ANALYTICAL DETERMINATION OF THE MASS OF FOLIAGE RESIDUES REMAINING ON CARROT ROOT CROWNS AFTER CLEANING WITH FLEXIBLE BLADES

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АНАЛІТИЧНЕ ВИЗНАЧЕННЯ МАСИ ЗАЛИШКІВ ГИЧКИ, ЩО ЗАЛИШАЄТЬСЯ НА ГОЛОВКАХ КОРЕНЕПЛОДІВ МОРКВИ ПІСЛЯ ОЧИЩЕННЯ ГНУЧКИМИ ЛОПАТЯМИ

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ABSTRACT

This study developed an analytical procedure for estimating the mass of carrot foliage residues remaining on the crowns of carrot root crops after cleaning with flexible blades. The proposed model relates the mass removed during a single blade contact to the residence time of the root crown within the cleaning zone, the average effective number of blade contacts, and the number of plants per metre of row. The calculations were performed using representative parameters of carrot root crown geometry, residue height, residue layer density, blade width, blade radius, post-impact contact duration, and plant spacing. A response surface was generated for practical ranges of cleaner forward speed and blade rotational frequency and subsequently approximated using a second-order regression model. The results showed that the mass of remaining residues decreases nonlinearly with increasing blade rotational frequency and increases with higher forward speed because the residence time within the cleaning zone becomes shorter. The most intensive cleaning was achieved by combining lower forward speed with increased blade rotational frequency; therefore, increasing the rotational frequency is advisable only together with an appropriate limitation of forward speed. The developed model provides a practical basis for selecting the operating parameters of a flexible-blade cleaner and explains why flexible blades can compensate more effectively for reduced contact time than technologies based solely on passive or single-contact residue removal.

АНОТАЦІЯ

У роботі представлена нова аналітична процедура для оцінювання маси залишків гички моркви, що залишається на головках коренеплодів після очищення гнучкими лопатями. Модель пов'язує масу, видалену за один контакт лопаті, з часом перебування головки коренеплоду в зоні очищення, середньою ефективною кількістю контактів лопатей та кількістю рослин на одному метрі рядка посівів моркви. Розрахунок виконано для характерних параметрів геометрії головки коренеплоду моркви, висоти залишків гички, густини ущільненого шару залишків, ширини і радіуса очисної лопаті, тривалості післяударної дії та міжрослинної відстані. Для практичних діапазонів поступальної швидкості очисника і частоти обертання лопатей побудовано поверхню відгуку та апроксимовано її квадратичною регресійною моделлю. Результати показали, що маса залишків зменшується нелінійно зі зростанням частоти обертання лопатей і збільшується за підвищення поступальної швидкості, оскільки час взаємодії у зоні очищення скорочується. Найінтенсивніше очищення досягається за поєднання меншої поступальної швидкості з підвищеною частотою обертання; тому збільшення частоти доцільне лише разом з обґрунтованим обмеженням швидкості руху. Модель формує практичне правило вибору режимів роботи гнучколопатевого очисника та пояснює, чому гнучкі лопаті здатні краще компенсувати скорочення часу контакту, ніж технології, основані лише на пасивному або одноразовому видаленні залишків.

INTRODUCTION

Mechanized harvesting of carrots must combine lifting, conveying, removal of foliage residues and preservation of the crown and shoulder tissues of the root crop. This requirement is important because carrot harvesting is still strongly influenced by labour demand, crop morphology, soil state and the coordination of active working-unit speeds (*Gaadhe and Tiwari, 2022; Gaadhe et al., 2023; Wang et al., 2025a; Wang et al., 2025b; Zeeshan and Malik, 2025*).

Several carrot harvesting and post-harvesting working units have been developed and tested. Prototype harvesters and tractor operated diggers have shown that travel speed, digging quality, clamping reliability and the motion speed of active units affect losses, contamination and root damage (*El-Gany et al., 2008; Ikram et al., 2018; Kowalczuk et al., 2003; Kumar et al., 2017; Leszczycski, 2011; Naresh et al., 2018; Oda et al., 2018; Shirwal and Mani, 2014; Shirwal et al., 2015*). Recent studies have also moved toward response surface evaluation of carrot combine components and intelligent optimization of harvester parameters (*Wang et al., 2025a; Wang et al., 2025b; Zeeshan and Malik, 2025*).

