs, cleaning forces are applied to the heads of root crops from one side, which, given the current trend towards increasing the speed of translational movement, does not always lead to high-quality cleaning. The creation of theoretical foundations for mechanical combing and crushing of the residual tops from sugar beet root heads on the root were thoroughly studied by V. Martynenko (1997), V. Martynenko & B. Kucher (2002) and V. Bulgakov *et al.* (2021b). They developed the fundamental scientific basis for removing top residues from root crop heads utilizing milling, shaft cutting, impact on the residues, as well as the use of a cleaner with blades mounted on a vertical drive shaft (such as a daisy). However, even in this case, the cleaning forces are applied to the residues on the root heads from one side only, and during the forward movement of the cleaner, the front and rear parts of the heads may not be processed at all. If the speed of the forward movement of the peeler is increased, the quality of work of such peelers is significantly reduced. The development of various designs of root crop head cleaners for removing tops from the root and the theoretical and experimental substantiation of their parameters are reflected in numerous works. In particular, A. Borys (2011) studied a combined copying and cancelling cleaner. M. Khelemendyk (2001) examined in detail the combination of shaped bar drums that slide onto each head. B. Shabelnyk (1998) investigated a head cleaner for fodder beetroots; M. Borys (2013) reviewed a combined paddle cleaner. O. Gurchenko (2007) investigated a combined paddle cleaner equipped with a passive head trimmer; I. Storozhuk & V. Pankiv (2015) – a combined cleaner with a rotary shaft and a passive head trimmer; Ye. Ihnatiev (2017) – a flanged cleaner with separate cleaning heads; O. Syplivets (2001) – conducted a study of a combined cleaner and a separate aftercut. The creation of new cleaners has been the subject of design developments in recent years (Patent of Ukraine No. 115404..., 2017; Berezhenko, 2020).

However, despite this design diversity and the theoretical and experimental studies of them, the results obtained indicate that they are unfortunately not able to achieve high-quality cleaning since almost all cleaners provide cleaning forces to root crop heads, albeit in different planes, but at high forward speeds they cannot clean all parts of the heads.

Thus, the search for the most effective design solutions for root crop head cleaners from root residues is relevant and should consider their kinematic, structural and operational characteristics, which should ensure the high-quality performance of this technological process.

The research aims to determine the optimal parameters of a new root crop head cleaner for removing root residues that can significantly improve the quality of the cleaning process.

MATERIALS AND METHODS

Experimental studies were carried out in 2022 in the field, using a new experimental setup manufactured at the National University of Life and Environmental Sciences of Ukraine at the Department of Mechanics, Faculty of Construction and Design. A new root crop head cleaner was developed at the Institute of Mechanics and Automatics of Agroindustrial Production of the National Academy of Agrarian Sciences of Ukraine under the direction of Prof. V. Bulgakov, which consists of two cleaning shafts with pivotal cleaning elements in the form of pairs of rubber blades mounted on hubs. The design of the two-shaft root crop head cleaner and the experimental setup for its study are new, and experimental studies using pairs of cleaning blades on each of the cleaning drive shafts were carried out for the first time. The cleaning shafts in this design cover each row of root crops on both sides and, due to counter-rotating movements, simultaneously strike the heads of root crops from both sides with the ends of their working cleaning elements, combing off the remains of the tops. The ends of the pairs of rubber blades on each of the two drive shafts are staggered, forming a cleaning channel with mutual overlap on the symmetry axis of the cleaner, which covers a row of root crops on both sides. The bulk of the green tops from the heads of root crops had to be cut off by a top harvester beforehand. But after that, they were left with residues in the form of uncut green tips, as well as dry and dead thin stems of considerable length, which lie on the soil surface. The root crops themselves are in the soil and firmly connected to it. After cleaning the heads of root crops from the remains of the tops on the roots, the next step is to dig the root crops out of the soil.

To simulate the functioning of this cleaner in real field conditions and, accordingly, to study the quality of its operation under different parameters and modes, a new design of a field experimental installation was developed and manufactured, which can be used only for the study of a two-shaft cleaner with pairs of cleaning rubber blades mounted pivotally on several hubs of each shaft, having counter-rotational motion, inside which it is installed. The

experimental setup has the following features: it provides for the study of the quality of cleaning the heads of root crops from one row of crops, is aggregated by a wheeled row crop tractor of class 1.4, which sets the cleaner, different speeds of translational movement along the row of root crops, and different angular speeds of rotational movements, provides conditions for the counter-rotational direction of its cleaning shafts, and also makes it possible to change and fix different angles of inclination of the cleaning shafts in the horizontal and vertical planes. It is also possible to set different heights of the ends of the pairs of flexible cleaning blades relative to the soil surface.

Figure 1 shows a diagram of the experimental setup for studying the quality of cleaning root crop heads from the remains of tops on the root. The experimental setup is a root crop head cleaner mounted on frame 3, which is single row. The frame 3 is mounted behind the wheeled aggregating tractor 1 with the help of the hitch 2. At the same time, frame 3 in its front part rests on two supports and copies wheels 5 with mechanisms for changing the distance of frame 3 to the soil surface. In the rear part of frame 3, there is a cleaner consisting of two horizontal

cleaning shafts 6. The shaft 6 is driven in counter-rotating movements by drive elements 4 from the rear PTO of the tractor 1. The cleaning shafts 6 are mounted horizontally in the transverse plane, and their longitudinal axes in this plane are located at an angle α . At the same time, five hubs 8 are mounted on each cleaning shaft 6 with a corresponding pitch using a keyed connection 9. Each hub 8 contains on its outer surfaces, mounted utilizing leashes 10, pairs of rubber blades 7, of which it contains four (located at the ends of mutually perpendicular axes). In this case, the ends of the rubber blades of one cleaning shaft are located in the gaps between the blades of the second cleaning shaft. The angle at which the cleaning shafts are installed ensures an appropriate root crop capture zone in the front part of the cleaner and is of little importance. The directions of translational movement of the experimental setup and the rotational movements of its components are shown in the diagram by arrows.

Figure 2 shows a non-exhaustive view from the end of the cleaning shaft 6 with pairs of rubber cleaning blades 7 mounted on hubs 8.

