https://doi.org/10.17221/172/2025-RAE

# Experimental study of the haulm-cutting module of root crop harvesting machines

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**Citation:** Baranovsky V., Pankiv M., Komar R., Pankiv V., Berezhenko Y. (2026): Experimental study of the haulm-cutting module of root crop harvesting machines. Res. Agr. Eng., 72: 155–166.

**Abstract:** Reducing the energy consumption during the harvesting of large root crops (such as sugar and fodder beets, and chicory), which are used to produce food and industrial products, is a priority issue for improving the efficiency of production processes in agro-industrial enterprises. One approach to addressing this issue involves reducing the energy expenditures by the working elements of the haulm removal module in root crop harvesters by implementing a single-phase harvesting method. An improved method for haulm cutting is proposed, whereby the cut haulm is deposited in the field between two adjacent dividing discs located in the inter-row space of the root crops. This eliminates the intermediate operation of unloading the haulm onto the harvested field, which is a feature of the conventional method. Based on the results of the planned factorial experiments, empirical models were obtained that describe the functional variation of the specific mass of haulm deposited in the protective row zone, depending on changes in the module travel speed, haulm yield, and rotational speed of the rotary haulm cutter. A graphical analysis showed that the specific mass of the deposited haulm ranges from 15 to 82 $g \cdot m^{-2}$ at rotary cutter speeds of 400, 600 and 800 rpm.

**Keywords:** housing; guide channel; flat screen; factors; regression equation; optimisation parameter

At the current stage, the energy efficiency of technological processes is a key benchmark and criterion of modern production trends across industries, including agricultural production in the global economy (Žitňák and Korenko 2011; Hevko et al. 2016).

The first and most energy-intensive stage in the harvesting process of large root crops (sugar beet, fodder beet, chicory) is the technological operation of cutting off the main haulm mass from the crop heads. The presence of haulm in the harvested roots significantly lowers the quality of the raw materials and reduces the yield of the processed products (Bulgakov et al. 2018; Fan et al. 2023).

The commonly accepted technology for haulm removal – implemented by haulm removal modules in modern root crop harvesters from leading manufacturers – is the rotary cutting of the haulm mass, followed by the transportation of the chopped haulm via an auger conveyor and unloading it onto the surface of the harvested field (forming a windrow), or scattering it across the field surface using a rotary spreader (Siberev 2019).

One direction for improving the efficiency of root crop haulm harvesting, based on solving a complex scientific and technical problem, is the search for new design schemes of the working elements and the creation of improved energy-efficient haulm removal modules for self-propelled bunker-type root crop harvesters (Wang et al. 2022; Dorokhov et al. 2023).

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The scientific hypothesis underlying the proposed solution aims to reduce the energy consumption during haulm removal by eliminating an intermediate component – namely, the transport mechanism (an auger conveyor) typically mounted in a guide channel – within the structural and layout design of the haulm removal module (Pankiv et al. 2021; Dorokhov et al. 2023).

The method proposed by the company "Crimme" (Germany) (Bentini et al. 2006; da Cunha et al. 2011), which involves depositing the cut haulm into the inter-row spaces of unharvested root crops, has not seen widespread practical use. In cases where the haulm yield exceeds 40 t·ha$^{-1}$, a significant portion of the cut haulm ends up in the working zone of unharvested root rows, leading to the clogging of the digging components and a substantial increase in plant impurities in the harvested roots (Berezhenko et al. 2021; Saggau et al. 2024). According to Silva et al. (2018) and Bulgakov et al. (2019), in some cases, the amount of plant impurities in harvested root crops ranges from 10% to 15%, depending on the haulm yield – significantly exceeding the agro-technical standard of 8% (Bulgakov et al. 2023).

This leads to disruptions in the root crop digging process, as harvesting machines are forced to stop in order to clean the working areas of the digging components.

The aim of the study is to increase the technological efficiency of large root crop harvesting by reducing the energy consumption during haulm removal and minimising plant impurities during root digging through improvements in the haulm transport and design of the haulm-cutting module in root crop harvesters.

## MATERIAL AND METHODS

Currently, two main methods of haulm removal are used in self-propelled root crop harvesters:
– depositing the cut haulm into windrows on the field surface (Figure 1A),
– scattering the cut haulm across the harvested field surface (Figure 1B).

A third method – depositing the cut haulm into the inter-row spaces of unharvested root crops (Figure 1C) – is used to a limited extent, typically when the haulm yield does not exceed 40 t·ha$^{-1}$, as noted in da Cunha et al. (2011).

The existing haulm removal methods are illustrated by block diagrams (Figure 2).

Based on the conducted analysis (Bulgakov et al. 2006, 2018), an improved method of primary haulm collection for large root crops is proposed (Figure 3) (Baranovsky et al. 2023a), along with a design and technological scheme of the haulm removal module (Figure 4) (Baranovsky et al. 2023b) intended for implementing the proposed method.

To carry out experimental studies of the technological process of primary haulm collection from sugar beet root crops (*Beta vulgaris*, produced in Ukraine, row spacing 0.45 m, average haulm yield of 15 t·ha$^{-1}$), a mock-up prototype of a mounted three-row haulm removal module was used (Figure 5A). This prototype was constructed based on the design and technological scheme (Figure 4).

The haulm removal module was aggregated with an MTZ-80 tractor (MTZ, Belarus) (Figure 5B).