Flexible blades are mechanically preferable for the final cleaning of carrot root crowns because the upper part of the carrot does not represent a flat cylindrical surface; rather, it exhibits a conical or rounded shoulder shape, variable neck diameter, irregularly distributed leaf bases, and locally attached residues. Flexible blades can adapt to this geometry, distribute the contact pressure more uniformly, and combine short-term impact action with subsequent scraping along the curved crown surface. In contrast, rigid brushes mainly operate through continuous frictional contact and may either fail to remove residues from recessed areas or require excessive normal force. Pneumatic cleaning, although non-contact in nature, is strongly influenced by residue adhesion, plant moisture content, and the presence of soil particles, while also requiring a considerable air-flow capacity.

The existing mathematical descriptions of carrot harvesting units are mainly empirical or semi-empirical. They commonly use input parameters such as forward speed, digging depth, blade or cutter angle, clamping speed, conveying speed, cutter speed, plant catch height, crop and soil physical properties (*Gaadhe et al., 2023; Wang et al., 2025a; Wang et al., 2025b; Xia et al., 2024; Zeeshan and Malik, 2025*). Such models are useful for optimizing a specific machine unit, but they are often limited by nonlinear interactions between speed factors, variable soil-crop conditions and the absence of a direct transition from a local contact event to a row scale estimate of remaining residues.

Adequate analytical modelling also requires crop specific physical and mechanical parameters. The geometry, density, strength and deformation behaviour of carrot roots and leaf bases affect both residue detachment and root damage (*Jahanbakhshi et al., 2018; Nath et al., 2019; Xia et al., 2024*). In addition, the within-row plant spacing determines the transition from residue mass on one crown to residue mass per meter of row; therefore, agronomic information on carrot plant density and spacing is directly relevant for engineering calculations (*McCollum et al., 1986; Nucez et al., 2008; Tegen and Jembere, 2021*).

A previous theoretical study of the flexible blade cleaner described the single-contact interaction between a blade and a carrot root crown and obtained the mass of foliage residues removed during one impact and post impact action (*Bulgakov et al., 2024*). That model used classical dynamics and harvesting-machine theory as the mechanical basis (*Meriam et al., 2020; Pogorelyi and Tatianko, 2004; Rykhlivskyi, 2021*). However, the single contact result alone is not sufficient for selecting machine operating modes because one root crown can interact with several blades during its residence time in the cleaning zone.

For the analytical study, a tractor-mounted cleaner intended for removing foliage residues from carrot root crowns was considered. The experimental machine was mounted on a wheeled tractor of traction class 1.4 and enabled the cleaning of a single prepared carrot row in which the main mass of the foliage had been removed previously, while residual foliage remained attached to the crowns. During operation, the machine moved along the crop row at a constant forward speed.

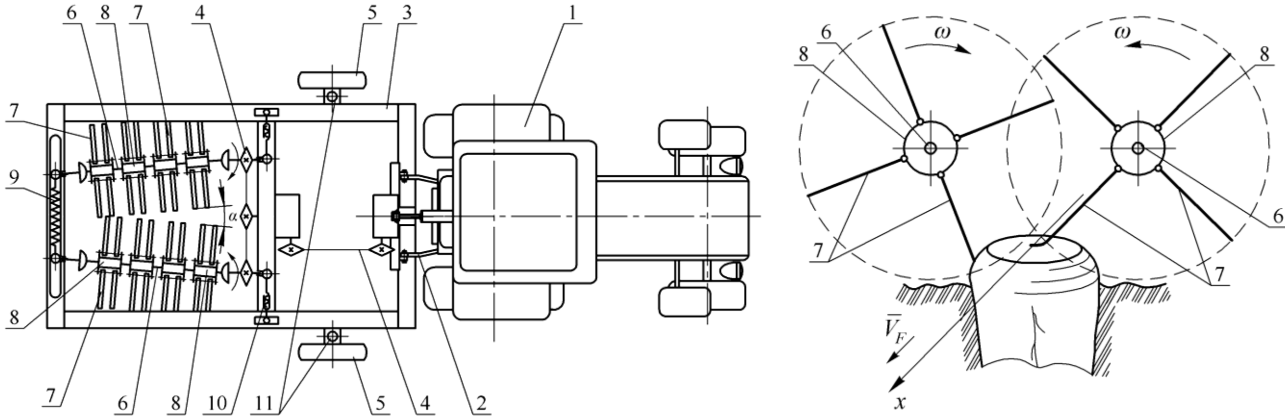
The existing research gap addressed in this paper is the lack of an analytical row scale relationship that converts the mass of residues removed in one flexible blade contact into the mass of residues remaining per meter of row while simultaneously accounting for cleaner forward speed and blade rotational frequency. The aim of the study was to obtain this relationship, to construct and approximate the response surface, and to interpret the obtained surface in terms of practical operating mode selection for a flexible blade root crown cleaner.

