Agraarteadus
2 • XXXI • 2020 202–207

Journal of Agricultural Science
2 • XXXI • 2020 202–207

EXPERIMENTAL RESEARCH INTO IMPACT OF KINEMATIC AND DESIGN PARAMETERS OF A SPIRAL POTATO SEPARATOR ON QUALITY OF PLANT RESIDUES AND SOIL SEPARATION

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Saabunud: Received: 08.10.2020
Aktsepteeritud: Accepted: 15.12.2020
Avaldatud veebis: Published online: 31.12.2020

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Keywords: cleaning device, plant residues, potato tuber, quality, separation, soil, spiral roll.

DOI: 10.15159/jas.20.26

ABSTRACT. The experimental investigations carried out in field production conditions have proved that the process of cleaning potato tubers from extraneous material with the use of a spiral separator takes place due to the active conveyance of the heap by the turns of the cantilever mounted cleaning spiral springs. The cleaning spiral springs not only rotate at the set angular velocity, but simultaneously their cantilevered ends perform oscillatory motion, which arises due to the deflection of their longitudinal axes under the action of the weight of the potato heap fed into the work zone of the separator. The results obtained in the process of the field experiment investigations carried out by the authors have provided for obtaining the relations that enable selecting the optimum design and kinematic parameters of the spiral-type potato cleaning devices for the targeted separation rate and, accordingly, estimating their impact on the quality of the performed work process.

Introduction

During the mechanised harvesting of potatoes with the use of combine harvesters, the separation of the large amount of the tubers from soil and plant residues is one of the major problems (Feller *et al*., 1987; Misener, McLeod, 1989; Peters, 1997; Bishop *et al*., 2012; Ichiki *et al*., 2013; Wang *et al*., 2017). Various cleaning devices, separators, clod smashers, elevators, screens *etc*. are employed to remove directly the considerable mass of soil and plant residues from the potato tubers (Petrov, 1984; Holland-Batt, 1989; Vasilenko, 1996; Feng *et al*., 2017; Guo, Campanella, 2017; Wei, Sun, 2017; Ye *et al*., 2017; Nowak *et al*., 2019).

Another important aspect in the potato harvesting is the separating of the tubers from soil and plant residues without inflicting damage on them. Therefore, the development of machines for cleaning potatoes from extraneous material directly after lifting from the soil the complete tuber-bearing bed (potato tubers, stuck soil, solid soil buildups, rhizomae, haulm debris, stones *etc*.) is an important topical scientific and technical problem in the field of agricultural engineering.

The aim of the study is to improve the quality indices of the process of cleaning potato tubers from soil and plant residues during their lifting from the soil by means of validating the rational design and kinematic parameters of the spiral separator.

The authors have developed a new design of the potato heap separator comprising four cantilevered power-driven spirals (Bulgakov *et al*., 2018a, 2018b, 2018c), which constitute an active undulated cleaning surface, onto which the lifted heap is fed (Fig. 1). At the same time, the design provides for changing the angle α of inclination of the said cleaning surface relative to the horizon, which increases the separation rate and ensures the progression of the tubers towards the discharge elevator. All these arrangements also promote better distribution of the heap over the working surface of the separator, more intensive disintegration of soil clods and, consequently, improved sieving down of the soil impurities and plant debris and reduced clogging of the cleaning spirals with the residues. Eventually, higher cleaning efficiency and productivity of the device for cleaning potatoes from soil and plant residues is achieved.

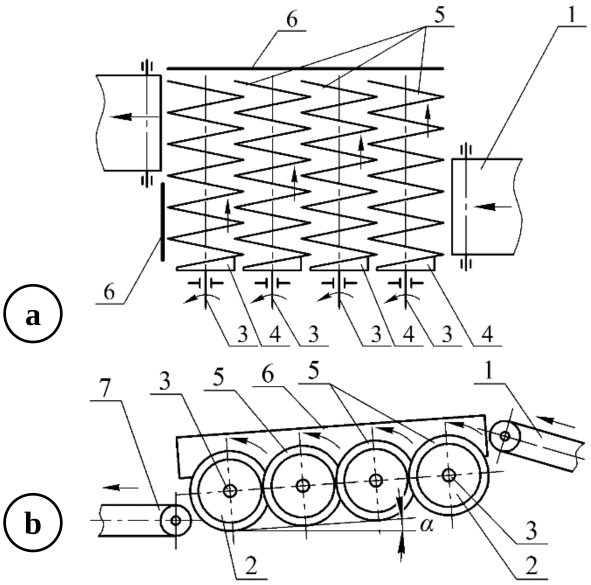

Figure 1. Design layout of spiral-type potato cleaning device: a – top view; b – side view: 1 – feeding elevator; 2 – spirals of cleaning rolls; 3 – shafts actuating rotary motion of spirals; 4 – hubs; 5 – free ends of spirals; 6 – screens; 7 – discharge elevator; *α* – inclination angle

