

Study of the crumpling conditions of carrot top residues on the root crown under impact contact of a cleaning blade and determination of the mass of removed residues

V. Bulgakov¹, M. Budzanivskyi², I. Holovach¹, Ye. Ihnatiev^{3,4} and J. Olt^{3,*}

¹National University of Life and Environmental Sciences of Ukraine, 15 Heroyiv Oborony Str., UA 03041 Kyiv, Ukraine

²Institute of Mechanics and Automatics of Agroindustrial Production of the National Academy of Agrarian Sciences of Ukraine, 11/1 Vokzalna Str., UA 08631 Hlevakha, Ukraine

³Estonian University of Life Sciences, Institute of Forestry and Engineering, 56 Kreutzwaldi Str., EE 51006 Tartu, Estonia

⁴Dmytro Motornyi Tavria State Agrotechnological University, 66 Zhukovsky Str., UA 69600 Zaporizhzhia, Ukraine

*Correspondence: jyri.olt@emu.ee

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Abstract. Effective removal of carrot top residues is essential for marketable root quality, while excessive blade impact can increase crop damage and harvesting losses. The aim of this study was to estimate the mass (M_{cr}) of carrot top residues removed from the root crown by a flexible cleaning blade after impact contact, and to analyse the sensitivity of the model to the kinematic and design parameters of the cleaner. The study combined a criterion for residue weakening during impact with a simplified model of post-impact removal. Literature data on carrot crown geometry and crop mechanical properties were used together with the design parameters of a two-shaft cleaner. The developed model was analysed for $\omega = 10\text{--}50\text{ rad s}^{-1}$, $\rho = 0.06\text{--}0.12\text{ m}$, $b = 0.03\text{--}0.06\text{ m}$ and $\delta_{cr} = 0.002\text{--}0.005\text{ m}$. Because values of the effective bulk density of the compacted top-residue layer and its thickness after impact were not found in the literature, $\rho_h = 850\text{ kg m}^{-3}$ and $t_{imp} = 0.008\text{ s}$ were assumed for modelling, whereas δ_{cr} was varied within an engineering range. At the initial values $\omega = 30\text{ rad s}^{-1}$, $\rho = 0.10\text{ m}$, $b = 0.04\text{ m}$ and $\delta_{cr} = 0.004\text{ m}$, the predicted mass removed in one blade pass was 3.264 g. The constructed response surfaces showed a monotonic increase of M_{cr} with all variables; within the selected limits, M_{cr} ranged from 0.65 to 6.53 g for the pair (ω, ρ) and from 1.22 to 6.12 g for the pair (b, δ_{cr}) . The calculated initial residue mass on the carrot crown of 13.86 g indicates that a blade pass can remove about 23.5% of the nominal load, which supports the use of multi-blade cleaners and two parallel shafts.

Key words: coefficient of restitution, elastic blade, kinematic parameters, post-impact removal, response surface analysis, two-shaft cleaner.

INTRODUCTION

Mechanical carrot harvesting involves lifting, detopping and cleaning of the root crown, and the quality of these operations determines product losses, residual top mass and mechanical damage. Incomplete cleaning leaves petiole residues that reduce marketability and complicate post-harvest handling, whereas excessive impact or rubbing can bruise, crack or uproot the root. Cleaner design must therefore balance residue-removal completeness, crop safety and energy demand (Kowalczyk et al., 2003; Jahanbakhshi et al., 2018; Nath et al., 2019).

Flexible cleaning blades are promising working elements because they can conform to irregular crown geometry and combine a short impact with post-impact sliding removal. Their operating efficiency and durability are coupled: increasing angular velocity, contact radius or blade width can enlarge the swept area but can also increase impact load, cyclic bending and wear. For elastomeric working elements, service life is additionally affected by strain amplitude and mean strain, loading frequency, temperature and hysteretic heating, material formulation, manufacturing defects, stress concentrations at the mounting, environmental ageing and abrasion by soil particles (Mars & Fatemi, 2004; Gehling et al., 2023).

Previous studies have characterised carrot geometry and mechanical properties, evaluated harvesting damage and modelled the motion or force interaction of elastic crown-cleaning elements. However, they do not provide a compact estimate of the mass of top residues removed by one blade pass after the impact phase. Such an estimate is needed for preliminary parameter selection and for sequential models in which the residue mass remaining after one pass becomes the initial mass for the next.

