RESEARCH ON PROCESS OF CLEANING TABLE BEET ROOT CROPS WITH SPIRAL CLEANER

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Abstract. This article presents a laboratory spiral-cleaner design and an experimental procedure for improving the cleaning of table beet roots from loose and bound soil. A 3^3 factorial experiment was carried out for three factors: root mass (150-400 g), drop height (14-30 cm) and soil moisture (15-23%). Regression equations and response surfaces were obtained for the amount of bound soil Q and separated loose soil Q'. The results show that bound soil is most strongly affected by root mass and drop height, whereas loose-soil separation is most sensitive to soil moisture. For the tested setup, the recommended operating window is to keep the root drop height in the lower part of the studied range, about 14 cm, and to perform cleaning at soil moisture close to 15-19%; at 23% moisture, reduced feed rate or an additional gentle cleaning pass may be required. The proposed spiral cleaner is therefore most useful as a low-aggressiveness cleaning module for table beet harvesters operating under friable and moderately moist soil conditions.

Keywords: spiral cleaner, root crop, cleaning quality, loose soil, bound soil.

Introduction

One of the problems encountered during the harvesting of table beet roots is soil loss caused by the mechanical impact of the working parts of harvesting machines and cleaning operations. Such processes lead to disruption of the soil structure and development of erosion. In root-crop harvesting this problem is normally described as soil tare: its value depends not only on the cleaner design, but also on soil type, soil water content, root mass and machine adjustment [1; 2]. Therefore, improvement of cleaning devices must be evaluated together with the physical state of the soil and the damage risk for roots.

Studies [1; 3-6] have shown that the technological aspects of harvesting and cleaning root crops from soil impurities have a significant impact on quality characteristics and storage life. Recent work on potato and beet harvesting confirms that the cleaning process is a compromise between removing soil clods and limiting impact or collision damage, especially when the crop-soil mixture contains sticky soil, stones and plant residues [7; 8]. An important stage of the technological process is cleaning of root crops from soil and plant residues immediately after their removal from the soil [9-10]. This stage must ensure a high level of product cleanliness with minimal mechanical damage to the root crops, as damage significantly reduces their storage life.

To address these challenges during harvesting of table beets, the use of a spiral separator as a basic technical solution is promising [11]. Experimental studies confirm that the use of such a separator allows for a sufficiently high degree of cleaning of the processed material from soil impurities and plant residues, provided that agronomic requirements for preventing damage to the root crops are met.

At the same time, the variety of harvesting conditions, in particular fluctuations in soil moisture and hardness in the bed area, the presence of stony inclusions, compacted soil formations and plant residues, as well as variations in the mass, geometric parameters and shape of root crops, necessitates the adjustment of the design and operational parameters of the spiral separator to ensure the specified throughput and stability of the cleaning process [12-13]. This is consistent with studies on sugar beet soil tare and potato-soil separation, where wet or sticky soil sharply reduces the efficiency of conventional cleaning devices [2; 7].

Furthermore, the methods used in laboratory conditions do not provide a comprehensive assessment of the functioning of working parts and machines as a whole; however, they are appropriate for isolating the effect of individual factors, comparing the degree of root damage and separation efficiency, and preparing rational ranges for subsequent field tests [8; 14-16].

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Contemporary optimisation of crop-soil separation devices often combines analytical modelling, simulation and factorial experiments [7; 8; 17]. The methodology for theoretical research described in [16; 18] can also be used as a basis for studying the behaviour of soil particles during cleaning of root vegetables and for separating a multicomponent mixture using additional factors, such as an air vortex flow. This can improve the separation of soil and plant debris from table beet roots, but experimental verification under different soil-moisture conditions is still required.

An analysis of existing research has shown that the problem of high-quality cleaning of table beet roots during their mechanised harvesting has not been fully resolved, especially for the simultaneous removal of loose soil and adhering moist soil without intensive rubbing or high drop impacts.

Therefore, the development of cleaning machines for table beet roots and the substantiation of their rational operating ranges remain important scientific and technical problems in agricultural production.

Materials and methods

With the aim of improving the quality of table beet root cleaning using a spiral cleaner, a new design for a laboratory setup has been developed based on theoretical research and analysis of previous experiments; a general view of this setup is shown in Fig. 1, a.