MATERIALS AND METHODS

The considered experimental setup (Fig. 1a) consisted of a main frame *3* mounted on tractor *1* by means of hitch *2*. Horizontal drive shafts *6* carrying the cleaning blades *7* were mounted on the main frame *3*. In field operation, the setup operated in floating mode, and the height setting of the cleaning blades *7*, i.e., the position of the flexible blade tips, was adjusted by means of gauge wheels *5*. The position of the gauge wheels relative to the frame could be changed by screw mechanisms *11*. The inlet spacing between the cleaning shafts was adjusted by mechanisms *10*, whereas the outlet centre-to-centre distance was adjusted by mechanism *9* (*Olt et al., 2024*).

The drive shafts of the cleaning unit were set into rotation by a universal-joint transmission from the tractor power take-off (PTO) through the drive elements *4*. The horizontal drive shafts *6*, fitted with flanges *8* carrying the cleaning blades *7*, were then driven by a chain transmission. During operation, the tractor-mounted cleaner moved along the crop row in the direction of the *x*-axis (Fig. 1b) at a constant forward speed V_F and performed the cleaning process.

The analysis was based on the previously obtained single-contact relationship for the mass of foliage residues removed by a flexible cleaning blade during impact and post-impact contact with the carrot root crown (*Bulgakov et al., 2019; Bulgakov et al., 2024*). In the present paper this relationship is summarized explicitly: the removed mass was assumed to be proportional to the effective density of the flattened residue layer, the radius of the blade contact point, the blade width, the duration of post-impact action, the thickness of the flattened layer and the blade rotational frequency. Consequently, the blade rotational frequency influences the model through two mechanisms: it increases both the mass removed during a single blade contact and the average number of blade contacts occurring during the residence time of a root crown within the cleaning zone.



a) b)

Fig. 1 – Schematic diagram of the experimental unit (a) and diagram of the interaction between the cleaning shafts and a carrot root crown (b):

1 – tractor; 2 – hitch; 3 – main frame; 4 – drive elements; 5 – gauge wheels; 6 – drive shafts; 7 – blades; 8 – flanges; 9, 10 – mechanisms for adjusting the position of the cleaning shafts; 11 – screw adjustment mechanism.

A four-blade rotor configuration was considered because the prototype cleaner shown in Fig. 1 is equipped with four flexible blades mounted on each cleaning shaft. The transition from the local mass removed during a single blade contact to the remaining residue mass per metre of row was performed by estimating the initial mass of foliage residues on a single root crown, the residence time of the crown within the cleaning zone, the average effective number of blade contacts per crown, and the number of plants per metre of row.

The adopted numerical values of the parameters for the studied crop, foliage residues, and working unit are given in Table 1. The effective density of flattened layer of foliage residues was taken as c_h = 850 kg·m^{-3}, which is lower than the density of fresh carrot tissue, reported by *Jahanbakhshi et al. (2018)* as about 1040 kg·m^{-3}, because the bundle of residues contains inter-stem voids. The thickness of the flattened layer was taken as h = 0.004 m, which depends on the height of the foliage residues h_r, the bundle diameter, and the area of the carrot root crown.

The mass of foliage residues removed by one blade in one contact was determined from the equation

$$M_{cr} = 2\pi \cdot \rho_h \cdot \rho_k \cdot b \cdot t_a \cdot h \cdot n_f \quad (1)$$

where ρ_h is the effective density of the flattened layer of foliage residues; ρ_k is the radius at the impact contact point; b is the cleaning blade width; t_a is the duration of the post-impact action; h is the thickness of the flattened layer; n_f is the blade rotational frequency.

The initial mass of foliage residues on one root crown was represented as a compacted cylinder with diameter d_c and height h_r:

$$M_0 = \rho_h \cdot \pi \cdot d_c^2 \cdot h_r \ \ M_0 = \rho_h \cdot \pi \cdot d_c^2 \cdot h_r / 4 \quad (2)$$

where M_0 is the initial mass of foliage residues on a single root crown; d_c is the diameter of the root crown neck; h_r is the height of foliage residues after cutting.