The present work was motivated by the need to couple the impact condition that weakens the residue layer with the area swept during the subsequent blade motion. The aim was to analytically estimate the mass of carrot top residues removed from the root crown by one flexible cleaning blade after impact contact. The specific objectives were to: formulate a crumpling criterion for the residue layer; derive the area, volume and mass removed during post-impact motion; quantify the sensitivity of the predicted mass to angular velocity, impact radius, blade width and flattened-layer thickness; and estimate the residue mass remaining after a single pass. The novelty of the study lies in coupling the impact and post-impact phases in one engineering model that yields a single-pass mass estimate rather than only a trajectory or force criterion.

LITERATURE REVIEW

A chronological review of crop-mechanics and flexible-element studies is important for distinguishing established design data from the unresolved single-pass mass-estimation problem. Lake & Lindley (1965) identified a fatigue limit for rubber under cyclic loading, providing a foundation for considering repeated deformation in flexible working elements. Kowalczyk et al. (2003) subsequently evaluated carrot-harvesting quality in one-row harvesters. Mars & Fatemi (2004) systematised the mechanical and environmental factors controlling rubber fatigue, while Gracie & Brown (2004, 2005) showed that defoliation and water availability influence carrot-root splitting and growth.

Later research focused more directly on crop damage and elastic cleaning tools. Leszczyński (2011) demonstrated that carrot-harvester settings affect root damage. Jahanbakhshi et al. (2018) quantified carrot resistance to bruising, bending and shearing, and Bulgakov et al. (2018) formulated the theory of cleaning standing sugar-beet crowns with elastic blades. In 2019, experimental and theoretical studies established the sensitivity of elastic crown-cleaner performance to machine settings and blade-root interaction (Bulgakov et al., 2019a; Bulgakov et al., 2019b); Nath et al. (2019) measured carrot geometry and detachment-related properties, and Stopa et al. (2019) used finite-element analysis to show that loading-element shape changes the surface-pressure distribution in carrot roots.

Recent studies have strengthened the crop-specific basis for cleaner design. Xia et al. (2021) combined finite-element simulation with impact experiments to determine carrot-damage thresholds, and Rykhlivskyi (2021) summarised design-relevant parameters for table root crops. Budzanivskyi (2023) evaluated a two-shaft crown cleaner, Gaadhe et al. (2023) related soil and crop parameters to carrot-harvester design, and Gehling et al. (2023) reviewed the effects of elastomer formulation, manufacturing and service conditions on fatigue. In 2024, the impact impulse and post-impact blade motion on carrot crowns were modelled in greater detail (Bulgakov et al., 2024a; Bulgakov et al., 2024b), while Rybacki et al. (2024) examined yield losses during mechanical heading and Senthilkumar et al. (2024) evaluated a power-operated carrot harvester-cum-detopper. Wang et al. (2025) further showed that carrot damage and missed-pulling rates vary with the operating speed of a clamping and conveying device.

Taken together, the literature provides crop dimensions, strength limits, blade-motion models and machine-level quality indicators. The unresolved step is a physically interpretable relation between the residue layer weakened during impact and the mass removed during the subsequent motion of one blade. The present study addresses this gap as a preliminary analytical framework; it does not replace experimental validation of individual contacts or field-scale cleaner performance.

MATERIALS AND METHODS

The analytical scheme is based on a two-phase interaction between a flexible cleaning blade and the carrot root crown: the impact phase and the post-impact removal phase. During impact, petiole residues are flattened and weakened, and during the subsequent blade motion along the crown surface a defined surface area of residues is removed. The adopted approach first applies a residue-crumpling criterion under impact and then estimates mass removed during post-impact motion of a single blade.

The impact impulse was defined in the classical way as the time integral of the impact force. The mean and maximum impact forces were related using an approximate relationship for a short-duration impact following the approach of Butenin et al. (1985) and Pogorelyi & Tatianko (2004).