During the movement of the haulm removal module at speed $\vartheta$ (km·h$^{-1}$) along the root crop rows (1) (Figure 4), the blades (6) of the rotary


Figure 1. Existing methods of the primary haulm collection in root crop harvesting: (A) depositing the haulm into a windrow on the harvested field, (B) scattering the haulm over the harvested field, (C) placing the haulm into the inter-row space of unharvested root crops

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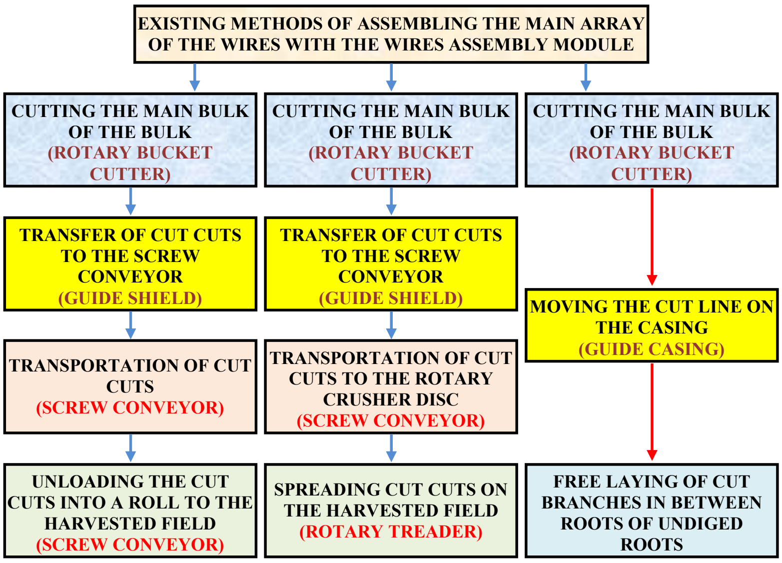


Figure 2. Existing methods of haulm collection in root crop harvesting

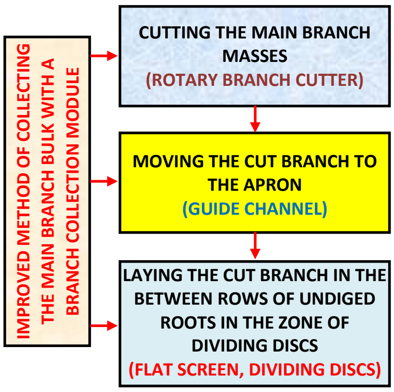


Figure 3. Block diagram of the improved method for the primary haulm collection in root crop harvesting

haulm cutter (4), rotating at frequency $n_r$ (rpm), simultaneously generate a directed airflow and cut the main mass of haulm (2) from the root crops. The created airflow propels the cut haulm along a trajectory toward the inlet opening (10) of the guide channel (9), through which it is transported to the outlet opening (11) and then to the flat screen (12), where the chopped haulm (13) is deposited on the field surface in the inter-row space of the unharvested root crops, in the zone where the dividing discs (7) are located.

The implementation of the improved method for the primary haulm collection is carried out as follows.

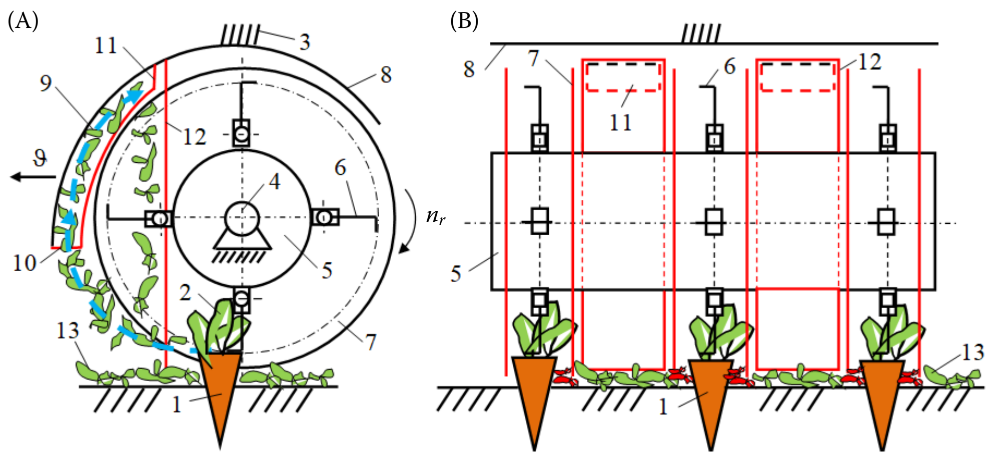


Figure 4. Design and technological scheme of the haulm removal module: (A) side view, (B) rear view
1 – root crop; 2 – haulm; 3 – frame; 4 – rotary haulm cutter; 5 – drum; 6 – blade; 7 – dividing disc; 8 – housing; 9 – guide channel; 10, 11 – inlet and outlet openings; 12 – flat screen; 13 – cut and chopped haulm deposited in the inter-row space of the unharvested root crops; $\vartheta$ – module speed; $n_r$ – rotor rotation frequency

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(A) (B)

