

RESULTS OF EXPERIMENTAL RESEARCH ON THE QUALITY OF CLEANING CARROT ROOTS WITH A SPIRAL CLEANER

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The article presents the results of a study of the influence of controlled factors on the quality of cleaning a pile of carrots from soil impurities and plant residues, as well as on the level of damage to root crops during the operation of the cleaner. To establish the nature and strength of the influence of the studied parameters, regression equations were developed that allow assessing the dependence of the main indicators of the cleaning process on the mass of carrot roots (m , g), the angular speed of rotation of the cleaner shafts (ω , $\text{rad}\cdot\text{s}^{-1}$) and the angle of inclination of the cleaning bed to the horizon (α , deg.). Experimental studies and statistical processing of the obtained results were performed using the Statistica 13.0 package of applied statistical programs. Based on the obtained data, three-dimensional spatial response surfaces were constructed that characterize the dependence of the amount of separated and adhered soil on the studied factors. The analysis was carried out for two variants of the root crop entering the cleaning bed, which made it possible to determine the features of the technological process depending on the initial position of the carrot. The obtained graphical relationships provide a visual representation of the results of laboratory experiments and allow to assess both the individual influence of factors and the nature of their interaction. The established patterns can be used to substantiate rational operating modes of the cleaner, increase the efficiency of removing soil impurities and plant residues and reduce mechanical damage to root crops. The results of the study create a basis for further optimization of the design and technological parameters of cleaning machines and improving the quality of post-harvest processing of carrots. The obtained results can also be used to develop practical recommendations for selecting the optimal operating parameters of spiral cleaners under different conditions of carrot harvesting and post-harvest processing.

Keywords: carrot roots, cleaner, laboratory setup, amount of separated soil, amount of adhered soil.

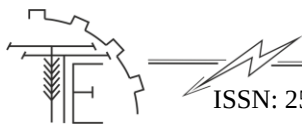
Eq. 6. Fig. 4. Tabl. 5. Ref. 12.

1. Problem formulation

Mechanized harvesting of carrot roots is accompanied by the need for effective separation of soil impurities and plant residues from the main product. The quality of this process largely determines the marketable appearance of the root crops, the level of their damage and the productivity of harvesting equipment. That is why the improvement of technological cleaning means remains one of the priority areas of development of machines for harvesting vegetable crops.

When substantiating the design and technological parameters of cleaning working bodies, it is necessary to take into account the agrophysical features of root crops. The greatest influence on the interaction of carrots with the working surfaces of machines is their geometric dimensions, mass, mechanical properties of tissues, shape, spatial arrangement in the soil, as well as the characteristics of the leaf apparatus. The combination of these parameters determines the conditions for the processes of digging, transportation and cleaning.





The efficiency of root harvesting machines largely depends on the depth of the roots, the degree of their deepening into the soil, as well as the dimensional and mass heterogeneity of the crop. The specific shape of most carrot roots, close to an elongated cylinder, in combination with the fragile structure of the tissues significantly complicates the process of their cleaning from impurities without damage. As a result, the technological process of separating carrot heaps requires the use of special technical solutions that can ensure high quality cleaning with minimal product injury.

In this regard, the creation of an effective device for cleaning carrot roots from soil impurities and plant residues is an urgent scientific and technical task of modern agricultural engineering.

2. Analysis of recent research and publications

Analysis of modern scientific works shows that a significant number of studies are devoted to improving the technological processes of digging and cleaning root crops. With the separate technology of harvesting carrots, a heap is formed after digging, which contains soil, plant residues and other impurities that require effective separation.

The main regularities of the processes of digging and cleaning sugar beet roots were studied in works [1-3]. The constructive solutions and mathematical models proposed by the authors can be used as a theoretical basis for improving machines designed for harvesting carrots.

Among the existing technical means, a promising direction is the use of spiral separators, which provide intensive destruction of the heap and effective separation of impurities. According to the results of experimental studies, it was established that the use of a spiral separator allows achieving a high degree of cleaning with minor damage to root crops, which does not exceed the permissible agrotechnical standards [4-6]. However, designs developed for other root crops do not fully take into account the morphological features of carrots and the specific conditions of its harvesting, which necessitates the improvement of their design and technological parameters [7].