Table 1

Adopted model parameters and factor variation ranges

Parameter	Symbol	Value	Source
Diameter of carrot root crown neck	d_c	0.0372 m	*Nath et al., 2019*
Height of foliage residues after cutting	h_r	0.015 m	*Nath et al., 2019*
Effective density of the flattened layer	ρ_h	850 kg·m^{-3}	*Jahanbakhshi et al., 2018*
Blade radius at the impact contact point	ρ_k	0.10 m	Adopted from the prototype geometry shown in Fig. 1
Cleaning blade width	b	0.04 m	
Duration of post-impact action	t_a	0.008 s	*Pogorelyi and Tatianko, 2004*
Thickness of the flattened layer	h	0.004 m	Adopted in this study from the average flattened residue-layer geometry
Plant spacing in the row	s_p	0.04 m	*McCollum et al., 1986; Nuñez et al., 2008; Tegen and Jembere, 2021*
Number of root crops per 1 m of row	N_p	25 m^{-1}	*Calculated from s_p*
Cleaner forward speed	V_F	0.5-3.0 m·s^{-1}	Selected operating range of the prototype cleaner
Blade rotational frequency	n_f	1.6-8.0 s^{-1}	

The residence time t_z of one root crown in the cleaner action zone was estimated as:

$$t_z = d_c / V_F \tag{3}$$

where t_z is the residence time of one root crown in the cleaning zone; V_F is the cleaner forward speed.

The average effective number of contacts of the four-blade rotor with one root crown was determined by:

$$z_e = 4 \cdot n_f \cdot t_z = 4 \cdot n_f \cdot d_c / V_F \tag{4}$$

In expression (4), it was taken into account that in one revolution a rotor with four blades can potentially create four actions in the zone where one root crown is located.

Then the mass of foliage residues remaining on one root crown after the passage of the cleaner is:

$$M_{rem1} = M_0 - z_e \cdot M_{cr}\,. \tag{5}$$

If the calculated value of M_{rem1} becomes negative, it is physically limited by zero. This situation did not occur within the studied factor range. For 1 m of row length, the following expression is obtained:

$$M_{rem} = N_p \cdot \left(M_0 - z_e \cdot M_{cr}\right), \tag{6}$$

where N_p is the number of root crops per 1 m of row. At the adopted plant spacing s_p = 0.04 m, $N_p = 1/s_p$ = 25m^{-1}.

Substituting the numerical values of the parameters from Table 1 gives numerical analytical equation

$$M_{rem} = 0.3465 - 0.002543 \cdot n_f^2 / V_F \tag{7}$$

Equation (7) is the exact numerical form of the theoretical model for the parameters of Table 1 and was used to construct the response surface $M_{rem} = f\left(V_F, n_f\right)$

To construct the response surface, a 41 x 41 theoretically calculated matrix of values was used within V_F = 0.5-3.0 m·s^{-1} and n_f = 1.6-8.0 s^{-1}. The resulting surface was then approximated by a second-order quadratic regression equation in natural variables using the least-squares method.

All analytical calculations, generation of the 41 x 41 theoretical matrix, least squares approximation and preparation of the response surface and contour plots were carried out in MathCAD. Spreadsheet control calculations of selected points were performed in Microsoft Excel 365 to verify numerical consistency.

RESULTS

For the parameters of Table 1, the initial mass of foliage residues on one root crown, calculated from equation (2), is M_0 = 0.01386 kg, while the initial mass of residues per 1 m of row is 0.3464 kg. The base frequency n_f = 4.8 s^{-1} corresponds to the midpoint of the adopted rotor-speed interval and was therefore used as a representative operating point. For the base point V_F = 1.5 m·s^{-1} and n_f = 4.8 s^{-1}, the value M_{rem} =

0.308kg·m^{-1} was obtained; that is, after the passage of the cleaner, about 88.8% of the initial mass of foliage residues remains in the row on average.

The regression equation fitted to the theoretically calculated response surface has the form:

$$M_{rem} = 0.3315 + 0.0564 \cdot V_F - 0.0214 \cdot n_f + 0.0122 \cdot V_F \cdot n_f - 0.0232 \cdot V_F^2 - 0.00185 \cdot n_f^2, \quad R^2 = 0.950. \tag{8}$$

Equation (7) shows that M_{rem} decreases nonlinearly as blade rotational frequency increases and, at the same time, increases as cleaner forward speed increases. This shape of the response surface is due to the fact that n_f affects two factors of the model simultaneously: first, as n_f increases, the mass M_{cr} removed in one contact increases; second, the average effective number of contacts z_e during the residence time of the root crown in the cleaning zone also increases. In contrast, an increase in V_F reduces the time t_z and, accordingly, the number of blade actions on one root crown.