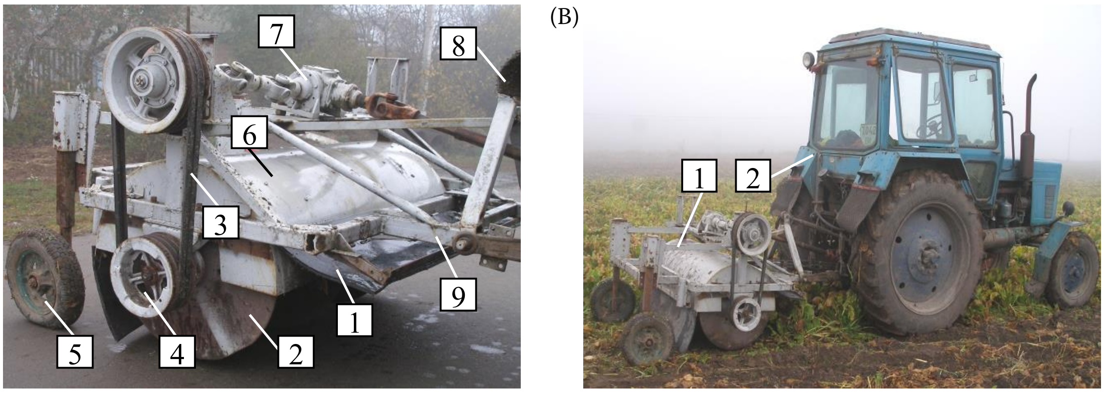


Figure 5. General view: (A) top-harvesting module (1 – frame; 2 – dividing disc; 3 – V-belt transmission; 4 – pulley; 5 – support wheel; 6 – casing; 7 – rotary top-harvesting drive; 8 – tractor hinged system; 9 – cutter), (B) unit (1 – header module; 2 – MTZ-80 tractor)

Experimental studies of the improved haulm removal module were conducted based on the implementation of the planned two-factor experiments (Kôno 1962) using three levels of variation for each input factor, with each experiment repeated three times (Table 1).

During the process of cutting the main haulm mass (2) (Figure 6) from the root crops (1) using the blades (5) of the rotary haulm cutter (4), and transferring the cut haulm (3) to the inlet of the guide channel, in addition to depositing the haulm (6) on the field surface in the inter-row space (7) of the unharvested root crops – specifically in zone (8) formed between two adjacent dividing discs – there may be cases of haulm loss (9). This lost haulm is deposited into the protective zone (10) of row (11) of the unharvested root crops, the width of which is denoted as $b_{pz}$ (m).

As a criterion for evaluating the amount of haulm deposited in the protective zone of the row of unharvested root crops – or as the optimisation parameter – the specific mass of the haulm $M_n$ (g·m$^{-2}$) was adopted. This parameter was determined under two conditions and at three different rotational speeds $n_r$ of the rotary haulm cutter: 400, 600, and 800 min$^{-1}$.

The comparison involved: the baseline design of the haulm removal module (Figure 4), and a modified version of the module with the guide channel (9), dividing discs (7), and flat screen (12) removed from the baseline structure.

The sequence of each subsequent experiment for determining the specific husk mass $M_n$ was established in accordance with the numbered order of the randomised design matrix of the two-factor experiment with three levels of factor variation.

The specific mass of the haulm $M_n$ was determined using the following procedure:

(*i*) During the biological maturity stage of sugar beet crops, test plots with haulm yields of 1.4, 1.6, and 1.8 kg·m$^{-2}$ were selected. The haulm yield was determined according to the standard methodology described in (Kainuma et al. 2014).

(*ii*) After a pass of the haulm removal unit or the cutting of the main haulm mass (2) (Figure 6), a control plot of length $L$ (m) was selected along row (11) of the unharvested root crops (1).

(*iii*) The width of row (11) of the unharvested root crops (1) (zone 10) was assumed to be 0.3 m. Accordingly, each side of the protective zone $b_{pz}$ surrounding the row had a half-width of 0.5 $b_{pz}$ = 0.15 m.

Table 1. Input factors and their levels of variation

| Name of the factor | Variation interval | Levels of variation by factors | | |
|---|---|---|---|---|
| | | lower (–1) | zero (0) | upper (+1) |
| Speed of movement of the module $\vartheta$ (km·h$^{-1}$) | 2 | 6 | 8 | 10 |
| Haulm yield $U$ (kg·m$^{-2}$) | 1 | 1 | 2 | 3 |

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(*iv*) From the surface of the defined area $S_{pz} = L \times b_{pz}$ ($m^2$), representing the protective zone of the row of unharvested root crops, the lost haulm was manually collected and weighed using Hölmer HSK-2216H electronic scales (Hölmer, Germany) with an accuracy of ±1.0 g.

(*v*) The specific mass of the haulm $M_{ni}$ for each *i*-th experimental replication was calculated using the formula:

$$M_{ni} = M_{pz}/S_{pz}$$

where: $M_{pz}$ – the mass of the haulm (g) collected from the measured area $S_{pz}$.

(*vi*) The obtained numerical values of the specific mass of the haulm $M_{ni}$ for each *i*-th (triplicate) repetition of the experiment were entered into the corresponding columns of the randomised design matrix of the planned two-factor experiment.

(*vii*) The calculated mean values of the specific husk mass $M_n$, or the resulting experimental data array, were entered into the results table of the experimental investigations.

The experimental data set of the specific haulm mass values $M_{ni}$ was processed using the Statistica 10 software package (StatSoft, 2010). The following steps were performed: selection of the form of the approximating empirical model based on the highest value of the numerical determination coefficient *R*-squared ($R^2$) at a significance level of 0.05 (Yin and Fan 2001; Karch 2020); calculation of the regression equation coefficients; verification of the model adequacy using Fisher's *F*-test (Sureiman and Mangera 2020); and evaluation of the significance of the regression coefficients using Student's *t*-test (Mishra et al. 2019). A graphical interpretation of the experimental results was also conducted.