The impact impulse S of the flexible cleaning blade acting on the root crown surface, previously defined as a linear function of the distance ρ (i.e., the distance from the blade rotation axis to point K of impact contact), was determined from the following expression (Bulgakov et al., 2024a):

$$S = m \cdot (1 + \varepsilon) \cdot \omega \cdot \rho , \quad (1)$$

where m – mass of the cleaning blade, kg; ε – coefficient of restitution; ω – angular velocity of blade rotation, rad s^{-1} ; ρ – distance from the blade rotation axis to point K of impact contact, m.

Thus, the closer the impact occurs to the blade tip, the larger the impact impulse S (with all other parameters in Eq. (1) held constant).

However, the magnitude of the impact force F_{imp} , rather than the impact impulse S itself, is more important. This is because many physical and mechanical characteristics of plants are directly related to the forces exerted on the plant by the working element. This primarily concerns strength characteristics, especially those associated with failure and damage of plants by machine working elements.

As a rule, the time dependence of the impact force during impact is unknown. However, it is known that this force increases from zero to a peak value over a very short impact time and then sharply decreases to zero again. According to Butenin et al. (1985), as a first approximation it can be assumed that the maximum impact force is twice its average value over the time interval t_{imp} .

Based on the mean value theorem from integral calculus and the expression for the impact impulse, one can write (Butenin et al., 1985):

$$S = F_{imp.av.} \cdot t_{imp} , \quad (2)$$

where S is the impact impulse, $\text{N}\cdot\text{s}$; $F_{imp.av.}$ is the mean value of the impact force, N ; t_{imp} is the impact duration, s.

From Eq. (2) we obtain:

$$F_{imp.av.} = \frac{S}{t_{imp}} . \quad (3)$$

In Eq. (3), the quotient of impulse ($\text{N}\cdot\text{s}$) and impact duration (s) gives the mean impact force in N .

Then, according to Pogorelyi & Tatianko (2004), we have:

$$F_{imp} = 2F_{imp.av.} = \frac{2S}{t_{imp}} , \quad (4)$$

where F_{imp} is the maximum impact force, N .

The impact duration can only be determined experimentally. According to Pogorelyi & Tatianko (2004), $t_{imp} \approx 0.6 \cdot 10^{-2}$ s.

It should also be noted that under the action of the impact force F_{imp} on the top residues on the carrot crown, these residues undergo a certain deformation. Moreover, the deformation of top residues largely depends on the arrangement of petioles on the carrot crown before the beginning of impact contact.

Thus, some petioles may undergo bending deformation, some compression deformation, and some bending and compression simultaneously. However, once the petioles are pressed by the cleaning blade against the carrot crown, during the remaining time of impact contact they will undergo compression deformation up to partial crumpling (flattening). The allowable force for crumpling the top residues can be determined by the expression:

$$F_{cr} = [\sigma_{cr}] \cdot S_K , \quad (5)$$

where F_{cr} is the force required to crumple the top residues, N ; S_K is the impact contact area, m^2 ; $[\sigma_{cr}]$ is the allowable compressive stress of the top residues, Pa (N m^{-2}).

Then the condition for crumpling (flattening) the top residues on the carrot crown is:

$$F_{imp} > F_{cr} ,$$

or, taking into account Eqs (4) and (5), we obtain the following condition:

$$\frac{2S}{t_{imp}} > [\sigma_{cr}] \cdot S_K \quad (6)$$

By varying the parameters included in Eq. (6), the crumpling conditions for the top residues can be determined for each specific case numerically. In doing so, the impact impulse should not be assigned arbitrarily but calculated from Eq. (1), which accounts for the blade mass m , its angular velocity ω , the distance ρ from the impact contact point to the blade rotation axis, and the coefficient of restitution ε , i.e., the key parameters that determine the magnitude of the impact impulse.

The blade–crown impact contact patch was assumed to be rectangular, with a width equal to b , where b is the blade width. The length a of the impact contact patch can vary depending on the distance from the blade suspension point to the impact point K . When the impact occurs closer to the blade tip, the blade fits the crown surface more tightly and the impact patch length becomes larger. A case is also possible when the impact occurs at the tip of the cleaning blade. It is assumed that, on average, the length a of the contact surface equals $a = (1.0 \dots 1.5) \cdot b$.