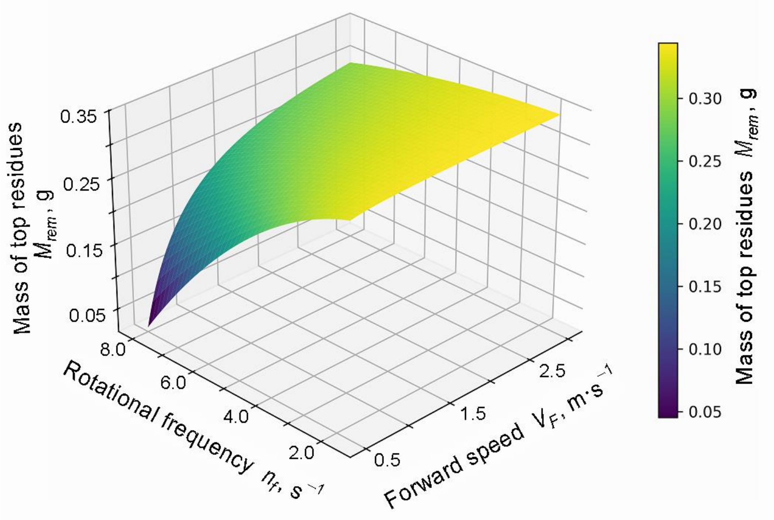


Fig. 2 – Response surface showing the effect of cleaner forward speed and blade rotational frequency on the mass of carrot crown residues remaining per meter of row

According to Fig. 2, within the studied factor range the mass of foliage residues per 1 m of row changes from 0.021 to 0.344 kg·m^{-1}. The maximum values are observed at the combination of high forward speed and low blade rotational frequency (V_F = 3.0 m·s^{-1}, n_f = 1.6 s^{-1}), whereas the minimum values occur at low forward speed and the maximum blade rotational frequency (V_F = 0.5 m·s^{-1}, n_f = 8.0 s^{-1}). At a constant V_F = 0.5m·s^{-1}, increasing n_f from 1.6 to 8.0 s^{-1} reduces M_{rem} from 0.333 to 0.021 kg·m^{-1}, i.e. by almost 94%. At V_F = 3.0 m·s^{-1}, the same increase in frequency reduces M_{rem} only from 0.344 to 0.292 kg·m^{-1}, i.e. by approximately 15%. Therefore, increasing the rotational frequency is most effective in the zone of lower cleaner forward speeds.

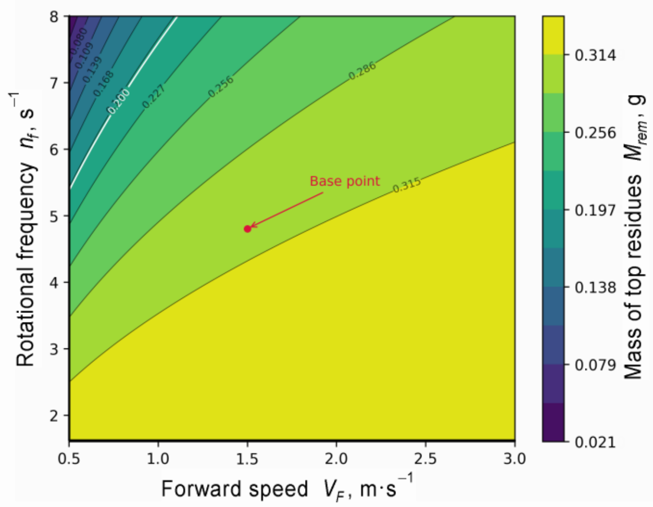


Fig. 3 – Contour map for selecting cleaner operating modes according to the remaining mass of carrot foliage residues per meter of row; the highlighted isoline indicates the practical threshold for intensive cleaning

The contour map in Fig. 3 is convenient for the engineering selection of operating modes for carrot root crown cleaning. It can be seen that the region M_{rem} < 0.20 kg·m^{-1} is concentrated mainly at V_F not higher than 1.1 m·s^{-1} and n_f not lower than 5.4-8.0 s^{-1}, depending on the specific forward speed. If V_F exceeds 1.5 m·s^{-1}, even high rotational frequencies do not provide a sharp reduction in M_{rem} within the adopted range. Therefore, for more intensive cleaning, it is more reasonable first to limit the cleaner forward speed and only then to increase the rotational frequency.