## RESULTS AND DISCUSSION

Based on the results of the experiments conducted in accordance with the numbered order of the randomised design matrix, an experimental dataset of the specific mass of haulm $M_n$ was obtained. This haulm was deposited in the protective zone of the row of unharvested chicory root crops for two designs of the haulm-harvesting module (Table 2). The main technical parameters of the haulm-harvesting module were as follows: number of rows – 3; diameter of the pitch circle of the rotary haulm cutter – 0.4 m; rotor drum diameter – 0.2 m; number of knife sections symmetrically mounted on the drum – 4; number of knives per section – 3; diameter of the divider discs – 0.45 m.

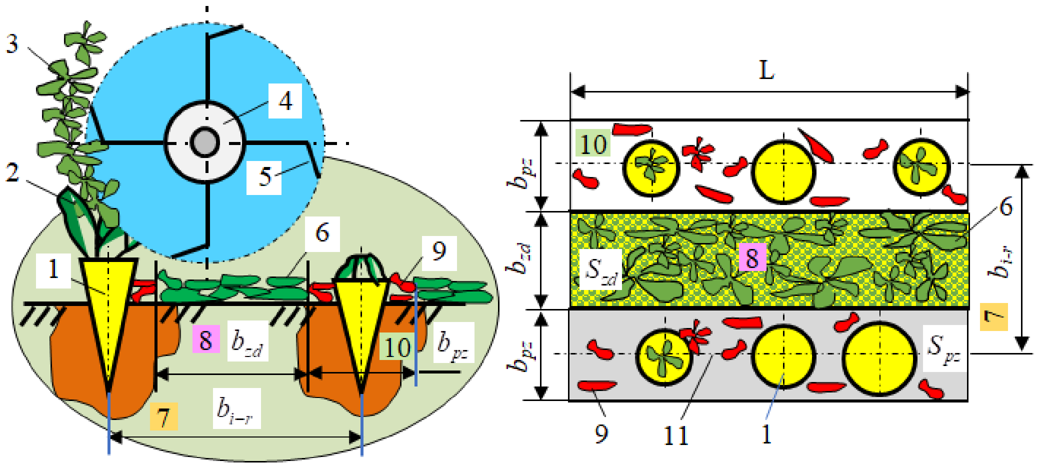


Figure 6. Diagram for calculating the specific mass of the haulm ($M_n$) deposited in the protective zone of a row of unharvested root crops

1 – root crop; 2 – main haulm mass; 3 – cut and chopped haulm; 4 – rotary haulm cutter; 5 – blade; 6 – haulm deposited in the zone between two dividing discs; 7 – inter-row space; 8 – zone between two dividing discs; 9 – haulm deposited in the protective zone of the row of unharvested root crops; 10 – protective zone of the row of unharvested root crops; 11 – row of the unharvested root crops; $b_{i-r}$ (m) – row spacing of the root crops; $b_{zd}$ (m) – width of the zone between two adjacent dividing discs; $b_{pz}$ (m) – width of the protective zone of the row of unharvested root crops

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Table 2. Results of the experimental studies

| No. | Value of the factor | | Value of the indicator (g·m$^{-2}$) | | | |
|---|---|---|---|---|---|---|
| | $\vartheta$ (km·h$^{-1}$) | $U$ (kg·m$^{-2}$) | $M_{400}$ | $M_{600}$ | $M_{800}$ | $M_{bd}$ |
| 5 | 8 | 2 | 53 | 49 | 45 | 576 |
| 7 | 6 | 3 | 71 | 66 | 61 | 875 |
| 3 | 10 | 1 | 33 | 30 | 26 | 286 |
| 1 | 6 | 1 | 24 | 21 | 15 | 275 |
| 8 | 8 | 3 | 75 | 72 | 67 | 881 |
| 6 | 10 | 2 | 58 | 55 | 52 | 583 |
| 2 | 8 | 1 | 28 | 24 | 20 | 281 |
| 9 | 10 | 3 | 82 | 78 | 72 | 889 |
| 4 | 6 | 2 | 49 | 45 | 40 | 569 |

$\vartheta$ – module speed; $U$ – haulm yield; $M_{400}$, $M_{600}$, $M_{800}$ – the specific mass of the haulm for the improved design of the haulm-harvesting module at rotary haulm cutter speeds of 400, 600, and 800 min$^{-1}$; $M_{bd}$ – the average specific mass of the haulm for the baseline design of the haulm-harvesting module at rotary haulm cutter speeds of 400, 600, and 800 min$^{-1}$

Based on the statistical processing of the experimental dataset of the specific haulm mass (Table 2) and the analysis of the obtained statistical indicators:

– It was established that the highest value of $R^2 = 0.996$, with a confidence level of $P = 1.000$, corresponds to the approximating mathematical model of a full second-degree polynomial, expressed as:

$$M_n = b_0 + b_1\vartheta + b_2U + b_{12}\vartheta U + b_{11}\vartheta^2 + b_{22}U^2 \quad (1)$$

where: $b_0$ – the intercept of the regression equation; $b_1$, $b_2$, $b_{12}$, $b_{11}$, $b_{22}$ – the regression coefficients for the respective factors and their interactions.

– The numerical values of the intercept $b_0$ and the regression coefficients for the respective factors and their interactions $b_1$, $b_2$, $b_{12}$, $b_{11}$, $b_{22}$ were determined (Table 3).