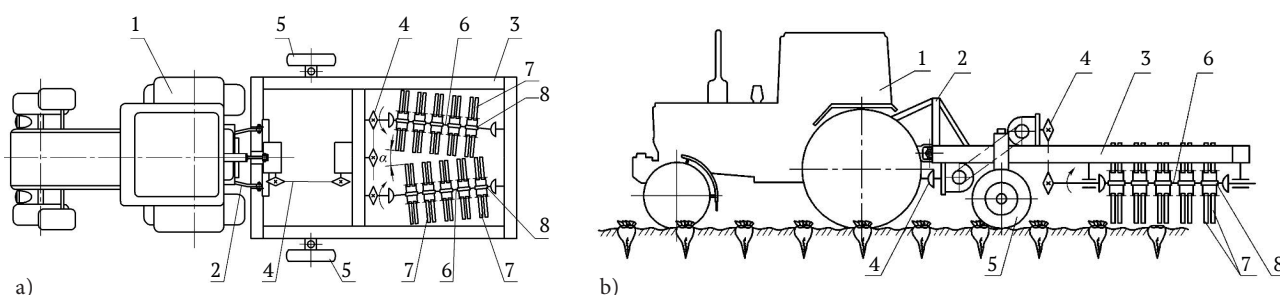


Figure 1. Diagram of a field experimental setup for studying the quality of cleaning root crop heads from the remains of tops on the root

Note: a) side view; b) top view, 1 – aggregating tractor; 2 – hitch; 3 – frame; 4 – elements of driving the cleaning shafts in counter-rotating motion; 5 – support and copy wheels; 6 – driving cleaning shafts; 7 – pairs of rubber cleaning blades; 8 – hubs with hinged cleaning blades

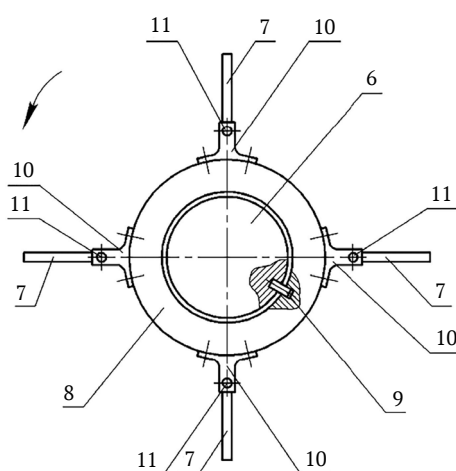


Figure 2. Installation of rubber blade pairs on the drive cleaning shaft

Note: 6 – cleaning shaft; 7 – rubber blade; 8 – hub; 9 – keyed connection of the shaft and hub; 10 – leash; 11 – hinge axis

Figure 3 shows a general view of one element of the cleaning working body, which consists of a pair of side-by-

side rubber blades 1 mounted pivotally on axis 2 on the hub of the cleaning blade with two leads 3.

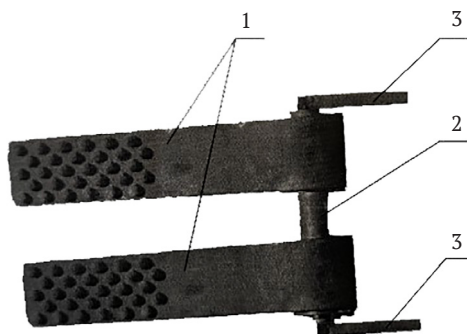


Figure 3. General view of the cleaning element

Note: 1 – rubber blades; 2 – hinge axle; 3 – hub leads

This cleaner uses conventional rubber blades used on the OGD-6A type cleaner (Root head cleaner, double-shaft, capable of cleaning 6 rows of root crops, “A” – modernised, can be separately aggregated with a tractor of class 1.4 or 2.0; Manufacturer: Ternopil Harvester Plant, Ukraine), which have standard dimensions: length 25...33 cm; width 6...8 cm, thickness 1.5...2.0 cm. At the outer ends of each blade, along their entire width, there were staggered rubber protrusions, 0.3...0.5 cm high and hemispherical in shape. The hinge point of each blade was reinforced with a thin metal – tin. All blades are made of solid moulded rubber.

Figure 4 shows a general view of the experimental set-up attached to a wheeled aggregating tractor during the field experimental studies.



Figure 4. Experimental setup during field experimental research

Figure 5 shows a view of a field of root crops prepared for the head cleaner, in which a linear metre is highlighted, from which the main bulk of the tops has already been cut with a standard top harvester, but the tops remain. This field area is bordered by a wooden frame, which is the size of a running metre with a width equal to the sum of half the standard row spacing from the crop row axis. All residues were collected from the area bounded by the frame after passing through the stubble harvester. However, before

passing the cleaner, the frame was removed from the scoring area, but its boundaries were fixed with wooden stakes that were driven into the soil.



Figure 5. The field area prepared for the cleaner

The methodology for conducting field experimental studies to determine the quality of cleaning root crop heads from the remains of tops on the root was in line with modern requirements in some respects (V. Nadykto, 2017; H. Beloev, 2021).

From the beginning, a field area with root crops was carefully prepared (the area with sugar beet crops was the most suitable for this purpose), which was (in terms of timing and agrophysical crop assessment) suitable for harvesting. The physical and mechanical properties of the soil with the crops, as well as the biological condition of the root crops themselves, were measured and comprehensively analysed. Then, the operation of cutting the tops from the heads of root crops was performed using a conventional tops harvester, type BM-6A (a tops harvester capable of

harvesting tops from 6 rows of root crops, manufactured by the Ternopil Harvester Plant, Ukraine). At the same time, the harvester itself did not have a head cleaner, which was previously disconnected from it. After the passage of the six-row pumpkin top harvester, the plantation was assessed based on the results of the first main continuous cut of the green mass of the pumpkin top. Here, the main indicator in assessing the performance of the top harvester was the quality of the cut of the heads (the presence of highly cut root bodies, chips, cracks, and root bodies being knocked out of the soil) and the presence of those residues of tops that the tops harvester was unable to cut and collect properly. Such a thorough assessment of the quality of the top harvester gave every reason to further compare and reliably assess the quality of cleaning the heads of root crops from residues on the root with the improved cleaner itself, i.e., to actually “separate” the quality of cleaning during the first and second cleaning.

Subsequently, the process of cleaning the heads of root crops with this cleaner took place, while two adjacent rows were immediately selected, and similar conditions were determined using a frame with the contours of one running metre. Next, all residues were manually cut off both after passing through the stubble harvester alone and after simultaneous passage through the stubble harvester and the cleaner. In both cases, all residues were carefully collected and weighed on an electronic balance with an accuracy of ± 0.1 g. The obtained weighing results in both cases, i.e., before and after the passage of the cleaner, made it possible to assess the quality of cleaning the heads of root crops from residues.