The spiral cleaner operates as follows. A pile of table beet roots, dug up from the soil (and therefore containing a lot of soil impurities, rootstocks and plant residues), is fed from above onto the cleaning channel, which is constructed in the form of cantilevered spiral springs 2 that are forced to rotate in one direction, and cleaning brushes 4, which are mounted on frames 3 at regular intervals at equal angles α (Fig. 1, b). As a result, all parts of the pile are essentially located inside the cleaning trough in the form of a trapezium, with the upper part pointing downwards. It is precisely this that ensures that, in the event of root crops striking the trough and bouncing, they will inevitably be returned to the interior of the cleaning trough, coming into contact only with the upper parts of the drive cleaning brushes 4.

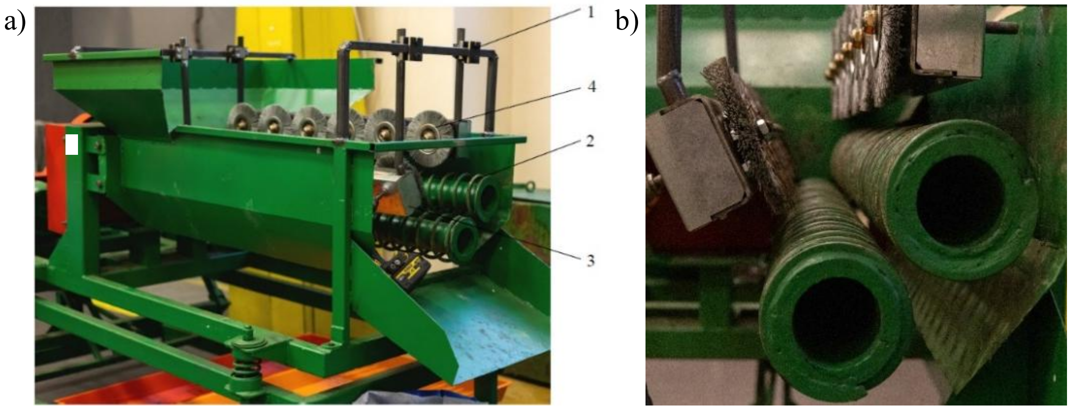

Fig. 1. **General view of the spiral cleaner (a) and cleaning trough (b) for cleaning table beet roots:** 1 – frame; 2 – cantilevered spiral springs; 3 – frames; 4 – brushes

During the experiments, table beet roots with naturally adhering soil were first weighed on electronic scales, after which they entered the cleaning trough of the cleaner and were transported to the unloading zone. The tested soil fraction consisted of the material adhering to the roots and loose clods entering the trough together with the roots after digging. Soil moisture was controlled at three levels of 15, 19 and 23% (Table 1) and was determined by the gravimetric weighing method from representative samples of the soil accompanying the roots. The 15% level corresponded to a friable state with predominant loose soil, 19% to an intermediate state, and 23% to a visibly more adhesive state in which bound soil on the root surface increased. These levels were selected to reproduce the practically important range from relatively easy separation to moist/sticky cleaning conditions. During cleaning, the pile of root vegetables is immediately spread across this surface and, by the rotating cantilevered spiral springs 2, begins to be transported not only in the radial direction but also in the axial direction of the cantilevered spiral springs 2 themselves. The cleaning brushes 4, meanwhile, have identical directions of rotational movement, which are directed towards the unloading conveyor; this ensures not only the effective capture of fine soil impurities and their removal beyond the cleaner, but also ensures highly efficient transport of the root vegetables. After complete cleaning, the table beet roots fall onto the discharge chute and are carried out of the cleaner. The roots were then weighed again. To determine the amount of loose soil, a chute was positioned beneath the cleaning channel, enabling the quantity of separated soil to be measured along the length of the conveyor. The amount of bound soil was determined as the difference between the weight of the root vegetable after cleaning and the weight of the beet itself.

To establish the influence of independent factors affecting the amount of loose and bound soil during cleaning in the working channel of the spiral cleaner, a comparative multifactorial experiment of the PFE P^k type was conducted, where P is the number of levels of variation of the factor; k is the number of factors present in the experiment. That is, as dependent variables in the optimisation functions of the multifactorial experiment model, we selected the functionals of the amount of bound soil $Q = f(x_1; x_2; x_3)$ and the amount of free-soil $Q' = f(x_1; x_2; x_3)$, where x_1; x_2; x_3 are natural independent variables for which a suitable factorial experimental design was selected. In the multifactorial experiment, the following parameters were treated as variables: root mass (m, g), coded by the index X_1, its drop height (h, cm), coded by the index X_2, and soil moisture (w, %), coded by the index X_3.