Based on the results of testing the significance of the calculated coefficients $b_1$, $b_2$, $b_{12}$, $b_{11}$, $b_{22}$ (Table 3) of the empirical model (1) using Student's $t$-test, it was established that the coefficient $b_{12} = 3.33\ 10^{-15}$, which characterises the interaction effect of factors $\vartheta$ and $U$ on the variation of the specific haulm mass indicator $M_{800}$, is statistically insignificant or negligible.

After confirming the adequacy of the empirical model (1) using Fisher's $F$-test, mathematical models in natural factors were obtained, describing the functional dependence of the specific haulm mass $M_{ni}$ on the forward speed of the improved design of the haulm-harvesting module $\vartheta$ and the haulm yield $U$ at rotary haulm cutter speeds of 400, 600, and 800 min$^{-1}$ respectively:

$$M_{400} = -1.56 - 1.42\vartheta + 26.5U + 0.25\vartheta U + 0.21\vartheta^2 - 1.17U^2 \quad (2)$$

$$M_{600} = -3.86 - 1.5\vartheta + 25.17U + 0.38\vartheta U + 0.21\vartheta^2 - 1.17U^2 \quad (3)$$

$$M_{800} = -26.89 + 1.52\vartheta + 31.83U + 0.08\vartheta^2 - 2.17U^2 \quad (4)$$

Table 3. Natural values of the regression equation coefficients

| Functional dependence | Natural values of the coefficients | | | | | |
|---|---|---|---|---|---|---|
| | $b_0$ | $b_1$ | $b_2$ | $b_{12}$ | $b_{11}$ | $b_{22}$ |
| $M_{400} = f(\vartheta; U)$ | –1.56 | –1.42 | 26.5 | 0.25 | 0.21 | –1.17 |
| $M_{600} = f(\vartheta; U)$ | –3.89 | –1.5 | 25.17 | 0.38 | 0.21 | –1.17 |
| $M_{800} = f(\vartheta; U)$ | –26.89 | 1.5 | 31.83 | 3.33 $10^{-15}$ | 0.08 | –2.17 |

$M_{400}$, $M_{600}$, $M_{800}$ – the specific mass of the haulm for the improved design of the haulm-harvesting module at rotary haulm cutter speeds of 400, 600, and 800 min$^{-1}$

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Based on the analysis of the response surfaces (Figure 7), it was established that, with the forward speed of the improved haulm-harvesting module ranging from 6 to 10 km·h$^{-1}$ and the haulm yield of chicory root crops ranging from 1 to 3 kg·m$^{-2}$, the approximated values of the specific haulm mass $M_{ni}$, deposited in the protective zone of the row of unharvested root crops, fall within the following range with an accuracy level of ± 1 g:

– at a rotary haulm cutter speed of 400 min$^{-1}$ – from 25 to 82 g·m$^{-2}$ (Figure 7A);
– at a rotary haulm cutter speed of 600 min$^{-1}$ – from 20 to 77 g·m$^{-2}$ (Figure 7B);
– at a rotary haulm cutter speed of 800 min$^{-1}$ – from 15 to 72 g·m$^{-2}$ (Figure 7C).

The functional influence of each factor on the specific haulm mass $M_{ni}$, deposited in the protective zone of the row of unharvested root crops, exhibits a dual nature.

According to Figure 7D:

– The dominant factor that significantly affects the variation in the specific haulm mass $M_{ni}$ is the haulm yield $U$. As $U$ increases from 1 to 3 kg·m$^{-2}$, the specific haulm mass $M_{ni}$ increases on average by 2.7 to 4.2 times.
– As the forward speed of the haulm-harvesting module increases from 6 to 10 km·h$^{-1}$, the specific haulm mass $M_{ni}$ increases on average by 1.5 to 1.7 times. This is due to increased losses of the cut haulm, which result from the higher instantaneous feed rate of the cut haulm to the inlet of the guide channel.
– As the rotary cutter speed $n_r$ increases from 400 to 800 min$^{-1}$, the specific haulm mass $M_{ni}$