The degree of cleaning of root crop heads from residues on the root was then calculated using the following formula:

$$\delta = \frac{M - M_{cl}}{M} \times 100, \quad (1)$$

where δ – root crop heads cleaning degree, %; M – weight of residual tops before the cleaner passage, g; M_{cl} – weight of residual tops after the cleaner operation, g.

The conditions for conducting field experimental studies of the improved cleaner were as follows: soil type and name by mechanical composition – black soil, low-humus, medium loamy; average soil hardness – 2.0...2.8 MPa; average soil moisture – 12.1...14.5%; surface relief – flat; root crop yield – 53.4 t·ha⁻¹; tops yield – 13.3 t·ha⁻¹; plant density – 82.9 thousand pcs.t·ha⁻¹; average distance between root crops – 8.8 cm; type of tops by shape: “rosette” – 21.1%, “semi-rosette” – 50.8%, “cone” – 28.1%; location of root heads relative to the soil surface level: from 0 to 20 mm – 36.4%.

The following instruments and equipment were used in the field experimental studies: the angular velocity of rotational movements of the drive cleaning shafts was measured and recorded using a strain gauge (Fig. 6), the translational speed of the experimental unit was measured using a measuring wheel (Fig. 7).



Figure 6. Load cell for measuring the angular speed of rotation of cleaning shafts



Figure 7. The track wheel mounted on the cleaner

The strain gauge was mounted on the rear PTO shaft of the aggregating tractor, which made it possible to immediately record and measure the angular velocity of its shank using the developed program and connected to a PC using an electronic converter. Next, the angular velocity of the cleaner's drive shafts was converted to the angular velocity of the cleaner, and the required variable angular velocities of the rotational movements of the cleaner shafts themselves were set using interchangeable sprockets in the drive. The design of the drive of the cleaning shafts in the experimental setup was made using cardan shafts, a gearbox and chain gears, which ensured their counter rotation in the direction of the axis of the row of root crops. The measuring wheel, which was connected to the cleaner frame, also provided accurate values of the translational movement of the cleaner during field experimental studies in different modes of its operation using the developed program and connection to a personal computer (PC) through a converter. The exact location of the ends of the rubber blades relative to the field surface was determined each time using a metal ruler, which allowed the screw mechanisms of the cleaner frame copy wheels to accurately set different values of the height of the location. These measurements were made with an accuracy of 1 mm.

To determine the influence of independent factors on the quality indicators of the investigated root crop head

cleaner from the residues of tops on the root, a comparative multifactorial experiment was planned and conducted, or a full-factorial experiment (FFE) of the FFE type P^k , where P – the number of levels of variation of the factor; k – the number of factors present in the experiment (Dushynsky, 2000). An indicator that characterises the quality of the cleaner's operation is the residue of stubble per linear metre ($\text{g}\cdot\text{m}^{-1}$) that occurs after it passes through the scoring section of the row. This parameter in the model of the multifactorial experiment was chosen as an optimisation function, i.e. a dependent variable that can be taken as a functional: $Y=f(x_1; x_2; x_3)$, where Y – residues of stubble from the first to the i -th case; $x_1, x_2, \dots, x_i$ – natural independent variable factors.

These natural independent factors were selected following the relevant conditional plan of the multivariate experiment, which was implemented in the following sequence. To determine the amount of stubble residue Y on each running metre, the following independent variables were taken as the independent variables:

• is the speed of translational movement V , which was encoded by the index X_1 ;

• is the angular speed of rotation of the cleaning shafts ω , which was coded by an index X_2 ;

• the height of the rubber blade ends relative to the horizontal soil surface h , which was coded by the index X_3 .

When coding the factors, the factor space is linearly transformed – the origin is moved to the centre of the experiment, and the scale on the axes is chosen in units of factor variation. The factors were coded using the following relationship:

$$X_i = \frac{2 \cdot (x_i - x_{i0})}{x_{\max} - x_{\min}}, \quad (2)$$

where X_i – the coded value of the factor (dimensionless value); x_i – the value of the factor in named (natural) units; x_{i0} – the natural value of the factor at the zero level; $x_{\max}, x_{\min}$ – the maximum and minimum values of the factor, respectively.

When constructing the planning matrix of the full-factorial experiment, coded designations of the upper, lower and zero levels of variation by each factor were introduced, which were respectively designated as (+1), (−1), (0). The factors that determine the quality of the technological process under consideration were selected and coded, and the levels of their variation were established simultaneously in natural and coded forms (Table 1).

Table 1. Results of coding factors and their levels of variation FFE 3^3

Factors	Markings		Variation levels, natural / coded		
	Coded	Natural			
Translational speed V , $\text{m}\cdot\text{s}^{-1}$	X_1	x_1	0.9/−1	1.6/0	2.1/+1
Angular velocity of rotational movements of the cleaning shafts ω , $\text{rad}\cdot\text{s}^{-1}$	X_2	x_2	36.6/−1	56.5/0	76.6/+1
Height of the blade ends relative to the soil surface h , cm	X_3	x_3	0/−1	2/0	4/+1

Source: compiled by the author

The natural variables were then coded based on the data in Table 1 and their values were set as follows:

$$\begin{aligned} X_1 &= 1.67 \cdot V - 2.67, \\ X_2 &= 0.05 \cdot \omega - 2.81, \\ X_3 &= 0.5 \cdot h - 1. \end{aligned} \quad (3)$$

After coding the factors, a planning matrix of the corresponding multivariate experiment of the FFE 3^3 type was compiled for the total number of experiments $N=3^3$.

To reliably assess the quality of the root crop head cleaner's operation from the residues of tops on the root during field experimental studies, the required number of

measurements of the controlled parameters (repetition of experiments) was determined according to the methodology outlined in (Hailys, 1992). In this case, the experiments were conducted in six replications.

When implementing the compiled plan matrices, to eliminate the influence of uncontrolled and unregulated factors on the results obtained, the plan matrix was randomised by the random balance method, which was implemented by randomly drawing the serial numbers of experiments, i.e., randomly.

The randomized design matrix of the multivariate experiment FFE 3^3 is shown in Table 2.