The nonlinear interaction between cleaner forward speed and blade rotational frequency can be expressed as an engineering compensation rule. To maintain the same calculated residue level when forward speed increases, the blade rotational frequency must increase approximately with the square root of forward speed. Therefore, doubling the forward speed requires about a 41% increase in blade frequency rather than a twofold increase. This rule is valid only within the studied range and must be constrained in practice by root damage, blade wear and power demand.

DISCUSSION

The obtained surface extends earlier observations on carrot harvesters by explaining the speed effect through contact mechanics. Studies of digging, clamping, conveying and cutting units reported that increased feed or forward speed can raise losses or reduce quality if the active unit speed is not adjusted (*El-Gany et al., 2008; Gaadhe et al., 2023; Wang et al., 2025a; Wang et al., 2025b*). The present model shows why this happens during final residue cleaning: forward speed shortens the residence time of the root crown in the cleaning zone, whereas blade rotational frequency simultaneously increases the single contact removal and the number of effective contacts.

Compared with alternative technologies, flexible blades are particularly effective during the final cleaning stage, where the carrot root crown surface is geometrically irregular and excessive contact pressure may cause mechanical damage. Cutting and clamping devices are effective for plant separation and conveying operations; however, their performance depends on accurate alignment and precise coordination of knife, belt, and conveying speeds. Rigid brushes are relatively simple and robust, but their cleaning efficiency is governed primarily by frictional interaction and applied normal force. Pneumatic systems eliminate direct mechanical contact; nevertheless, their effectiveness decreases when residues are moist, strongly attached, or mixed with soil particles. Therefore, the flexible-blade concept occupies an intermediate position by providing direct mechanical residue removal while maintaining compliance with the morphology of the carrot root crown.

Direct calculation of percentage error between the theoretical values and actual field measurements was not added because a matched independent dataset for the exact carrot crop, residue height, plant density, residue layer properties and kinematic grid of this analytical study is not available in the submitted material. Artificially combining the theoretical model with measurements obtained under different conditions would not provide a scientifically valid validation. Therefore, the present paper clearly states the model as an analytical design model and specifies the validation protocol required in future work: measure the actual residue mass per meter of row at each speed-frequency combination using the machine shown in Fig. 1 and report point relative error, mean absolute percentage error and root mean-square error.

Another limitation is that the current model uses average crop morphology, a constant effective density and a constant thickness of the flattened residue layer. In real harvesting conditions these parameters vary between varieties, root sizes, top moisture states and soil contamination levels. Future extensions should therefore treat carrot root crown diameter, residue height, residue adhesion and layer thickness as stochastic or experimentally distributed variables and should couple residue removal with root damage and energy demand criteria.

CONCLUSIONS

The proposed analytical model transforms the local interaction between a flexible blade and foliage residues into a row-scale estimation of the residue mass remaining on carrot root crowns after cleaning. This transition represents the main theoretical contribution of the study because it integrates single-contact residue removal, residence time within the cleaning zone, the number of blade actions, and plant density into a unified engineering calculation.

The model demonstrates that forward speed and blade rotational frequency do not exert symmetrical effects on the cleaning process. Forward speed primarily reduces the available contact time, whereas blade rotational frequency increases both the mass removed during a single contact and the average number of blade contacts. Consequently, the cleaning performance is governed by their nonlinear interaction rather than by either factor individually.

For the practical design and adjustment of a flexible-blade cleaner, intensive cleaning should be achieved through coordinated operation at moderate or low forward speed combined with sufficiently high blade rotational frequency. When forward speed must be increased to improve field productivity, the blade rotational frequency should be increased according to the square-root speed compensation principle, while considering the limitations associated with root damage, blade wear, and power consumption.

The current model is limited by the use of average carrot morphology, constant residue layer density and thickness, and the absence of direct validation based on percentage error analysis using full-scale field data. Future research should therefore include experimental measurements of residue mass, root damage, and energy consumption for different carrot cultivars and soil moisture conditions, as well as the integration of more complex and variable crop morphologies into the analytical model.

AUTHOR CONTRIBUTIONS

Conceptualization, V.B.; methodology, I.H., O.L. and J.O.; software, Y.I.; validation, J.O. and M.B.; formal analysis, O.L., I.H. and J.O.; investigation, V.B., Y.I., M.B. and J.O.; data curation, Y.I., V.B. and J.O.; writing original draft preparation, I.H.; writing review and editing, M.B. and Y.I.; visualization, Y.I. and M.B.; project administration, J.O.; funding acquisition, J.O. All authors have read and agreed to the published version of the manuscript.