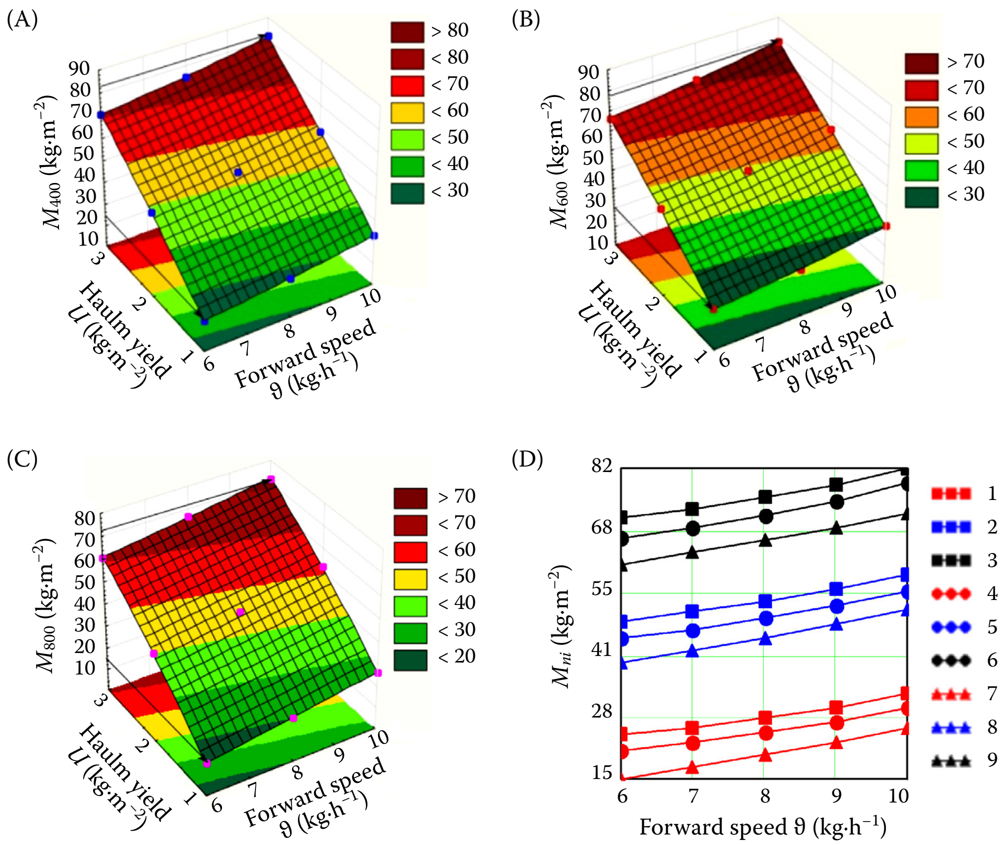


Figure 7. Graphical interpretation of the research results: (A), (B), (C) response surface of the variation in the specific haulm mass $M_{ni}$ as a function of $M_{400} = f(\vartheta; U)$, $M_{600} = f(\vartheta; U)$, $M_{800} = f(\vartheta; U)$ respectively, (D) variation in the specific haulm mass $M_{ni}$ as a function of: 1, 2, 3 – $M_{400} = f(\vartheta)$; 4, 5, 6 – $M_{600} = f(\vartheta)$; 7, 8, 9 – $M_{800} = f(\vartheta)$; 1, 4, 7 – $U$ = 1 kg·m$^{-2}$; 2, 5, 8 – $U$ = 2 kg·m$^{-2}$; 3, 6, 9 – $U$ = 3 kg·m$^{-2}$

$M_{400}$, $M_{600}$, $M_{800}$ – the specific mass of the haulm for the improved design of the haulm-harvesting module at rotary haulm cutter speeds of 400, 600, and 800 min$^{-1}$

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Table 4. Results of the statistical calculations

| Indicator | Mean | Variance | SD | $CV$ (%) |
|---|---|---|---|---|
| $M_{400}$ | 52.56 | 447.16 | 21.15 | 40.2 |
| $M_{600}$ | 48.89 | 396.78 | 19.92 | 40.7 |
| $M_{800}$ | 44.22 | 401.83 | 20.05 | 45.3 |
| $M_{bd}$ | 579.44 | 44 721.0 | 211.52 | 36.5 |

$M_{400}$, $M_{600}$, $M_{800}$ – the specific mass of the haulm for the improved design of the haulm-harvesting module at rotary haulm cutter speeds of 400, 600, and 800 min$^{-1}$; $M_{bd}$ – the average specific mass of the haulm for the baseline design of the haulm-harvesting module at rotary haulm cutter speeds of 400, 600, and 800 min$^{-1}$; SD – standard deviation; $CV$ – coefficient of variation

decreases on average by 1.2 to 1.7 times. This is due to the reduced losses of the cut haulm resulting from an increase in the velocity of the haulm movement along its trajectory to the inlet of the guide channel, caused by the increased dynamic force of the airflow generated by the higher rotational speed of the rotary cutter knives.

The results of calculating the statistical indicators of the obtained experimental data set of the specific gravity of the Mpi tip (Table 2) are given in Table 4.

Table 5. Values of the correlation coefficients

| Factor | Indicator | | | |
|---|---|---|---|---|
| | $M_{400}$ | $M_{600}$ | $M_{800}$ | $M_{bd}$ |
| $F1(\vartheta)$ | 0.20 | 0.23 | 0.25 | 0.03 |
| $F2(U)$ | 0.98 | 0.99 | 1.00 | 0.97 |

$M_{400}$, $M_{600}$, $M_{800}$ –the specific mass of the haulm for the improved design of the haulm-harvesting module at rotary haulm cutter speeds of 400, 600, and 800 min$^{-1}$; $M_{bd}$ – the average specific mass of the haulm for the baseline design of the haulm-harvesting module at rotary haulm cutter speeds of 400, 600, and 800 min$^{-1}$; factor $\vartheta$ (mean value $F1$ = 8, standard deviation $F1$ = 1.732) has only a weak direct influence and does not affect the indicators $M_{400}$, $M_{600}$, $M_{800}$ and almost does not correlate with $M_{bd}$; factor $U$ (mean value $F2$ = 2, standard deviation $F2$ = 0.866) is a key factor that almost completely determines the variations of $M_{400}$, $M_{600}$, $M_{800}$ and $M_{bd}$

The obtained correlation coefficients, which show the influence of the factor on the indicators of the specific gravity of the tip, were determined by Pearson's equation, Table 5.

The significance of the coefficients of the regression Equations (2)–(4) was assessed using Student's $t$-test (Table 6).

The critical value of the $t$-statistic is $t_{cr}(f = 3; \alpha = 0.05) = 3.185$.