Table 2. Randomised design of a FFE-type experiment 3^3

No. experiment	Factor levels				Factor interrelation				Optimisation factor Repetitions						Average values T, $\text{g}\cdot\text{m}^{-1}$
	x_0	x_1	x_2	x_3	$x_1 \times x_2$	$x_1 \times x_3$	$x_2 \times x_3$	$x_1 \times x_2 \times x_3$	1	2	3	4	5	6	
1	+1	−1	−1	−1	+1	+1	+1	−1	14.6	12.8	14.5	26.6	28.8	24.6	20.3167
2	+1	+1	−1	−1	−1	−1	+1	+1	12.2	13.9	12.8	9.8	16.2	15.5	13.40
3	+1	0	−1	−1	0	0	+1	0	31.6	37.2	38.4	28.4	37.3	36.8	34.95
4	+1	−1	+1	−1	−1	+1	−1	+1	2.8	2.7	6.1	5.8	5.1	2.7	4.20
5	+1	+1	+1	−1	+1	−1	−1	−1	4.1	9.3	9.2	10.4	8.9	11.1	8.8333
6	+1	0	+1	−1	0	0	−1	0	4.7	6.2	5.8	8.1	8.7	9.7	7.20
7	+1	−1	0	−1	0	+1	0	0	5.9	10.3	12.6	13.5	8.2	11.4	10.3167

Continued Table 2.

No. experiment	Factor levels				Factor interrelation				Optimisation factor Repetitions						Average values
8	+1	+1	0	-1	0	-1	0	0	8.9	13.7	10.8	10.7	14.5	12.8	11.90
9	+1	0	0	-1	0	0	0	0	9.7	17.3	16.8	21.7	31.6	30.4	21.25
10	+1	-1	-1	+1	+1	-1	-1	+1	124.8	156.1	156.2	111.4	120.3	120.8	131.60
11	+1	+1	-1	+1	-1	+1	-1	-1	167.8	156.3	154.1	110.7	106.9	121.4	136.20
12	+1	0	-1	+1	0	0	-1	0	68.4	72.3	70.9	70.5	90.1	84.3	76.0833
13	+1	-1	+1	+1	-1	-1	+1	-1	6.2	6.0	8.8	7.9	9.9	10.1	8.15
14	+1	+1	+1	+1	+1	+1	+1	+1	90.1	87.0	64.7	54.7	58.7	58.4	68.9333
15	+1	0	+1	+1	0	0	+1	0	34.1	43.5	43.1	53.6	34.1	44.3	42.1167
16	+1	-1	0	+1	0	-1	0	0	15.8	18.2	21.7	22.4	21.6	22.3	20.3333
17	+1	+1	0	+1	0	+1	0	0	99.0	110.8	125.3	130.1	128.6	131.5	120.8833
18	+1	0	0	+1	0	0	0	0	60.1	71.0	80.8	82.7	88.6	91.4	79.10
19	+1	-1	-1	0	+1	0	0	0	88.1	106.7	100.7	85.3	132.5	89.1	100.40
20	+1	+1	-1	0	-1	0	0	0	102.5	99.4	112.8	99.9	94.3	110.3	103.20
21	+1	0	-1	0	0	0	0	0	42.2	52.6	59.6	59.1	66.8	59.5	56.6333
22	+1	-1	+1	0	-1	0	0	0	4.1	4.2	9.1	7.6	7.2	8.8	6.83333
23	+1	+1	+1	0	+1	0	0	0	64.7	61.6	44.6	43.3	50.5	50.1	52.4667
24	+1	0	+1	0	0	0	0	0	10.9	12.3	11.2	13.9	13.1	12.3	12.2833
25	+1	-1	0	0	0	0	0	0	8.0	13.2	18.8	19.6	15.5	20.0	15.85
26	+1	+1	0	0	0	0	0	0	66.7	73.1	74.1	76.1	83.8	78.5	75.3833
27	+1	0	0	0	0	0	0	0	69.4	84.8	91.6	95.5	42.2	61.8	74.2167

Source: compiled by the author

Statistical processing of the results of experimental studies obtained after the implementation of the multifactorial experiment was carried out in the following sequence.

Thus, the response function (i.e., the optimisation parameter) was taken as an approximating mathematical model of a full square polynomial (Hailys, 1992), which describes the real experimental process:

$$Y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + b_{12} \cdot x_1 \cdot x_2 + b_{13} \cdot x_1 \cdot x_3 + b_{23} \cdot x_2 \cdot x_3 + b_{123} \cdot x_1 \cdot x_2 \cdot x_3 + b_{11} \cdot x_1^2 + b_{22} \cdot x_2^2 + b_{33} \cdot x_3^2, \quad (4)$$

where Y – experimentally obtained values; $b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{123}, b_{11}, b_{22}$ and b_{33} – regression coefficients of the corresponding values of the input factors x_i, x_1, x_2 and x_3 – initial coded factors.

The coefficients of the approximating polynomial, represented as a full quadratic equation, were determined by the corresponding general formulas (Hailys, 1992), subject to orthogonality and symmetry:

❖ free term b_0 and coefficients b_i i -th factor will be:

$$b_i = (\sum_{u=1}^N x_{iu} \cdot \bar{y}_u) \cdot (\sum_{u=1}^N x_{iu}^2)^{-1} = (\sum_{u=1}^N x_{iu} \cdot \bar{y}_u) \cdot (N)^{-1}, \quad (5)$$

❖ interrelation coefficient b_{ij} can have two such values under the influence of two and three variable factors:

$$b_{ij} = (\sum_{u=1}^N x_{iu} \cdot x_{ij} \cdot \bar{y}_u) \cdot (N)^{-1}, \quad (6)$$

$$b_{ijk} = (\sum_{u=1}^N x_{iu} \cdot x_{ij} \cdot x_{ku} \cdot \bar{y}_u) \cdot (N)^{-1},$$

where x_{iu}, x_{ij} and x_{ku} – the value of the coded variable in the corresponding column of the experiment plan; $\bar{y}_u$ – average value of u -th experiment; u – serial number of the experiment; i – factor number; j, k – factor number other than i ; N – number of conducted experiments.

The reproducibility of the obtained values of the experimental array with an identical number of repetitions for each experiment was checked by the Cochran criteria,

which was determined as follows:

$$G = (S_{vmax}) \cdot (\sum_{u=1}^n S_v)^{-1}, \quad (7)$$

where G – Cochran's calculated value of the criterion; S_{vmax} – numerical value of the maximum variance in u -th point; S_v – variance, which characterises the dispersion of research results of u -th experiment.

The variance of the reproducibility of the experiments was determined according to the following expression:

$$S^2(Y) = [\sum_{u=1}^N (Y_{ui} - \bar{Y}_u)^2] \cdot [N \cdot (m-1)]^{-1}, \quad (8)$$

where Y_{ui} – numerical values of i -th response of u -th experiment; $\bar{Y}_u$ – average response value of u -th experiment; m – repetition values of each u -th experiment.