NOMENCLATURE

The main symbols used in the paper are summarized in Table 2.

Table 2

Main symbols and their meanings

Symbol	Meaning	Unit
M_{cr}	mass of foliage residues removed during a single blade contact	kg
M_{rem}	mass of foliage residues remaining on carrot root crowns per 1 m of row	kg·m^{-1}
$M_{rem\,1}$	mass of foliage residues remaining on one root crown after cleaning	kg
M_0	initial mass of foliage residues on one root crown	kg
V_F	cleaner forward speed	m·s^{-1}
n_f	blade rotational frequency	s^{-1}
z_e	average effective number of blade contacts with one root crown	–
t_z	residence time of one root crown in the cleaning zone	s
N_p	number of root crops per 1 m of row	m^{-1}
s_p	plant spacing in the row	m
d_c	diameter of the carrot root crown neck	m
h_r	height of foliage residues after cutting	m
ρ_h	effective density of the flattened layer of foliage residues	kg·m^{-3}
ρ_k	blade radius at the impact contact point	m
b	cleaning blade width	m
t_a	duration of the post-impact action	s
h	thickness of the flattened layer	m
ω	angular speed of the rotor	rad·s^{-1}

REFERENCES

[1] Bulgakov, V., Pascuzzi, S., Arak, M., Santoro, F., Anifantis, A.S., Ihnatiev, Y. and Olt, J. (2019), An experimental investigation of performance levels in a new root crown cleaner, *Agronomy Research*, vol.17, no.2, pp.358-370. doi: https://doi.org/10.15159/AR.19.132.

[2] Bulgakov, V., Holovach, I., Savchenko, I., Rykhlivskyi, P., Budzanivskyi, M., Aboltins, A., Rucins, A., Olt, J. and Ihnatiev, Y. (2024), Theoretical study of flexible blade movement in cleaning carrot root crop heads without extracting them from soil, Engineering for Rural Development, vol.23, pp.722-731. doi: https://doi.org/10.22616/ERDev.2024.23.TF137.

[3] El-Gany, A., Horia, M., El-Sahhar, E.A., Mostafa, M.M. and Abd-Elhady, F.A. (2008), A developed machine to harvest carrot crop, *Misr Journal of Agricultural Engineering*, vol.25, no.4, pp.1163-1173.

[4] Gaadhe, S.K. and Tiwari, V.K. (2022), Carrot harvesting methods: a review, International Journal of *Plant & Soil Science*, vol.34, no.10, pp.7-16. doi: https://doi.org/10.9734/ijpss/2022/v34i1030918.

[5] Gaadhe, S.K., Chavda, S.K., Bandhiya, R.D., Gojiya, D.K. and Chavda, D.B. (2023), Optimizing carrot harvesting machine design: Incorporating soil and crop parameters, *International Journal of Environment and Climate Change*, vol.13, no.10, pp.3680-3689. doi: https://doi.org/10.9734/IJECC/2023/v13i103039.

[6] Ikram, K., Nadeem, M., Ghani, M.U. and Mubashar, M. (2018), Fabrication and performance evaluation of carrot digger, *Journal of Global Innovations in Agricultural Sciences*, vol.6, no.3, pp.84-87.

[7] Jahanbakhshi, A., Abbaspour-Gilandeh, Y. and Gundoshmian, T.M. (2018), Determination of physical and mechanical properties of carrot in order to reduce waste during harvesting and post-harvesting, *Food Science & Nutrition*, vol.6, no.7, pp.1898-1903. doi: https://doi.org/10.1002/fsn3.760.

[8] Kowalczuk, J., Leszczycski, N. and Bieganowski, F. (2003), Evaluation of the quality of carrot root harvested with Alina and Simon one-row harvesters, *Acta Agrophysica*, vol.2, no.1, pp.105-111.

[9] Kumar, V., Kumar, A., Naresh, V.R., Mukesh, S. and Pooniya, R. (2017), Performance and evaluation of tractor drawn carrot bed loosening implement, *Annals of Biology*, vol.33, no.1, pp.135-138.

[10] Leszczycski, N. (2011), The influence of working parameters of a carrot harvester on carrot root damage, Eksploatacja i Niezawodnoњж - *Maintenance and Reliability*, vol.1(49), pp.35-41.