The design of the spiral separator for separating potatoes from soil and plant residues comprises several power-driven spiral rolls 2 made in the form of spiral springs, which are cantilever supported and form an undulated separating surface. On one side this cleaning surface is connected with the loading (feeding) elevator 1, on the opposite side it is connected with the discharge elevator 7. The design also includes screens preventing the loss of potato tubers during their cleaning. The first flat screen 6 is fixed on a frame over the above-mentioned cleaning surface, the second screen 6 is fixed beside the discharge elevator 7. The spiral rolls 2 comprise the hubs 4 and the cleaning spirals cantilevered on the hubs. The hubs, in their turn, are connected to the drive shafts 3 that actuate the rotary motion of the spirals.

The cleaning spirals of the rolls 2 have mutual overlapping. The position in space of the whole cleaning surface formed by the cleaning spirals of the rolls 2 can be changed, that is, the angle *α* of its inclination relative to the horizon can be adjusted as required. The rotation of the cleaning spirals of the rolls 2 actuated by the drive shafts 3 can be set at different angular velocities, which would result in different circumferential velocities of rotation of the spiral turns. The sense of the rotary motion performed by the cleaning spirals of the rolls 2 is the same for all spirals. The cleaning spirals of the rolls 2 are mounted with mutual overlapping, while their free ends 5 can perform oscillatory motion under the action of the variable load of the potato heap lifted from the soil and fed onto the spirals by the feeding elevator 1.

The proposed design of the spiral potato separator envisages also the use of more than four spirals of the cleaning rolls and they can have different lengths, which, overall, provides for configuring the active cleaning surface of any area in the cleaning device. That said, the pitch of the cleaning roll spirals and their mutual overlapping must rule out the trapping of even small-size potato tuber bodies, *i.e.* prevent their loss and damaging.

Such a design solution (Fig. 2) of the proposed potato heap cleaning device provides openings of significant areas in its cleaning surface, which are formed by the spaces between the turns within each spiral and the clearances between the windings of the adjacent cleaning spirals. That increases the area, through which the separation of the soil impurities and plant debris down and outside the cleaning machine is performed.

At the same time, the described design features such an advantage as the absence of any shafts on the centrelines of the cleaning spirals. That allows to ensure the unobstructed passage down of all extraneous material and also prevents the undesirable wrapping of the shafts with plant debris. The hollowness of the internal space inside each cleaning spiral spring provides for the improved ability to transport positively all the mass of soil and plant residues entering that space towards the outlet (cantilever) end of the spiral and discharge it through the free end face onto the field surface.

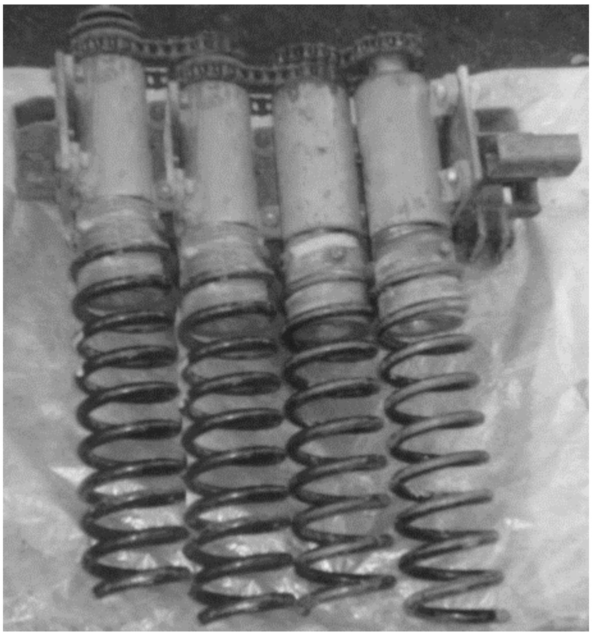

Figure 2. Design solution of separation module in experimental unit

The cantilever mounting of the spiral ends results in their forced oscillations, which materially activates the process of separating the extraneous material from the potato tubers.