A separate problem is the assessment of the efficiency of cleaning systems. Known methods for determining the degree of damage and the quality of separation are characterized by significant labor intensity and, as a rule, are used only during field tests during the harvest period [8, 9]. Laboratory methods allow determining only individual process indicators, without providing a comprehensive assessment of the functioning of the machine in real operating conditions [10].

Thus, the analysis of scientific sources confirms that the problem of increasing the efficiency of cleaning carrot roots during mechanized harvesting has not been finally resolved. This indicates the feasibility of conducting further research aimed at improving the design of cleaning working bodies and substantiating their rational parameters.

3. The purpose of the article

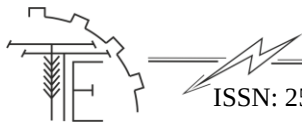
Improving the quality of cleaning carrots from soil impurities and plant residues by determining the rational parameters of the operation of an improved root crop pile cleaner.

4. Results and discussion

To improve the quality of cleaning the pile of carrot roots from soil impurities and plant residues, laboratory experiments were conducted to study the influence of the main structural and kinematic parameters of the improved cleaner on the amount of separated and adhered soil when cleaning carrot roots. Experimental studies were conducted using a specially manufactured new experimental setup, the operation of which is shown in the article [11]. When conducting laboratory experimental studies, methods regulated by state standards were used, as well as partial methods that were developed specifically for these studies and are described in the works [11, 12].

Based on the study of the technological process of cleaning the pile of carrot roots from soil impurities and plant residues with a spiral cleaner, evaluation of the results of theoretical and experimental studies in this area, the main adjustable parameters were determined and adopted, which include: the mass of the carrot root, the angular speed of rotation of the cleaner shafts and the angle of inclination of the cleaner's working surface to the horizon.

At the same time, the initial parameters (optimization functions) in the study of this technological process, which characterize the quality of work, are the amount of separated and adhered soil during cleaning of carrots in the working channel of the cleaner, which were taken in the form of a functional $S = f(x_1; x_2; x_3)$ and $D = f(x_1; x_2; x_3)$, where S and D are the amount of separated and adhered soil during cleaning of carrots



in the working channel of the cleaner; are natural independent variable factors, the corresponding conditional plan of the multifactorial experiment was chosen.

When conducting a multifactorial experiment, the following parameters were variables: the mass of the carrot root crop (m, g), which was coded by the index X1, the angular speed of rotation of the cleaner shafts (ω , $\text{rad}\cdot\text{s}^{-1}$), which was coded by the index X2, and the angle of inclination of the cleaning channel to the horizon (α , deg.), which was coded by the index X3.

Since, when conducting experiments, the independent parameters are heterogeneous and have different units of measurement, while the numbers that characterize the values of these factors have different orders, they were brought to a single system of calculations by transitioning from real values to coded ones.

During coding of the selected factors, the factor space is linearly transformed, while the origin of the coordinates is transferred to the center of the experiment, the scale along the axes is selected in units of variation of the factors.

Factor coding was performed using the dependence

$$X_i = \frac{2(x_i - x_{i0})}{x_{\max} - x_{\min}}, \quad (1)$$

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

To construct the multifactorial experiment design matrix, coded designations of the upper, lower and zero levels of variation by each factor were introduced. In this case, the designations (+1), (-1), (0) were introduced, respectively. The results of coding of variable factors and their levels of variation are given in Table. 1.

Table 1.

Results of factor coding and their levels of variation in the study of the amount of adhered and separated soil during carrot cleaning in the working channel of the cleaner

Factors	Interv. varied.	Рівні варіювання					
		nature.	cod.	nature.	cod.	nature.	cod.
Carrot root mass, m, g	80	80	-1	160	0	240	+1
Angular speed of rotation of the cleaner shafts ω , $\text{rad}\cdot\text{s}^{-1}$	4,2	27,2	-1	31,4	0	35,6	+1
The angle of inclination of the treatment channel to the horizon α , gr.	10	0	-1	10	0	20	+1

Coding of factors of natural variables was performed using the data of Table 1, using dependence (1). The results of coding are shown in the form of a system of equations:

$$\left. \begin{aligned} X_1 &= 0,0125 \cdot m - 2; \\ X_2 &= 0,238 \cdot \omega - 7,476; \\ X_3 &= 0,1 \cdot \alpha - 1. \end{aligned} \right\}, \quad (2)$$

After coding the factors, a plan-matrix of the corresponding multifactorial experiment of the PFE 33 type was compiled for the total number of experiments.