[11] McCollum, T.G., Locascio, S.J. and White, J.M. (1986), Plant density and row arrangement effects on carrot yields, *Journal of the American Society for Horticultural Science*, vol.111, no.5, pp.648-651.

[12] Meriam J.L., Kraige L.G., Bolton J.N., (2020), *Meriam's Engineering Mechanics: Dynamics, SI Version, Global Edition*, 9th edition, John Wiley & Sons, USA, 624 pp. ISBN: 978-1-119-66528-1.

[13] Naresh, V., Rani, M., Jain, A., Kumar, A. and Narender (2018), Design and development of tractor operated carrot digger, *AMA, Agricultural Mechanization in Asia, Africa and Latin America*, vol.49, no.3, pp.79-85.

[14] Nath, S., Kumar, A., Mani, I., Singh, J.K. and Sureja, A.K. (2019), Determination of physical and mechanical properties of carrot (Daucus carota) for designing combine harvesting mechanism, Indian *Journal of Agricultural Sciences*, vol.89, no.6, pp.1011-1016. doi: https://doi.org/10.56093/ijas.v89i6.90825.

[15] Nucez, J., Hartz, T., Suslow, T., McGiffen, M. and Natwick, E.T. (2008), *Carrot Production in California*, University of California Agriculture and Natural Resources. Publ. 7226, Oakland, CA, USA.

[16] Oda, A.M., Abd El-Wahab, M.K., Tawfik, M.A. and Wasfy, K.I. (2018), Evaluating of a prototype machine for carrot crop harvesting suitable for small holdings, *Zagazig Journal of Agricultural Research*, vol.45, no.1, pp.213-226. doi: https://doi.org/10.21608/zjar.2018.49835.

[17] Olt J., Bulgakov V., Adamchuk V., Ilves R., Ihnatiev Y., Budzanivskyi M., Holovach I., (2024), *Machine for cleaning root crop head from top residues* (Juurviljapeade pealsejääkidest puhastamise masin), Estonia, Patent, No. EE 05877 B1.

[18] Pogorelyi, L.V. and Tatianko, N.V. (2004), *Sugar Beet Harvesting Machines: History, Design, Theory, Forecast, Feniks*, Kyiv, Ukraine, 232 pp. (in Russian).

[19] Rykhlivskyi, P.A. (2021), *Substantiation of Parameters of Working Bodies of Machines for Harvesting Table Root Crops*, PhD Thesis, Hlevakha, Ukraine, 200 pp. (in Ukrainian).

[20] Shirwal, S. and Mani, I. (2014), Study on design parameters effecting mechanical carrot harvester, *International Journal of Engineering Sciences & Research Technology*, vol.3, no.3, pp.1664-1670.

[21] Shirwal, S., Mani, I., Sirohi, N.P. and Kumar, A. (2015), Development and evaluation of carrot harvester, *AMA, Agricultural Mechanization in Asia, Africa and Latin America*, vol.46, no.1, pp.28-34.

[22] Tegen, H. and Jembere, G. (2021), Influences of spacing on yield and root size of carrot (Daucus carota L.) under ridge-furrow production, *Open Agriculture*, vol.6, no.1, pp.826-835. doi: https://doi.org/10.1515/opag-2021-0062.

[23] Wang, B., Hu, Z., Wu, F. and Gu, F. (2025a), Analysis and evaluation of harvest quality effectiveness of carrot clamping and conveying device, *Agriculture*, vol.15, no.3, 275. doi: https://doi.org/10.3390/agriculture15030275.

[24] Wang, B., Hu, Z., Gu, F., Wu, F., Cao, M. and Sun, Y. (2025b), Analysis and evaluation of the experimental effect of double-disc knife-cutting device for carrot combine harvester, *Agriculture*, vol.15, no.7, 682. doi: https://doi.org/10.3390/agriculture15070682.

[25] Xia, X., Xu, J., Zeng, G., Ye, J. and Chen, J. (2024), Investigation of the mechanical characteristics of carrot leaves used in a pulling type harvester, *BIO Web of Conferences*, vol.142, 01017. doi: https://doi.org/10.1051/bioconf/202414201017.

[26] Zeeshan, S. and Malik, M.A.I. (2025), Automated carrot harvesting machine with YOLOv8 for precision and optimal efficiency, *Journal of Engineering*, vol.2025, article ID 7098166. doi: https://doi.org/10.1155/je/7098166.