In order to prevent the soil from sticking to the cleaning spirals and sealing the clearances between the spiral windings (especially in case of wet soil), the spiral springs are mounted with mutual overlapping, which implies the turns of one of the spirals partially entering the spaces between the turns of the second spiral. For the purpose of ensuring the progression of the potato tubers along the cleaning surface that has an undulated shape, the design includes the possibility to change the angle α of its inclination relative to the horizon. Each cleaning spiral features eccentricity, which makes the spiral perform forced oscillatory motion during its operation. The said motion promotes the agitation of the potato heap fed onto the spiral.

Materials and methods

In accordance with the earlier prepared programme (Bulgakov *et al*., 2019a, 2019b, 2020a, 2020b) of a multiple-factor experiment, the authors carried out the experimental research into the impact that the main design and kinematic parameters of the spiral potato separator had on the intensity, with which it separated soil impurities and plant debris from potatoes. As regards the parameters of the spiral potato separator that could influence the separation process most of all, within the framework of the experimental investigations, the task of the greatest interest was the research into the impact that had: the angle α of the cleaning surface inclination relative to the horizon; the circular velocity V of the rotary motion performed by the cleaning spirals; the eccentricity ε, with which the cleaning spiral were mounted; and the material feeding rate Q, *i.e*. the rate, at which the potato heap was fed for separating it from soil and plant residues. Such design parameters as the diameter of the cleaning spiral (d_s = 133 mm), the angle of lead of its helical line (γ = 12 deg), the diameters of the bars, from which the cleaning spirals were wound (d_p = 11 mm) had earlier been determined by the authors theoretically, therefore, in the experimental investigations they were assumed as known constant values.

For the purpose of carrying out the described experimental research, the authors implemented a fractional factorial experiment of the 2^{4-1} design with a test replication number of 3. The model that described the impact of the factors on the optimisation parameter was assumed to be a linear relation (Brandt, 2014):

$$y = b_0 + b_1 \alpha + b_2 V + b_3 \varepsilon + b_4 Q \ . \qquad (1)$$

After obtaining the initial experimental data, they were processed with the use of the Microsoft Excel application software. The results of the experimental data processing were presented in the form of a regression equation, which was the mathematical model of the work process under consideration relating its parameters to each other.

The mathematical model in the form of the following linear regression equation was generated after processing the results of the experimental data obtained during the research into the impact that the above-mentioned parameters have on the intensity of the soil and plant residues separation with the use of a multiple correlation coefficient of R = 0.789 and a number of experiments of 8:

$$I_S = 126.334 + 1.086\alpha - 43.107V + 0.975\varepsilon - 0.081Q \qquad (2)$$

At the same time, the following correlations of the separation intensity had been observed: with the angle α of the separator inclination relative to the horizon – 0.505, with the circular velocity V of the cleaning spiral rotation – 0.562, with the eccentricity ε of the spiral mounting – 0.527, with the material feeding rate Q – 0.019.

It was concluded on the basis of the above-mentioned experimental research that the factors that had a significant effect on the course of the process included the circular velocity V of the cleaning spiral rotation, the eccentricity ε of the spiral mounting and the angle α of the inclination of the whole cleaning surface relative to the horizon. The eccentricity ε as a design parameter is usually set depending on the conditions of operation of the potato heap cleaning device (its value is set at the maximum, when the fed potato heap has a large moisture content). For that reason, the further experimental research was focused on exploring the impact of the circular velocity V of the rotary motion of the cleaning spirals and the angle α, at which the cleaning surface was inclined relative to the horizon, on the extraneous material separation intensity I_S at constant values of the cleaning spiral mounting eccentricity ε and the rate Q of feeding the material, that is, the separated potato heap.

The above-mentioned further research was implemented in the form of a complete factorial experiment of the 3^2 design with 4 additional points, in which the cleaned potato mass rate was set at 20 kg s^{-1} and the cleaning spirals were mounted with an eccentricity of 7 mm.

The statistical analysis of the data obtained as a result of the experiments was carried out with the use of the PC equipped with the "Statistica" application software, version 5.0.