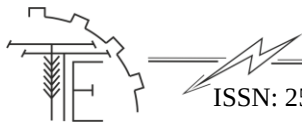
In order to reliably assess the performance of the developed purifier during the research, the required number of measurements of the controlled indicators (repeatability of experiments) was carried out with threefold repeatability.

The research was conducted for two cases of root crops entering the purification channel:

- in the case of movement of the thicker part of the carrot root crop back, and the tail part forward;
- in the case of movement of the thicker part of the carrot root crop forward, and the tail part back.

During the implementation of the compiled plan-matrix, in order to eliminate the influence of the moment magnitude on the obtained results from uncontrolled and unregulated factors, the plan-matrix was randomized using the random balance method, which was implemented by extracting the serial numbers of the experiments from the urn.

During the processing of the obtained experimental data, after the implementation of planned



experiments, the response functions (optimization parameters) were taken in the form of an approximating mathematical model of a complete square polynomial [12], which describes the real experimental process:

$$S = b_0^S + b_1^S \cdot x_1 + b_2^S \cdot x_2 + b_3^S \cdot x_3 + b_{12}^S \cdot x_1 \cdot x_2 + b_{13}^S \cdot x_1 \cdot x_3 + b_{23}^S \cdot x_2 \cdot x_3 + b_{11}^S \cdot x_1^2 + b_{22}^S \cdot x_2^2 + b_{33}^S \cdot x_3^2; \quad (3)$$

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

where $b_0^{S(D)}, b_1^{S(D)}, b_2^{S(D)}, b_3^{S(D)}, b_{12}^{S(D)}, b_{13}^{S(D)}, b_{23}^{S(D)}, b_{11}^D, b_{22}^D, b_{33}^D$ – regression coefficients of the corresponding values of input factors x_i ; x_1, x_2, x_3 – input coded factors.

Statistical significance of the coefficients of the regression equation $b_{i(jk)}$ was carried out using the Student's t-test. If the significance condition was not met, then such a coefficient $b_{i(jk)}$ the regression equation was assumed to be insignificant (equal to zero), and the corresponding term x_i regression equations excluded.

The values of the coefficients of the regression equations for two cases of the root crop falling into the cleaning channel are presented in tables 2 – 5.

Table 2.

The values of the coefficients of the regression equations for determining the amount of separated soil in the case of the movement of the thicker part of the carrot root crop backwards and the tail part forwards

$b_0^{S_1}$	$b_1^{S_1}$	$b_2^{S_1}$	$b_3^{S_1}$	$b_{12}^{S_1}$	$b_{13}^{S_1}$	$b_{23}^{S_1}$
129,9259	12,6296	17,8148	– 7,6296	3,4074	2,7407	3,3704

Table 3.

Values of coefficients of regression equations for determining the amount of separated soil in the case of movement of the thicker part of the carrot root forward and the tail part backward

$b_0^{S_2}$	$b_1^{S_2}$	$b_2^{S_2}$	$b_3^{S_2}$	$b_{12}^{S_2}$	$b_{11}^{S_2}$	$b_{22}^{S_2}$
133,037	19,0	23,3704	– 5,6296	2,2963	0,8272	– 0,9506

Table 4.

Values of coefficients of regression equations for determining the amount of stuck soil in the case of movement of the thicker part of the carrot root backwards and the tail part forwards

$b_0^{D_1}$	$b_1^{D_1}$	$b_2^{D_1}$	$b_3^{D_1}$	$b_{23}^{D_1}$	$b_{11}^{D_1}$
7,9259	2,963	2,3333	– 0,9559	0,1482	0,1235

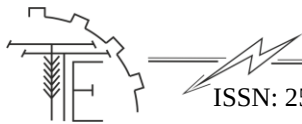
Table 5.