The weight of table beet roots before and after cleaning was determined using electronic scales. Beet roots were selected without mechanical damage, and the weight of each root was subsequently determined with a permissible weight deviation of ± 5 g. The drop height of the root was determined using a ruler mounted on a spiral cleaner. Soil moisture was checked before each experimental series using representative soil samples from the material adhering to the roots and from the loose soil in the feed material; the measured value was used to assign each trial to the 15, 19 or 23% moisture level.

Factors were coded using the following relationship:

$$X_i = \frac{x_i - x_{i0}}{\Delta x}, \tag{1}$$

where X_i – coded value of the factor (dimensionless quantity);
x_i – value of the factor in named (natural) units;
x_{i0} – natural value of the factor at the zero level;
Δx – range of variation of the factor.

When constructing the design matrix for the multi-factor experiments, coded designations were introduced for the upper, lower and zero levels of variation for each factor, which were denoted as (+ 1), (–1) and (0) respectively. The results of coding the variable factors are presented in Table 1.

Table 1

Results of factor coding and their variation levels for MFD 33

Factors	**Factor designations**		**Variation intervals**	**Levels of variation, natural/coded**		
	coded	**natural**				
Root weight *m*, g	X_1	x_1	125	150/–1	275/0	400/ + 1
Root crop drop height *h*, cm	X_2	x_2	8	14/–1	22/0	30/ + 1
Soil moisture *w*, %	X_3	x_3	4	15/–1	19/0	23/ + 1

The coding of the continuous variables is based on the data in Table 1, which are defined by the following expressions:

$$\left.\begin{aligned} X_1 &= 0.008 \cdot m - 2.2; \\ X_2 &= 0.125 \cdot h - 1; \\ X_3 &= 0.25 \cdot w - 4.75. \end{aligned}\right\} \tag{2}$$

After coding the factors, a design matrix was constructed for the corresponding 3^3 factorial experiment for a total number of trials $N = 27$.

During the implementation of the designed design matrices, to eliminate the influence of the amounts of free and bound soil on the results obtained during cleaning in the working channel of the spiral cleaner from uncontrolled and unregulated factors, the design matrix was randomised using the randomised block design method, which was implemented by drawing the serial numbers of the trials from a box.

When processing the experimental data obtained following the completion of the planned experiments, the response functions (optimisation parameters) were modelled using an approximate mathematical model of a linear function and, where curvature was significant, a full quadratic polynomial [17], which describe the actual experimental processes:

- for cohesive soil

$$Q = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3, \tag{3}$$

- for loose soil

$$Q' = b_0' + b_1' x_1 + b_2' x_2 + b_3' x_3 + b_{12}' x_1 x_2 + b_{13}' x_1 x_3 + b_{23}' x_2 x_3 + b_{11}' x_1 + b_{22}' x_2 + b_{33}' x_3, \tag{4}$$

where Q, Q' – experimental values of the amounts of free and bound soil during cleaning in the working channel of the spiral cleaner;

b_0, b_1, b_2, b_3, b_0, b_1', b_2', b_3', b_{12}', b_{13}', b_{23}', b_{11}', b_{22}', b_{33}' – regression coefficients of the corresponding values of the input factors x_i;

x_1, x_2, x_3 – input coded factors.

The statistical significance of the regression equation coefficients $b_{i(jk)}$ was assessed using the t Student's t-test. If the significance criterion was not met, the corresponding coefficient $b_{i(jk)}$ of the regression equation was considered insignificant (equal to zero), and the corresponding term x_i of the regression equation was excluded.

The values of the regression equation coefficients are presented in Table 2.

Table 2

Values of significant coefficients of the regression equations

b_0	b_1	b_2	b_3	b_0'	b_1'	b_2'	b_3'	b_{12}'	b_{22}'
13.778	-4.655	3.593	2.0	141.432	18.815	0.9344	27.086	-4.531	-5.264

In natural units (coordinates), the regression equation for the amount of free and bound soil during cleaning in the working channel of the spiral cleaner, depending on the root crop mass, its drop height and soil moisture, based on the results of the conducted PFE 33 in coded units, is equal to:

- for bound soil

$$Q = 10.926 - 0.037m + 0.449h + 0.5w, \tag{5}$$

- for loose soil

$$Q' = -43.852 + 0.187m + 2.562h + 6.772w - 0.004mw - 0.082h^2. \tag{6}$$

Based on the obtained regression equations (5) and (6), it is possible to determine the influence of controllable factors on the cleaning quality of table beet and to select rational operating ranges for the cleaner, primarily by limiting the drop height and by accounting for the moisture state of the soil entering the working channel.