Verification of the statistical significance of the regression coefficients using Student's $t$-test showed that, for all the optimisation parameters $M_{400}$, $M_{600}$ and $M_{800}$, the linear terms $b_1$ and $b_2$ have a statistically significant effect. These terms correspond to the factors of the forward speed of the unit $\vartheta$ and the haulm yield $U$, respectively.

Most of the quadratic and interaction terms are statistically marginally significant.

The overall adequacy of the models (2)–(4) was assessed using Fisher's $F$-test. The critical value of the $F$-statistic is $F_{\mathrm{cr}}(f_1 = 5; f_2 = 3; \alpha = 0.05) = 9$.

The obtained values were: $F_{400r} = 274.12 \gg F_{cr}$; $F_{600r} = 274.47 \gg F_{cr}$; $F_{800r} = 184.81 \gg F_{cr}$. Thus, the adequacy check of the models (2)–(4) confirmed their consistency with the experimental data at a significance level of α = 0.05.

Table 6. Results of the assessment of the significance of the coefficients of the regression equations

| Coefficient | Actual values of the correlation coefficient $t_r$ | | | Conclusion |
|---|---|---|---|---|
| | $M_{400}$ | $M_{600}$ | $M_{800}$ | |
| $b_0$ | 139.07 | 122.98 | 100.18 | significant |
| $b_1$ | 23.25 | 23.62 | 22.81 | significant |
| $b_2$ | 114.66 | 107.44 | 93.24 | significant |
| $b_{12}$ | 3.34 | 3.80 | 3.31 | extremely significant |
| $b_{11}$ | 3.68 | 3.86 | 3.47 | extremely significant |
| $b_{22}$ | 3.24 | 3.36 | 5.03 | extremely significant |

$M_{400}$, $M_{600}$, $M_{800}$ – the specific mass of the haulm for the improved design of the haulm-harvesting module at rotary haulm cutter speeds of 400, 600, and 800 min$^{-1}$

https://doi.org/10.17221/172/2025-RAE

The technological effectiveness and feasibility of applying the new method for cutting the main haulm mass of sugar beet root crops, as well as the improved design of the haulm-harvesting module, were confirmed through the graphical interpretation of the results obtained from the field experimental studies (Figure 8).

The use of the improved design of the haulm-cutting module makes it possible to reduce the specific mass of the cut and deposited haulm in the protective zone of the row of unharvested root crops by 9 to 11 times compared with the baseline design (Figure 8), which represents a promising direction for further scientific research into the process of root crop harvesting.

The presented results of the experimental studies on the specific mass of the cut and deposited haulm in the protective zone of the row of unharvested root crops are new and original in the context that, for the first time, a new technological process for cutting the main haulm mass and a new working body of the haulm-cutting module have been investigated, with the research results being reported for the first time. No similar research findings by other scholars, which would confirm studies of the specific mass of the cut and deposited haulm in the protective zone of the row of unharvested root crops, have been identified; therefore, the obtained results cannot be compared with any existing data.

In this context, it is considered appropriate to analyse the obtained results of the specific mass of haulm $M_{400}$, $M_{600}$, and $M_{800}$, which is placed in the protective zone of the row of unharvested root crops, in comparison with the results of experimental studies of an adequate design of a haulm-collecting module presented by Berezhenko et al. (2021). The authors established that within the range of variation of the module travel speed from 1.2 to 1.6 m·s$^{-1}$ and the variation of chicory root-crop haulm yield from 1.5 to 2.2 kg·m$^{-2}$, the specific feed rate of haulm cut by the knives of a rotary haulm cutter at a rotor rotational speed of 600 min$^{-1}$ and placed between two adjacent dividing discs falls within the following ranges: at a planting density of chicory root crops of 11.0 thousand plants·m$^{-2}$ – from 24.3 to 32.6 kg·m$^{-2}$; at a planting density of 9.0 thousand plants·m$^{-2}$ – from 18.5 to 26.7 kg·m$^{-2}$; at a planting density of 7.0 thousand plants·m$^{-2}$ – from 11.8 to 16.7 kg·m$^{-2}$; at a planting density of 5.0 thousand plants·m$^{-2}$ – from 8.7 to 12.7 kg·m$^{-2}$.

Based on this, it can be stated that the proportion of the values of the specific mass of haulm $M_{600}$ (from 20 to 77 g·m$^{-2}$) placed in the protective zone of the row of unharvested root crops,

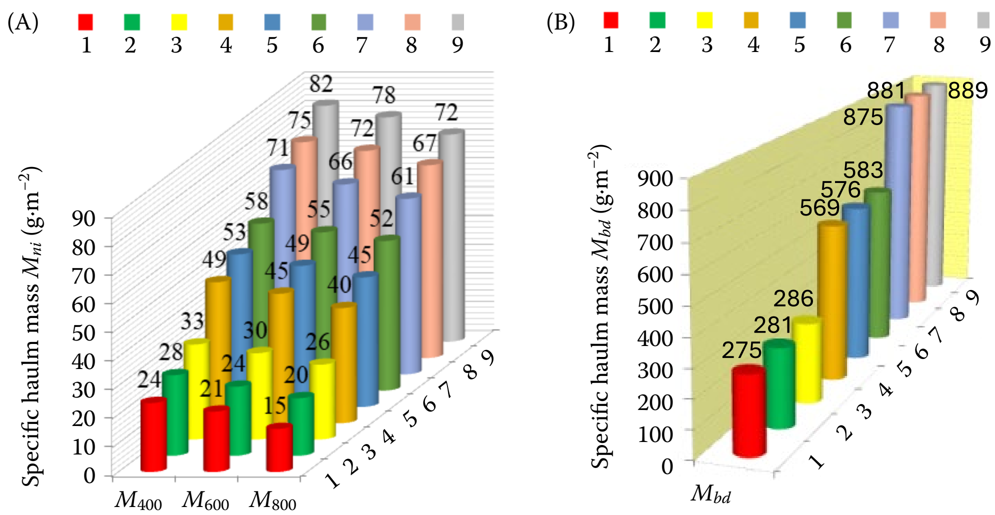


Figure 8. Graphical interpretation of the results of experimental studies on haulm-cutting modules: (A), (B) diagram of the values of the specific mass of the cut and deposited haulm in the protective zone of the row of unharvested root crops by the working bodies of the improved and baseline designs of the haulm-cutting module, respectively