Results and discussion

The obtained experimental data were used for carrying out multivariate regression analysis with the use of various kinds of functions.

The data obtained during the research into the impact of the separator tilt angle α and the circular velocity V of the cleaning spirals in their rotary motion on the separation intensity I_S were processed.

The mathematical models were obtained in the form of regression equations for different types of functions (at a probability of P = 0.95, $t_{\alpha cr}$ = 2.17):

– for the linear function, in the following form:

$$I_S = 146.596 + 1.712\alpha - 49.905V \,, \qquad (3)$$

at D = 0.893, R = 0.945, s = 6.175;

– for the power function, in the following form:

$$I_S = 233.279 \cdot \alpha^{0.037} \cdot V^{-1.865} \,, \qquad (4)$$

at D = 0.936, R = 0.967, s = 0.092;

– for the exponential function, in the following form:

$$I_S = 262.9707 \cdot 1.0338^{\alpha} \cdot 0.4094^{V} \,, \qquad (5)$$

at D = 0.848, R = 0.921, s = 0.142;

– for the logarithmic function, in the following form:

$$I_S = 138.191 + 1.805 \cdot \ln\alpha - 104.367 \cdot \ln V \,, \qquad (6)$$

at D = 0.918, R = 0.958, s = 5.39;

– for the inverse function, in the following form:

$$I_S = -38.340 - \frac{0.00003}{\alpha} + \frac{216.389}{V} \,, \qquad (7)$$

at D = 0.902, R = 0.95, s = 5.897;

– for the multivariate second-degree polynomial, in the following form:

$$I_S = 246.317 + 4.642\alpha - 155.297V - 0.105\alpha^2 - 0.395\alpha V + 26.158V^2 \,, \qquad (8)$$

at D = 0.978, R = 0.989, s = 3.35.

The selection of the function to be eventually used for the adequate description of the mathematical model was carried out by means of comparing their coefficients of multiple determination D. The function with the greatest value of the coefficient would prevail. In the case under consideration the multivariate second-degree polynomial was such a prevailing function.

Proceeding from the conditions described above, the authors chose the multivariate second-degree polynomial (Table 1) with the number of factors equal to 3, the number of variables equal to 6, at a probability level of P = 0.95, t_{α} = 2.17, for a second-degree polynomial.

The response surface of the relation between the extraneous material separation intensity on the one hand and the separator inclination angle α and the circular velocity V of the rotary motion of the cleaning spirals on the other hand (Fig. 3) as well as its two-dimensional section (Fig. 4) were plotted with the use of the above-mentioned application programme "Statistica", version 5.0.

The extremum value of the tilt angle α was determined with the use of the method of two-dimensional sections by differentiating the regression equation with respect to the separator inclination angle α and equating the derivative to zero. The following was obtained as a result:

$$\frac{dI_S}{d\alpha} = 3.709 - 0.199\alpha = 0 \,, \qquad (9)$$

which gives $\alpha \approx 18.56$ deg.

Table 1. Results of regression analysis

Variable	Correlation	Linearized coefficient of regression	Statistical error of regression coefficient	t_α	Coefficient of elastisity	Significance of regression coefficient
Dependent (outcome) variable						
I_S		+246.317				
Independent (predictor) variable						
α	+0.732	+4.642	+1.392	+3.51	+0.78	significant
V	–0.597	–155.297	+109.822	–1.41	–5.46	not significant
α^2	+0.605	–0.105	+0.021	–5.14	–0.27	significant
$\alpha \cdot V$	–0.639	–0.395	+0.598	–0.66	–0.14	not significant
V^2	–0.592	+26.158	+26.209	+1.00	+1.94	not significant

The obtained results provided for analysing in more detail the impact that the angle α of the separator inclination and the circular velocity V of the cleaning spirals had on the percentage of the sieved soil and the separation intensity I_S. For that purpose, the obtained experimental data were used for plotting the diagrams of the relations between the separation intensity I_S on the one hand and the separator inclination angle α and the circular velocity V of its rotating cleaning spirals on the other hand.

As is seen in the presented diagrams, the separation intensity I_S. depends on the separator inclination angle α and the circular velocity V of the cleaning spiral rotation (Fig. 3) in such a way that, when the separator inclination angle α increases up to 12 deg, significant growth of the optimisation parameter is observed. In case of the further increase of the angle α, at which the spiral tool's separating surface is inclined with respect to the horizon, the change in the said parameter is already insignificant, which can be explained by the potatoes rolling down without being cleaned from extraneous material.