Results and discussion

Using the STATISTICA software, graphical representations of the intermediate general regression models were constructed in the form of response surfaces showing changes in the amount of bound soil Q and separated loose soil Q' during cleaning in the working channel of the spiral cleaner as a function of two variable factors $x_{i(1,2)}$, whilst the corresponding third factor $x_{i(3)}$ = const was fixed at zero level (m = 275 g, h = 22 cm or w = 19%, depending on the plotted factor pair) (Fig. 2 and Fig. 3).

Analysis of the regression equation for the amount of bound soil during cleaning in the working channel of the spiral cleaner revealed that the greatest influence on the value of Q is exerted by the root crop mass m (a change in m within the range of 150-400 g leads to a 37.4% reduction in Q). Next in terms of the intensity of influence on the amount of bound soil Q is the throwing height h (a change in h within the range of 14-30 cm leads to an increase in Q by 30.3%), and the smallest influence on the value of Q is exerted by soil moisture w (a change in w within the range of 15-23% leads to an increase in Q of 18.1%). From a practical point of view, the drop height should not be increased beyond the minimum needed for stable feeding, because higher drops intensified the remaining bound soil in the studied range.

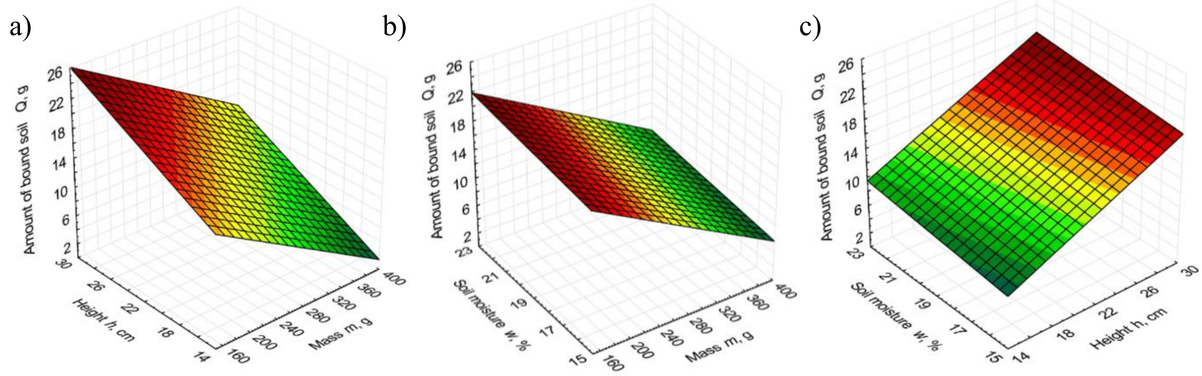

Fig. 2. **Response surface for the amount of bound soil:**
a – *Q* = (*m*; *h*); b – *Q* = (*m*; *w*); c – *Q* = (*h*; *w*)

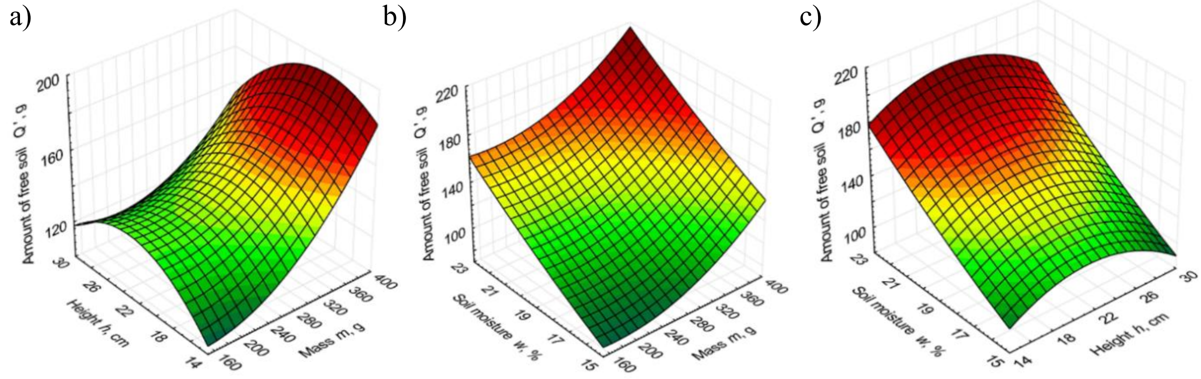

Fig. 3. **Response surface for the amount of loose soil:**
a – *Q*' = (*m*; *h*); b – *Q*' = (*m*; *w*); c – *Q*' = (*h*; *w*)