The calculated value of the Cochran criterion $G = 0.0702$. The calculated values of the Cochran criterion were compared with the table values $G_T = 0.1327$ with a limit of $\alpha = 0.05$. Condition $G \leq G_T$ is true and variances are assumed to be homogeneous, which means that the process is reproducible.

Statistical significance of the coefficients of the regression equation b_i was tested by t -Student's test and was determined in the following sequence:

❖ is the variance of experimental errors in the lines of the FFE plan:

$$S^2(b) = \frac{1}{N \cdot m} \cdot S^2(Y); \quad (9)$$

❖ reproduction error:

$$S(b) = \sqrt{S^2(Y)}; \quad (10)$$

❖ condition of coefficients significance $b_{i(jk)}$:

$$b_{i(jk)} > t_T \cdot S(b), \quad (11)$$

where t_T – the table value of the Student's coefficient, which is selected from the table depending on the degree of freedom of correspondence f and significance level α , $t_T = 1.96$.

The degree of compliance freedom equals:

$$f = (m - 1) \cdot N. \quad (12)$$

If the significance condition is not met, the following coefficient b_i of regression equation was assumed to be insignificant (equal to zero), and the corresponding term x_i of regression equation was excluded.

Thus, the following regression equation was obtained:

$$Y = 48.6309 + 10.1185 \cdot x_1 - 17.1025 \cdot x_2 + 20.4086 \cdot x_3 + 4.0951 \cdot x_1 \cdot x_2 - 6.5278 \cdot x_2 \cdot x_3 + 6.1716 \cdot x_1 \cdot x_3 + 1.6531 \cdot x_1 \cdot x_2 \cdot x_3 - 2.207 \cdot x_3^2. \quad (13)$$

The adequacy of the chosen mathematical model to the experimental data, i.e., the correspondence of the mathematical model to the real process, was checked by the F Fisher's criteria by calculation:

variance of adequacy:

$$S_{ag}^2 = \frac{m}{N-g} \cdot \sum_{u=1}^N (\bar{Y}_u - \hat{Y}_u)^2, \quad (14)$$

where $N-g$ – number of degrees of freedom of the variance of adequacy; g – number of significant coefficients in the regression equation; $\bar{Y}_u$ – average response value in u -th experiment; $\hat{Y}_u$ – response value in u -th plane point, calculated by the regression equation;

calculated Fisher's conformity criteria F_p :

$$F_p = \frac{S_{ag}^2}{S^2(Y)}, \quad (15)$$

where $S^2(Y)$ – experiment reproduction variance;

tabulated value of the Fisher's criteria F_T per set variance levels α and two degrees of conformity were defined using the following expressions (Dushynsky, 2000):

$$f_{ag} = N - g, \quad (16)$$

and

$$f_y = N \cdot (n - 1). \quad (17)$$

The condition for the adequacy of the chosen mathematical model was tested using the following inequality:

$$F_p < F_T. \quad (18)$$

The obtained value F_p was compared with the table value F_T . The calculated value of Fisher's criteria is equal to $F_p = 1.48$, and, according to $F_T = 1.88$ at the 5% level of significance. Thus, the condition of adequacy of the chosen mathematical model is met, i.e., the regression equation of the multivariate experiment is adequate to the experimental data. The multiple correlation coefficient R was then determined using the following expression:

$$R = \sqrt{1 - \frac{\sum_{u=1}^N (\bar{Y}_u - \hat{Y}_u)^2}{\sum_{u=1}^N (\bar{Y}_u - \bar{Y})^2}}, \quad (19)$$

where $\bar{Y}$ is the average value of the function determined from the experimental data.

The calculations have established that the value of the multiple correlation coefficient is $R = 0.85$. Accordingly, in

natural coordinates, the regression equation after transformation and simplification of expressions will be as follows:

$$Y = 63.498 - 4.9527 \cdot V - 0.8498 \cdot \omega + 19.5504 \cdot h - 0.2723 \cdot \omega \cdot h + 1.2733 \cdot V \cdot h + 0.2026 \cdot V \cdot \omega + 0.0688 \cdot V \cdot \omega \cdot h - 0.5518 \cdot h^2. \quad (20)$$

Thus, the obtained regression equation (20) describes the dependence of the residues Y of tops on the heads of root crops when they are cleaned by the improved design of the cleaner on its translational speed V , the angular speed of rotational movement ω of its two cleaning shafts when they move in the opposite direction, and the height h of the ends of the rubber blades relative to the soil surface, which separate the residues from the heads of root crops.

The use of the regression equation (20) allowed us to process and analyse the results of the experimental studies using the Statistica 13.0 software package for PC.

RESULTS AND DISCUSSION

Based on the results of statistical calculations, three-dimensional spatial dependences of the response surfaces of the top residues per linear metre during the operation of the root crop head cleaner and their two-dimensional cross-section were constructed to visualise the results of the experimental field studies.

The obtained regression dependencies of the residues of tops per linear metre during the operation of the root crop head cleaner in the form of a functional characterised the effects of single factors (speed of translational movement of the cleaner V , angular speed ω of rotation of the cleaning blades and height h of the blades relative to the soil surface) and their interaction on the optimisation parameter.

Figures 8-10 show the response surfaces of the residues of tops per linear metre during the operation of the root head cleaner and their two-dimensional cross-section as a function of two variable factors $x_{i(1,2)}$ with the constant unchanged corresponding third factor $x_{i(3)} = \text{const}$, the value of which was at the zero level. The response surfaces of the residues of tops per linear metre were also constructed for the minimum and maximum levels of the third factor $x_{i(3)} = \text{const}$ and, respectively, the two variable factors $x_{i(1,2)}$.

According to the obtained graphical dependencies, the range in which the minimum values of tops residues Y are observed when cleaning root crop heads and the optimal values of the translational speed of the cleaner and the angular velocity V of rotational movements of its cleaning shafts is the zone where the angular velocity ω of rotations is almost maximum and should be within $65 \dots 80 \text{ rad} \cdot \text{s}^{-1}$, and the translational speed of the cleaner should be within $1.0 \dots 1.8 \text{ m} \cdot \text{s}^{-1}$ (Fig. 8). Physically, this is explained by the fact that almost maximum values ω provide a greater number of blows to each head of the root crop. As for the speed V , it's not a high enough value, for example, $1.0 \text{ m} \cdot \text{s}^{-1}$ or even less, significantly increases the processing time of each head, which will naturally improve the quality of their cleaning from residues.