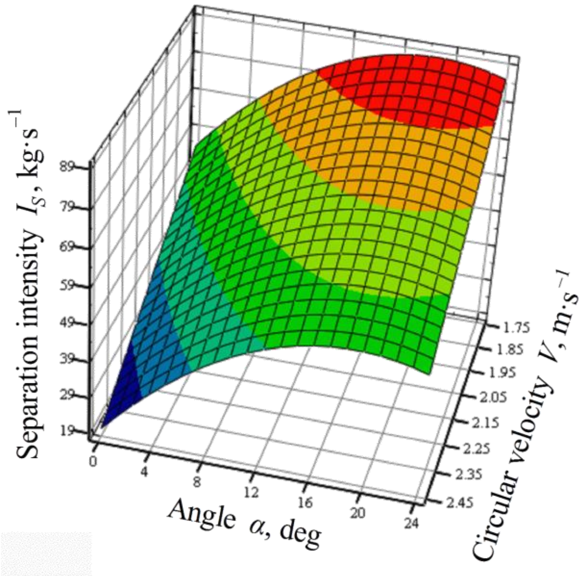

Figure 3. Response surface of relation between separation intensity I_S on the one hand and separator inclination angle α and circular velocity V of cleaning spiral rotation on the other hand.

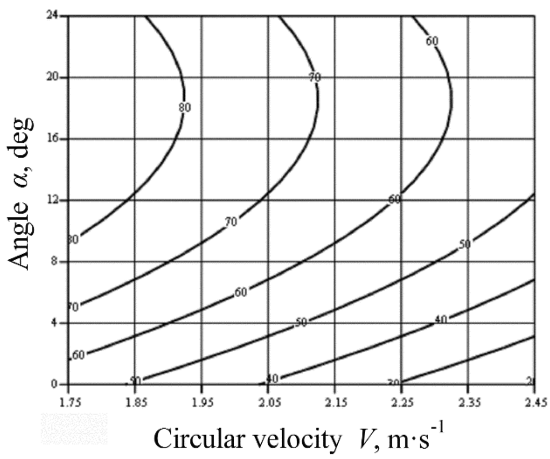

Figure 4. Two-dimensional section of response surface of relation between separation intensity I_S on the one hand and separator inclination angle α and circular velocity V of cleaning spiral rotation on the other hand.

When the circular velocity V of the cleaning spirals in their rotary motion (Fig. 4) increases up to 2 m s^{-1}, while the separator inclination angle α is at its rational value of 12 deg, the separation intensity I_S shows high values – in excess of 70 kg s^{-1}, but after reaching 2 m s^{-1}, its substantial decrease is observed.

That is due to the fact that, with the increase of the circular velocity V of the cleaning spiral rotation, the time of contact between the components of the potato heap and the spiral surfaces of the tool in the cleaning machine is reduced and also many potato tubers as well as larger soil particles, having obtained from the cleaning spirals sufficient initial velocities, just fly over the whole working surface of the cleaning tool and its screens. Such circumstances place limitations on the increase of the said circular velocity V of the cleaning spiral rotation.

Conclusions

1. A novel design of a device for separating potatoes from plant residues and soil has been developed, which offers an active separating surface of undulated shape formed by power-driven cantilevered spirals that are mutually eccentric positioned so as to permit the angle of their inclination to the horizontal to be readily adjusted.
2. Field experiment investigations have been carried out and the obtained data have been used for generating the model of a full factorial experiment. The results of the experiment have been statistically processed, which provided for performing the correlation and regression analysis of the obtained data with the use of the Microsoft Excel application software.
3. The completed research resulted in obtaining the relations for the intensity of the separation process. The said relations provide for determining the optimum design and kinematic parameters of the spiral-type machine for cleaning potatoes from extraneous material, which can be used in the design and development of new potato combine harvesters.
4. When the circular velocity V of the separating spirals increases up to 2 m s^{-1} and the separator inclination angle α is at a rational value of 12 deg, the separation intensity I_S has high values, reaching more than 70 kg s^{-1}.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author contributions

VA, VB – study conception and design;
VK, YI – acquisition of data;
AB, ZR – analysis and interpretation of data;
JO, VB – drafting of the manuscript;
JO – critical revision and approval of the final manuscript.

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