An analysis of the regression equation for the volume of loose soil separated during cleaning in the working channel of a spiral cleaner revealed that soil moisture *w* has the greatest influence on the value of *Q*' (a change in *w* within the range of 15-23% leads to a 35.5% increase in *Q*'). Next in terms of the intensity of influence on the amount of free soil *Q*' is the throwing height *h* (a change in *h* within the range of 14-30 cm leads to a decrease in *Q*' of 26.3%), and the root crop mass *m* has the least influence on the value of *Q′* (a change in *m* within the range of 150-400 g leads to an increase in *Q′* of 16.1%). A high value of *Q′* indicates more loose soil removed from the crop-soil pile; however, it must be interpreted together with *Q*, because the same increase in soil moisture also increases the amount of bound soil remaining on the roots.

For the tested cleaner, the rational operating recommendation is not to treat root mass as a machine setting but to adapt the drop height and the timing or intensity of cleaning to the moisture state of the soil. The most favourable tested condition for minimising bound soil is the combination of high root mass, low drop height and low soil moisture (m ≈ 400 g, h ≈ 14 cm, w ≈ 15%). For roots close to the central mass level (m ≈ 275 g), the recommended drop height is 14-22 cm, with preference for 14 cm when the feed contains wet adhering soil; cleaning at w ≈ 15-19% is preferable, whereas at w ≈ 23% the cleaner should be operated with reduced feed rate or followed by additional gentle cleaning.

Compared with operating root-crop equipment, which commonly uses webs, turbine wheels, roller groups and brush elements, the proposed spiral cleaner has a narrower laboratory throughput but offers a compact working channel in which axial conveying and soil removal occur simultaneously. In sugar beet harvesters, cleaning efficiency is obtained mainly by shear, friction between roots, turbine rotation and brushes; stronger cleaning can decrease soil tare but may increase mass losses [19].

Modern bar-lift chain and roller-type potato separators can reach high separation quality, but their performance depends on screen speed, inclination angle, roller spacing and the sticky state of the soil

[7; 8]. For table beet roots, the spiral-brush arrangement is beneficial because it limits drop height and uses controlled shear/friction rather than repeated high-energy impacts; this is the expected practical benefit of the proposed design and should be verified next under field throughput conditions.

Based on the results of these studies, it is possible to select the optimal parameters for the root crop cleaner, which will ensure improved cleaning quality of table beet using a spiral cleaner.

Conclusions

1. The article presents a laboratory setup and methodology for cleaning table beet roots with a spiral cleaner. The experimental description was refined by explicitly accounting for the tested soil-moisture levels of 15, 19 and 23%, which correspond to the transition from friable to more adhesive soil conditions. The variable factors of the 3^3 experiment were root mass, drop height and soil moisture.
2. The regression analysis showed that bound soil Q is reduced mainly by increasing root mass and by decreasing drop height. Within the studied range, increasing m from 150 to 400 g reduced Q by 37.4%, whereas increasing h from 14 to 30 cm increased Q by 30.3%. Therefore, for practical operation the drop height should be kept in the lower part of the studied range, preferably about 14 cm, especially when the crop-soil mixture contains moist adhering soil.
3. The amount of separated loose soil Q' was most sensitive to soil moisture: increasing w from 15 to 23% increased Q' by 35.5%, while increasing the drop height from 14 to 30 cm reduced Q' by 26.3%. The recommended operating window for the tested device is h = 14-22 cm and w = 15-19%; at w close to 23%, additional field validation is needed to determine the permissible feed rate, root damage and energy demand. Compared with operating root-crop cleaning equipment based on webs, turbine wheels, rollers and brushes, the spiral cleaner can be considered a compact low-aggressiveness module, but its throughput and durability should be verified in future field tests.

Author contributions

Conceptualization, V.B., A.R., J.O.; validation, A.A. and A.R.; investigation, O.T., I.H.; data curation, Ye. I.; software, V.M. All authors have read and agreed to the published version of the manuscript.

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