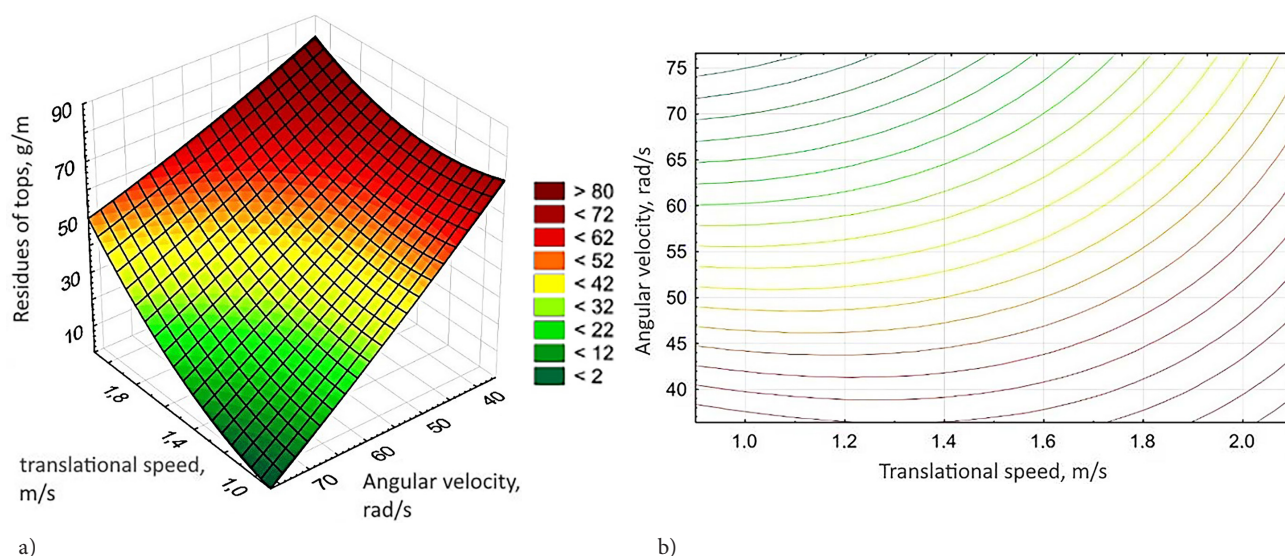


Figure 8. Response surface (a) and its two-dimensional cross-section (b) of the leftover haulm on a running metre
Note: $Y=f(V; \omega)$, as velocity function V of translational motion and angular velocity ω and rotational movements of the cleaning shafts
Source: compiled by the author

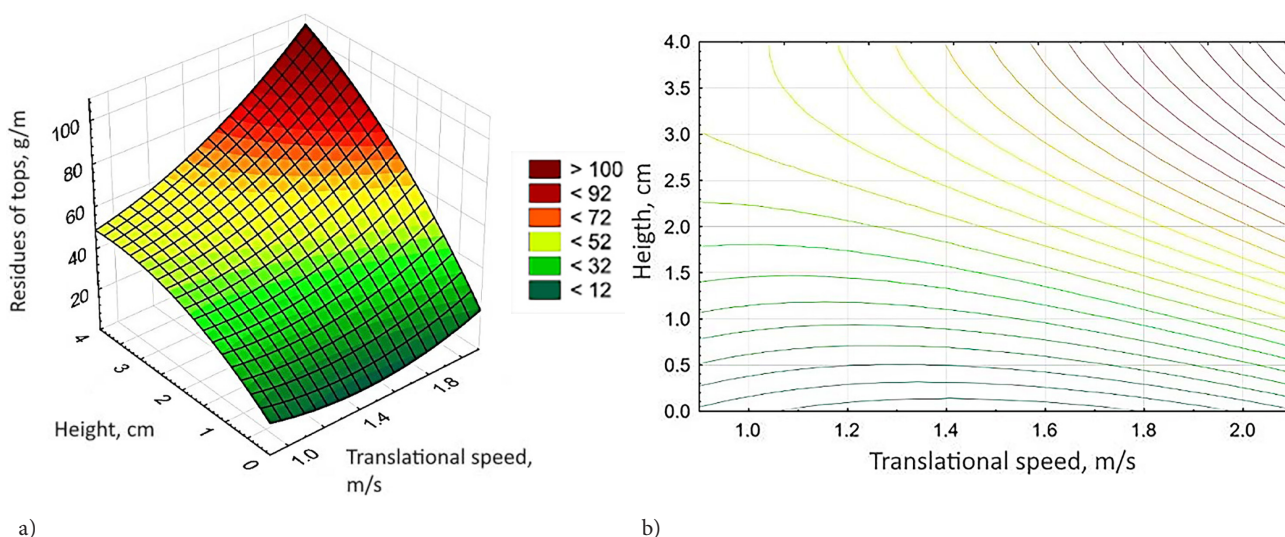


Figure 9. Response surface (a) and its two-dimensional cross-section (b) of the leftover haulm on a running metre
Note: $Y=f(V; h)$, as velocity function V of translational movement and height h for setting the cleaning blades above the soil surface level
Source: compiled by the author

Similar results are observed from the graphical dependencies shown in Figure 9. Thus, the minimum residues Y on the heads of root crops are in the zone when the height h of the ends of the rubber blades above the soil surface should have minimum values and be in the range of 0.3...2.5 cm. In this case, the forward movement speed V of the cleaner can be in a wider range of values, namely 1.0...2.0 m·s⁻¹. However, it should be noted that the minimum heights of the ends of the rubber cleaning blades relative to the soil surface level are not very desirable. This results from the fact that these ends of the

rubber blades should not touch the soil surface at all. Physically, this results in their initial impacts not on the root crop heads themselves, but on the soil. This significantly reduces the quality of cleaning of the root crop heads themselves. Furthermore, when the corresponding rotational movements are set to the cleaning shafts, the rubber blades are capable of stretching (i.e., their length increases under the influence of inertial forces), which can lead to their contact with the soil surface, the capture of its particles and, as a result, a decrease in cleaning performance and premature wear.