1, 2, 3, 4, 5, 6, 7, 8, 9 – numerical values representing the combinations of factor levels $\vartheta$ and $U$ according to the sequential number (No) of the experiments conducted (Table 2); $M_{400}$, $M_{600}$, $M_{800}$ – the specific mass of the haulm for the improved design of the haulm-harvesting module at rotary haulm cutter speeds of 400, 600, and 800 min$^{-1}$

https://doi.org/10.17221/172/2025-RAE

in comparison with the specific mass of haulm placed in the inter-row space of unharvested root crops in the zone between two adjacent dividing discs, is extremely small and amounts on average to approximately 0.001% ... 0.0002%. Considering the obtained results and their technological efficiency, further investigation into the technological process of operation of the improved haulm-collecting module as part of a root-harvesting machine is highly rational and necessary.

The obtained results are generally consistent with the trends reported in previous studies on the technological process of sugar beet haulm cutting. In particular, theoretical investigations of the interaction between the rotary cutting blades and the bundle of leaves have shown that the efficiency of haulm removal and the magnitude of the plant mass losses are strongly influenced by the rotational speed of the cutting rotor and the feed rate of the plant material into the cutting zone (Bulgakov et al. 2017). These findings correspond well with the present results, where an increase in the rotational speed of the rotary cutter from 400 to 800 rpm leads to a decrease in the specific mass of haulm deposited in the protective zone due to the improved dynamic removal of the cut plant material.

Similar conclusions regarding the influence of the operating parameters of topping machines were obtained in experimental studies on sugar beet toppers, where the efficiency of the haulm removal increased with the increase in the rotational speed of the cutting mechanism and the optimisation of the cutting height (Salman 2013). In those studies, the topping efficiency reached up to 88% at optimal combinations of the power take-off (PTO) speed and forward travel speed, confirming that the technological parameters of the cutting device significantly affect the amount of residual plant material after topping.

Furthermore, investigations into the technological process of haulm cutting without wrapping around the root heads indicate that the improper adjustment of cutting parameters may lead to increased losses of sugar-bearing plant material and reduced harvesting efficiency (Ihnatiev 2016). This observation also supports the tendencies identified in the present study, where the increase in the forward speed of the haulm-harvesting module from 6 to 10 $km \cdot h^{-1}$ resulted in a noticeable increase in the specific mass of the haulm deposited in the protective zone due to the higher instantaneous feed of the plant material.

In addition, theoretical studies of the motion of cut sugar beet tops particles in conveying systems demonstrate that the trajectory and velocity of the plant particles are significantly influenced by the airflow generated by the rotating elements of the cutting device (Pascuzzi et al. 2024). This confirms the explanation proposed in the present research that the reduction in the haulm deposition in the protective zone at higher rotor speeds is associated with the increased air-flow velocity and improved transportation of the cut plant mass toward the guide channel.

Therefore, the results obtained in this study are in good agreement with previously published theoretical and experimental investigations concerning the technological parameters of sugar beet topping machines. At the same time, the present work expands the existing body of knowledge by providing quantitative estimates of the specific haulm mass deposited in the protective zone of the row of unharvested root crops when using an improved haulm-harvesting module.

## CONCLUSION

(*i*) The technological efficiency of the harvesting process for large root crops is improved by reducing the energy consumption during the operations of removing the main bulk of haulm through the enhancement and optimisation of the parameters of the haulm-harvesting module of root crop harvesting machines.

(*ii*) Empirical models have been developed that describe the functional variation in the specific mass of the haulm cut from the root crop heads, ranging from 15 to 82 $g \cdot m^{-2}$, which is deposited within the protective zone of the row of unharvested root crops, depending on the haulm yield variation from 1 to 3 $kg \cdot m^{-2}$ and the operating speed of the haulm-harvesting module from 6 to 10 $km \cdot h^{-1}$.

(*iii*) The results of the correlation analysis, which characterises the relationship between the influence of factors $\vartheta$ and $U$ on the specific mass of the tip enclosed in the protective zone of a row of unexcavated chicory roots, are adequate or correspond to the results of the regression analysis, which are displayed by graphical interpretation, Figure 7.

https://doi.org/10.17221/172/2025-RAE

(*iv*) The obtained experimental results represent:
- Initial baseline conditions for further research on the process of large root crop excavation in the context of analysing the influence of the specific mass of the haulm cut and placed within the protective zone of the unharvested row on the technological stability of the process and on the quality index of excavation, i.e., the amount of plant impurities in the harvested heap;
- A further step in improving the methodology and techniques for optimising the rational parameters of the working elements of root crop harvesting machines.

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Received: October 7, 2025
Accepted: May 11, 2026
Published online: August 20, 2026