Values of coefficients of regression equations for determining the amount of stuck soil in the case of movement of the thicker part of the carrot root forward and the tail part backward

$b_0^{D_2}$	$b_1^{D_2}$	$b_2^{D_2}$	$b_3^{D_2}$	$b_{12}^{D_2}$
7,0741	2,5185	1,8889	– 1,2222	0,1111

So, after performing the appropriate calculations and transformations in natural coordinates, the regression equation for determining the amount of separated S and adhered D soil when cleaning carrots with a cleaner for two cases of the root crop entering the cleaning channel after transformation and simplification of the expressions will take the form:

– in the case of movement of the thicker part of the carrot root crop backward, and the tail part forward:



$$S_1 = 57,2906 - 0,2028 \cdot m + 1,9657 \cdot \omega - 3,4861 \cdot \alpha + 0,0102 \cdot m \cdot \omega + 0,0652 \cdot \omega \cdot \alpha + 0,0044 \cdot m \cdot \alpha. \quad (3)$$

$$D_1 = -12,887 + 0,031 \cdot m + 0,52 \cdot \omega - 0,207 \cdot \alpha + 0,0035 \cdot \omega \cdot \alpha + 0,00002 \cdot m^2. \quad (4)$$

– in the case of the thicker part of the carrot root moving forward and the tail part moving backward:

$$S_2 = -92,868 - 0,017 \cdot m + 7,891 \cdot \omega - 0,563 \cdot \alpha + 0,007 \cdot m \cdot \omega + 0,00013 \cdot m^2 - 0,054 \cdot \omega^2. \quad (5)$$

$$D_2 = -9,204 + 0,021 \cdot m + 0,398 \cdot \omega - 0,122 \cdot \alpha + 0,0003 \cdot m \cdot \omega. \quad (6)$$

According to the results of calculations carried out using the package of applied statistical programs for processing and analyzing the results of experimental research for the PC "Statistica 13.0", three-dimensional spatial dependences of the response surfaces of the amount of separated and adhered soil when cleaning carrots with a cleaner for two cases of the root crop getting into the cleaning channel were constructed for a visual representation of the results of the conducted experimental laboratory studies, which will make it possible to characterize the effects of factors and their interaction on the optimization parameters, i.e. $S_1 = f(m, \omega, \alpha)$, $D_1 = f(m, \omega, \alpha)$ і $S_2 = f(m, \omega, \alpha)$, $D_2 = f(m, \omega, \alpha)$.

Fig. 1 and 2 show the response surfaces of the amount of separated S and adhered D soil when cleaning carrots with a cleaner in the case of the movement of the thicker part of the carrot root back and the tail part forward and their two-dimensional cross-section as a function of two variable factors χ (1, 2) at a constant unchanged level of the corresponding third factor χ (1, 2) = const.

From the analysis of the regression equation (3) of the amount of separated soil in the case of the movement of the thicker part of the carrot root back and the tail part forward during cleaning in the working channel of the spiral cleaner, it was found that the greatest influence on the value of S_1 has the value of the angular speed of rotation of the cleaner shafts ω (a change in ω within 27.2...35.6 rad·s⁻¹ leads to an increase in S_1 by 24%). Next in terms of intensity of influence on the amount of stuck soil S_1 is the mass of the root crop m (a change in m within 80...240 g leads to an increase in S_1 by 18%) and the smallest influence on the value of S_1 has the angle of inclination of the working surface of the cleaner to the horizon α (a change in α within 0°...20° leads to a decrease in S_1 by 10.7%).

From the analysis of the regression equation (4) of the amount of stuck soil in the case of the movement of the thicker part of the carrot root crop back and the tail part forward during cleaning in the working channel of the spiral cleaner, it was found that the greatest influence on the value of D_1 has the value of the mass of the root crop m (a change in m within 80...240 g leads to an increase in D_1 by 54.1%). Next in intensity of influence on the amount of stuck soil D_1 is the angular speed of rotation of the cleaner shafts ω (a change in ω within 27.2...35.6 rad·s⁻¹ leads to an increase in D_1 by 45.4%) and the smallest influence on the value of D_1 has the angle of inclination of the cleaner working surface to the horizon α (a change in α within 0°...20° leads to a decrease in D_1 by 21.8%).