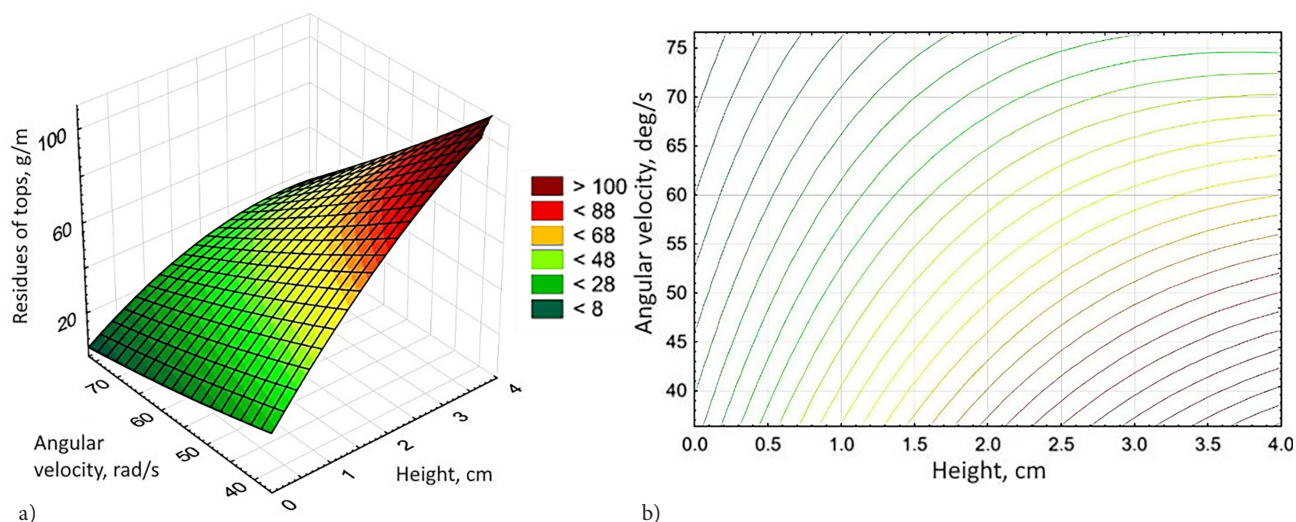


Figure 10. Response surface (a) and its two-dimensional cross-section (b) of the leftover haulm on a running metre

Note: $Y = f(h; \omega)$ as a function of the height h for the cleaning blades above the soil surface and the angular speed ω of the rotation of the cleaning shafts

Source: compiled by the author

The dependence of residues Y on the heads of root crops on the height h of the cleaning blades above the soil surface and the angular velocity ω of the rotational movements of the cleaning shafts indicates that the zone of optimal values of these parameters is at the maximum values ω and minimum values h , which is rather natural (Fig. 10).

In general, the analysis of the above regression equation and the graphical dependencies obtained show that the factors that increase the amount of stubble residue per linear metre are the height of the blades relative to the soil surface h and the speed V of forward movement. An increase in the angular velocity ω of the rotation of the cleaning shafts leads to a decrease in the amount of stubble residue.

Changing the forward speed of the cleaner V in the range of 0.9 to 2.1 m·s⁻¹, the amount of stubble residue increases by 1.55 times, when changing the angular speed of rotation of the cleaning shafts ω in the range of 36.4...76.6 rpm, the amount of stubble residue decreases by 2.09 times, and in the range of changes in the height of the blades relative to the soil surface h from 0 cm to 4 cm, the amount of stubble residue increases by 2.58 times.

It should be noted that during the field experimental studies to determine the quality of cleaning the heads of root crops from residues, the heads themselves were not damaged by rubber blades. After the run of the head harvester, which made a continuous cut of the green mass of the tops, there were cases of cutting off the upper parts of the heads, but only those that were high above the soil surface. No noticeable damage in the form of chips, cracks, or tearing of surfaces was observed after the cleaner passed through. There were also no cases of root crops being knocked out of the soil.

Comparing the results of the field experimental studies of the new cleaner with similar results of previous studies

by other authors, certain difficulties arise. For example, no experimental studies have been conducted using a methodology that would allow evaluating the quality of head cleaning only by the cleaner itself, separating the indicators of continuous cutting by a stump harvester. Almost all known previous studies of recent years (Žitňák & Korenko, 2011; Berezhenko, 2020) concerned the assessment of the quality of head cleaning in general, i.e., the initial continuous cut (and root crop head cleaners, of whatever design, can clean the heads only after the main cut of the tops), then additional cleaning from residues and even mechanical cutting of the upper part of each head. In other words, the quality of the entire technological process of harvesting the tops was investigated and evaluated.

However, comparing the quality indicators of this root crop head cleaner with similar indicators of other types (albeit in terms of the general indicators of the entire process of simultaneous cutting and cleaning), there is reason to believe that the amount of residual tops is reduced by almost 1.8 to 2.2 times compared to the cleaners with horizontal rotation shafts and flexible cleaning blades mounted on them, which move across the rows of root crops (Pogorely, 1983; Martynenko, 1997; Martynenko & Kucher, 2002) and almost 1.25 to 1.28 times compared to the cleaners with vertical cleaning shafts with flexible elements moving along the rows of crops (Pogorely, 1983; Borys, 2012).

Comparing the results achieved in our field experiments, they are even better than in the cases when the blade root head cleaners are used in conjunction with the top head cutters. Thus, the results presented by I. Storozhuk & V. Pankiv (2015) are almost similar to ours, and the results presented by E. Berezhenko (2020) show that in our case, the number of residual tops on the heads of root crops is reduced by about 5%.

It is possible to make a detailed and, to the extent feasible, comprehensive analysis of the high-quality indicators obtained by us and to make general comparisons with the results achieved by other authors. First of all, there is every reason to believe that this is since in our cleaner, the coverage of each root crop head during residue cleaning from both sides creates conditions under which the ends of the rubber cleaning vanes, acting simultaneously from both sides, can apply forces to the front of the heads and their rear, despite the straightforward forward movement. The ends of the rubber cleaning vanes achieve this due to their overlapping and the fact that they can enter the gaps between the root crops on both sides. In other words, the ends of the rubber blades of the two cleaning shafts, which are directed towards each other, first enter the space between the adjacent root crop heads, and then, in their forward movement, touch the front and rear parts of the heads located in the row.

Furthermore, in this particular case, since the ends of the rubber blades of one shaft are located between the ends of the blades of the second shaft, conditional zones of application of cleaning forces to each head are provided, which overlap. In other words, the cleaning rubber blade located on one side of the head first starts to interact with the side surface of the head located on the other side. This means that virtually all surfaces of the root crop heads, which have both spherical and flat external shapes, fall within the action zone of the ends of the rubber blades of both cleaning shafts. This not only ensures that the root bodies that are high above the surface level are not knocked out of the soil, but also covers all the surfaces of the heads.