Fig. 3 and 4 show the response surfaces of the amount of separated S and stuck D soil when cleaning carrots with a cleaner in the case of movement of the thicker part of the carrot root crop forward, and the tail part backward, and their two-dimensional cross-section as a function of two variable factors χ (1, 2) at a constant unchanged level of the corresponding third factor χ (1, 2) = const.

From the analysis of the regression equation (5) of the amount of separated soil in the case of the movement of the thicker part of the carrot root crop forward and the tail part backward during cleaning in the working channel of the spiral cleaner, it was found that the greatest influence on the value of S_2 has the value of the angular speed of rotation of the cleaner shafts ω (a change in ω within 27.2...35.6 rad·s⁻¹ leads to an increase in S_2 by 30.6%). Next in intensity of influence on the amount of stuck soil S_2 is the mass of the root crop m (a change in m within 80...240 g leads to an increase in S_2 by 25.7%) and the least influence on the value of S_2 has the angle of inclination of the cleaner working surface to the horizon α (a change in α within 0°...20° leads to a decrease in S_2 by 8.2%).

From the analysis of the regression equation (6) of the amount of stuck soil in the case of the movement of the thicker part of the carrot root forward and the tail part backward during cleaning in the working channel of the spiral cleaner, it was found that the greatest influence on the value of D_2 has the value of the root mass m (a change in m within 80...240 g leads to an increase in D_2 by 51.9%).

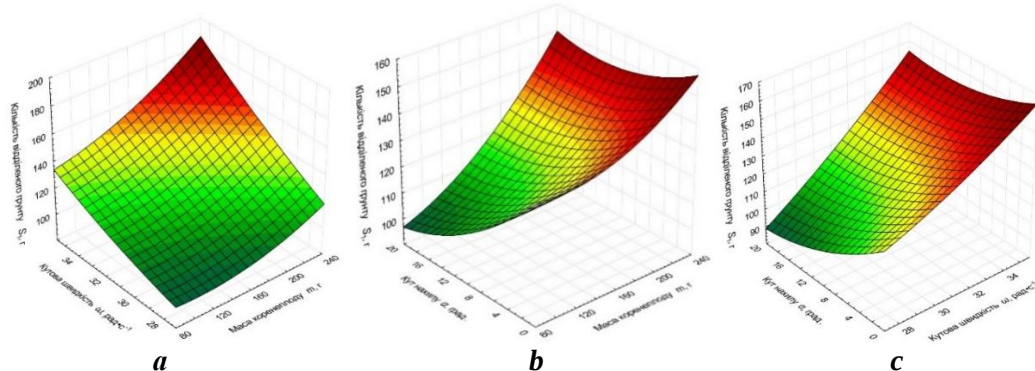


Fig. 1. Response surface of the amount of separated soil when cleaning carrots with a cleaner in the case of movement of the thicker part of the carrot root back and the tail part forward:

$$a - S_1 = f(m, \omega); b - S_1 = f(m, \alpha); c - S_1 = f(\omega, \alpha)$$

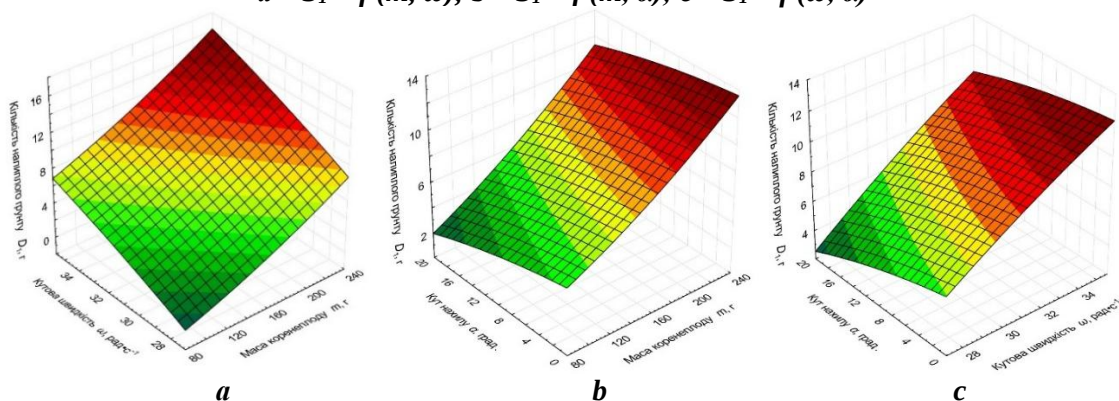


Fig. 2. Response surface of the amount of stuck soil when cleaning carrots with a cleaner in the case of moving the thicker part of the carrot root back and the tail part forward:

$$a - D_1 = f(m, \omega); b - D_1 = f(m, \alpha); c - D_1 = f(\omega, \alpha)$$

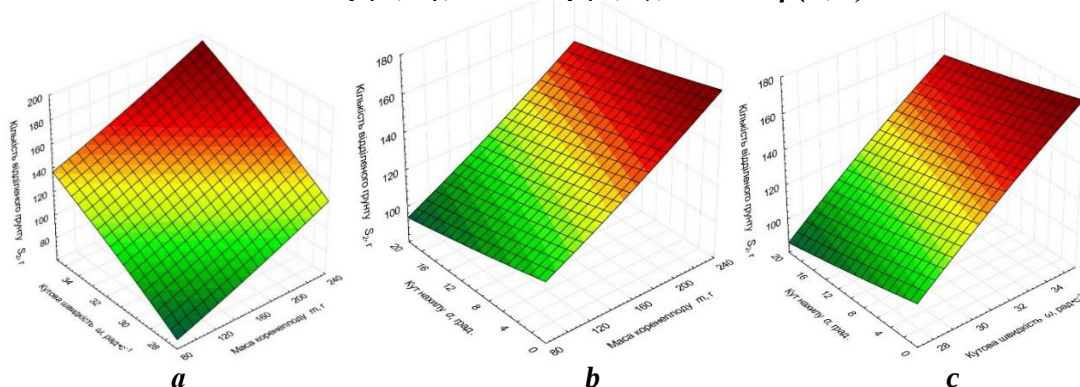


Fig. 3. Response surface of the amount of separated soil when cleaning carrots with a cleaner in the case of movement of the thicker part of the carrot root back and the tail part forward:

$$a - S_2 = f(m, \omega); b - S_2 = f(m, \alpha); c - S_2 = f(\omega, \alpha)$$

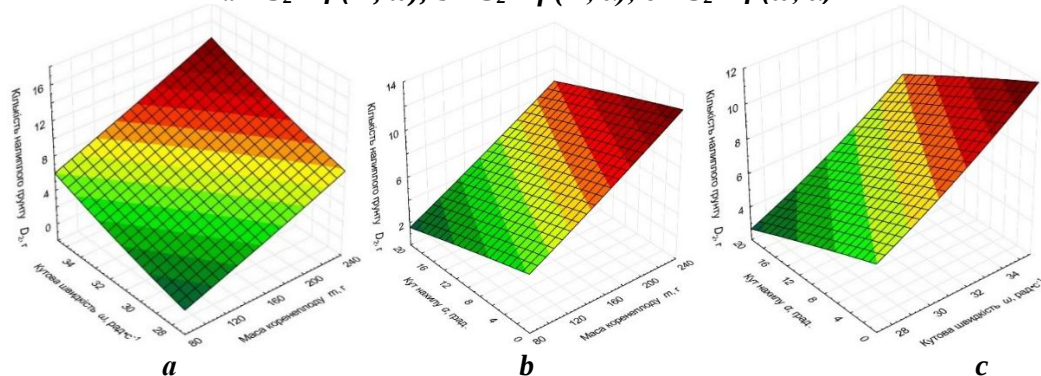
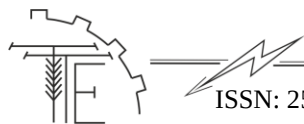


Fig. 4. The response surface of the amount of stuck soil when cleaning carrots with a cleaner in the case of moving the thicker part of the root of the carrot back, and the tail part forward:

$$a - D_2 = f(m, \omega); b - D_2 = f(m, \alpha); c - D_2 = f(\omega, \alpha)$$



Next in terms of intensity of influence on the amount of adhered soil D_2 is the angular speed of rotation of the cleaner shafts ω (a change in ω within 27.2...35.6 rad·s⁻¹ leads to an increase in D_2 by 42.5%) and the angle of inclination of the cleaner working surface to the horizon α has the smallest influence on the value of D_2 (a change in α within 0°...20° leads to a decrease in D_2 by 29.9%).