It is the installation of four rubber cleaning blades on each hub that guarantees more intensive and consistent interaction of their ends with the surface of each root crop head. In addition, the presence of four hubs on each cleaning shaft carrying cleaning elements in the form of rubber blades significantly prolongs the time of their interaction (contact), which significantly affects the quality of cleaning.

Since two rubber cleaning vanes are mounted on each axis of the hinge, each hub, with two leads, the effect is that the first of the blades strikes the short green stalk of the chaff first and can capture it (if the stalk has not separated) and bend it. After that, the second rubber blade (after a very short period) immediately strikes again, but on the bent part of the green stalk, which guarantees its absolute separation. Gripping and bending are also facilitated by the fact that the outer (working) ends of each rubber blade have hemispherical rubber protrusions staggered along their entire width. Their position and shape facilitate the capture and bending of short and strong residues. In addition, the width of the ends of the rubber blades, their shape and the presence of protrusions contribute to the effective capture and detachment of dry and dead residues, which can be located both in the rows of crops and the gaps between the root crops themselves in the row. Moving in a bent position along the root crop head, the rubber cleaning vane can move along it with its narrow, end part. In this

case, the sharp edges of the blade cut off the remaining tops. They effectively cut off both green, strong residues and dry, fallen stalks that are located on the spherical surfaces of the heads. Such design features of the advanced peeler contribute to a significant increase in the quality of cleaning of each root crop head, regardless of its shape and the presence of residues.

Even the small angle α at which the two cleaning shafts intersect in the horizontal plane creates favourable conditions so that at the end of the cleaning zone, i.e. at the very ends of the drive cleaning shafts, the cleaning rubber blades completely cover the entire upper part of each root head, which guarantees complete separation of the green and strong residues of the tops (green stem ends), which are also located here. It is in this part of the peeler that the cleaning force is significantly increased, as the blade ends strike the heads with direct, central blows from top to bottom. And, as this occurs while the cleaner is moving forward, the ends of the rubber blades are very effective in gripping and simultaneously dislodging the residue on the top of the heads.

Thus, the new design of the cleaner has a longitudinally located active cleaning channel, in which cleaning forces are applied to each root crop head from virtually all sides (from above, due to the counter-rotating movement of both cleaning shafts) and both sides. The provided adjustments allow to adjust the functioning of the cleaner for high-quality cleaning of any root crop. This not only significantly improves the quality of cleaning, but also ensures that root crops are not knocked out of the soil. No other known design that performs a similar technological process has such features and technical characteristics.

CONCLUSIONS

An improved design of a root crop head cleaner from root residues and a new mathematical model of a multifactorial experiment to assess the quality of its operation have been developed. According to the results of the field experimental study of the root crop head cleaner from root residues, equipped with pairs of rubber cleaning blades mounted on driven horizontal shafts with appropriate length pitches that cover the row on both sides, it was found that it is possible to significantly improve the quality of cleaning.

The regression analysis and numerical calculations using statistical methods with the help of a PC allowed us to establish the optimal design, kinematic and operational parameters of the improved cleaner, which ensure the highest quality of cleaning (the lowest amount of stubble residue per linear metre). For example, the position of the ends of the rubber cleaning blades relative to the soil surface, i.e. the parameter h should not exceed 1.5 cm. The angular speed ω of the counter-rotational movements of the cleaning shafts should be between 36.4 and 76.6 RPM. The translational speed V of the cleaner should not exceed $2.0 \text{ m}\cdot\text{s}^{-1}$.

The next stage of research is the experimental determination of the power and force characteristics of the developed design of the root crop head cleaner, depending on the external conditions of harvesting the tops and the

condition of the plantation where they are grown, as well as on the different geometric and physical and mechanical characteristics of its cleaning blades. In the future, it is also necessary to consider the issue of constructive changes to this cleaner. In particular, it provides its drive cleaning shafts with vibratory movements in different planes. The greatest ability to do this, which will not require a very complicated improvement, will be the creation of forced oscillatory movements of the drive cleaning shafts in the directions of their longitudinal axes. It should be assumed

that these oscillations will further improve the quality of cleaning root crops from residues on the root in any condition of both the crop and the plantation on which they are grown.

None.

ACKNOWLEDGEMENTS

CONFLICT OF INTEREST

None.

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Експериментальні дослідження якості очищення головок коренеплідних культур від решток на корені новим очисником

Анотація. У зв'язку з тим, що до очистки головок коренеплідних культур від решток висуваються високі технічні вимоги, розробка нових, більш вдосконалених очисників, є важливим і актуальним питанням. Метою даного дослідження було підвищення якості технологічного процесу очистки шляхом визначення оптимальних кінематичних, конструктивних та експлуатаційних параметрів нового очисника головок коренеплідних культур від решток на корені. Для цього була виготовлена нова конструкція очисника головок коренеплідних культур, яка дозволяла використовувати різні за механічними властивостями та розмірами очисні елементи, та змінювати його кінематичні параметри в залежності від тієї культури яку він обробляє. Також була виготовлена нова експериментальна установка, в якій було встановлено цей очисник і за допомогою якої змінювали його експлуатаційні параметри. Для проведення дослідження була розроблена нова математична модель багатофакторного експерименту. За результатами проведеного польового експериментального дослідження, кореляційного аналізу та статистичних числових розрахунків за допомогою ПК встановлені оптимальні конструктивні, кінематичні та експлуатаційні параметри вдосконаленого очисника, при яких спостерігається найвища якість очистки (найменша кількість залишків гички на погонному метрі). За результатами проведеного кореляційного аналізу були отримані такі оптимальні параметри вдосконаленого очисника головок коренеплідних культур від решток на корені: розташування кінців гумових очисних лопатей відносно поверхні ґрунту, тобто параметр h не повинен перевищувати 1.5 см. Кутова швидкість ω зустрічно обертових рухів очисних валів повинна відповідати такому інтервалу значень – 36.4...76.6 rpm. Швидкість V поступального руху очисника повинна бути не більшою ніж $2.0 \text{ m}\cdot\text{s}^{-1}$. Отримані конструктивні, кінематичні та експлуатаційні параметри можуть бути успішно використані в конструкторських бюро при проектуванні перспективних машин для збирання різних коренеплідних культур, в науково-дослідних установах та університетах при проведенні сучасних досліджень в галузі агроінженерних наук

Ключові слова: гичка; залишки; план-матриця; оптимальні параметри; гумові лопаті