5. Conclusion

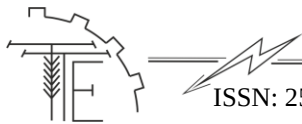
1. The corresponding regression equations were compiled to establish the influence on the quality of cleaning the carrot pile from soil impurities and plant residues and damage to root crops of controlled factors, which will allow choosing rational design and kinematic parameters of the carrot root crop cleaner.

2. From the analysis of the regression equations of the amount of separated soil for two cases of root crop entering the cleaning bed, it was established that the greatest influence on the value S has the value of the angular speed of rotation of the cleaner shafts ω . Next in intensity of influence on the amount of stuck soil S is the mass of the root crop m and the least influence on the value S has the angle of inclination of the working surface of the cleaner to the horizon α .

3. From the analysis of the regression equations of the amount of stuck soil for two cases of root crop entering the cleaning bed, it was established that the greatest influence on the value D has the value of the mass of the root crop m . Next in intensity of influence on the amount of stuck soil D is the angular speed of rotation of the cleaner shafts ω and the angle of inclination of the cleaner's working surface to the horizon α has the smallest influence on the value of D .

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РЕЗУЛЬТАТИ ЕКСПЕРИМЕНТАЛЬНИХ ДОСЛІДЖЕНЬ ЯКОСТІ ОЧИЩЕННЯ КОРЕНЕПЛОДІВ МОРКВИ СПІРАЛЬНИМ ОЧИСНИКОМ

У статті представлено результати комплексного дослідження впливу керованих факторів на якість очищення вороху моркви від ґрунтових домішок і рослинних решток, а також на рівень механічного пошкодження коренеплодів у процесі роботи очисника. Для встановлення характеру, сили та взаємодії досліджуваних параметрів розроблено відповідні рівняння регресії, які дають змогу кількісно оцінити залежність основних показників технологічного процесу від маси коренеплоду моркви (m , г), кутової швидкості обертання валів очисника (ω , рад·с⁻¹) та кута нахилу очисного русла до горизонту (α , град.). Такий підхід дає можливість визначити найбільш значущі фактори та встановити межі їх раціонального варіювання. Експериментальні дослідження та статистичну обробку отриманих результатів виконували із застосуванням пакета прикладних статистичних програм Statistica 13.0. На основі одержаних даних побудовано тривимірні просторові поверхні відгуку, що характеризують залежності кількості відділеного та налиплого ґрунту, а також рівня пошкодження коренеплодів від досліджуваних факторів. Аналіз проводили для двох варіантів потрапляння коренеплоду на очисне русло, що дало змогу встановити особливості перебігу процесу залежно від початкової орієнтації моркви та умов її контакту з робочими органами. Отримані графічні та аналітичні залежності забезпечують наочне представлення результатів лабораторних експериментів і дають можливість оцінити як окремі впливи кожного фактора, так і характер їх взаємодії. Встановлені закономірності можуть бути використані для обґрунтування раціональних режимів роботи очисника, підвищення ефективності видалення ґрунтових домішок і рослинних решток та зменшення механічного пошкодження коренеплодів. Результати дослідження створюють наукову основу для подальшої оптимізації конструктивно-технологічних параметрів очисних машин і підвищення якості післязбиральної обробки моркви. Отримані результати також можуть бути використані для розроблення практичних рекомендацій щодо вибору оптимальних робочих параметрів спіральних очисників за різних умов збирання та післязбиральної обробки моркви.

Ключові слова: коренеплоди моркви, очисник, лабораторна установка, кількість відділеного ґрунту, кількість налиплого ґрунту.

Ф. 6. Рис. 4. Табл. 5. Літ. 12.

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