Then the impact contact area S_K can be determined by the following expression:

$$S_K = a \cdot b . \quad (7)$$

The allowable normal stress $[\sigma_{cr}]$ of carrot top residues in crumpling can only be determined experimentally. However, as noted by Pogorelyi & Tatianko (2004), the allowable shear forces for top residues are 2–2.5 times lower than the corresponding normal forces. According to Bulgakov (2011), the allowable shear stress $[\tau]$ for a single petiole is $1.14 \cdot 10^6$ Pa; therefore, as a first approximation we assume that for a single petiole $[\sigma_{cr}] = 2.5[\tau] = 2.85 \cdot 10^6$, Pa. However, as noted by Pogorelyi & Tatianko (2004), the available data also indicate that the total strength of petioles grouped into a bunch is an order of magnitude higher than the strength of a single petiole.

The following data are required for the numerical calculation: m is the mass of the cleaning blade, kg; ω is the angular velocity of blade rotation, $\text{rad} \cdot \text{s}^{-1}$; $\rho = r + l$ is the distance from the blade rotation axis to the impact contact point K , m; ε is the coefficient of restitution, dimensionless; t_{imp} is the impact duration, s; $[\sigma_{cr}]$ is the allowable normal stress of top-residue crumpling, Pa ($\text{N} \cdot \text{m}^{-2}$); b is the blade width, m; a is the length of the impact contact patch, m; ρ_h is the bulk density of compacted carrot top-residue layer, $\rho_h = 850 \text{ kg} \cdot \text{m}^{-3}$.

A value of the impact impulse S should be selected to satisfy inequality (6). The minimum value that satisfies this condition is preferable because it reduces energy demand.

The next step is to determine analytically the mass of top residues that can be removed from the carrot root crown by one cleaning blade during its post-impact motion along the crown surface.

Obviously, the post-impact displacement of the contact point K from the impact point to the blade tip L_n is:

$$L_n = L - l , \quad (8)$$

where L is the blade length, m; l is the distance from the blade suspension point to the impact contact point K_{imp} , m.

The time t_k of post-impact motion of the contact point K after impact is:

$$t_k = \frac{L_n}{\omega \cdot (h_{cr} + r)} = \frac{L - l}{\omega \cdot (h_{cr} + r)}, \quad (9)$$

where h_{cr} is the blade deflection, m; r is the distance from the rotation axis of the cleaning drum to the blade suspension point, m; $h_{cr} + r$ is the distance from the blade rotation axis to the crown surface (Fig. 1) (Budzanivskyi, 2023).

Then the removal area S_{cr} of the top residues equals:

$$S_{cr} = \sqrt{\dot{x}^2 + \dot{y}^2} \cdot t_k \cdot b, \quad (10)$$

where $\sqrt{\dot{x}^2 + \dot{y}^2}$ is the absolute velocity of the contact point K moving along the carrot root crown, m s^{-1} ; b is the width of the cleaning blade, m.

The calculation procedure for $\dot{x}$ and $\dot{y}$ is described by Budzanivskyi (2023), Eq. (21).

As a first approximation (which considerably simplifies the calculation), instead of the above velocity $\sqrt{\dot{x}^2 + \dot{y}^2}$ the following expression can be used:

$$\sqrt{V_F^2 + \omega^2 \cdot \rho^2} = \sqrt{V_F^2 + \omega^2 \cdot (r + l)^2};$$

then the removal area S_{cr} is approximately:

$$S_{cr} \approx \sqrt{V_F^2 + \omega^2 \cdot (r + l)^2} \cdot t_k \cdot b. \quad (11)$$

Moreover, the closer to the blade tip the impact occurs, the more the velocity $\sqrt{V_F^2 + \omega^2 \cdot (r + l)^2}$ approaches the velocity $\sqrt{\dot{x}^2 + \dot{y}^2}$.

Then the volume of top-residue material removed by this blade is determined by the following expression:

$$V_{cr} = S_{cr} \cdot \delta_{cr}, \quad (12)$$

where δ_{cr} is the thickness of the layer of top-residue material flattened after impact on the carrot root crown, m.

Finally, the mass of top residues removed by the blade in one pass equals:

$$M_{cr} = \rho_h \cdot V_{cr} = \rho_h \cdot S_{cr} \cdot \delta_{cr}. \quad (13)$$

Next, we determine the mass of top residues on the carrot root crown after the residues are removed by one blade. It can be assumed that in the root neck zone, the top stems grow rather densely, practically without gaps between adjacent stems. With

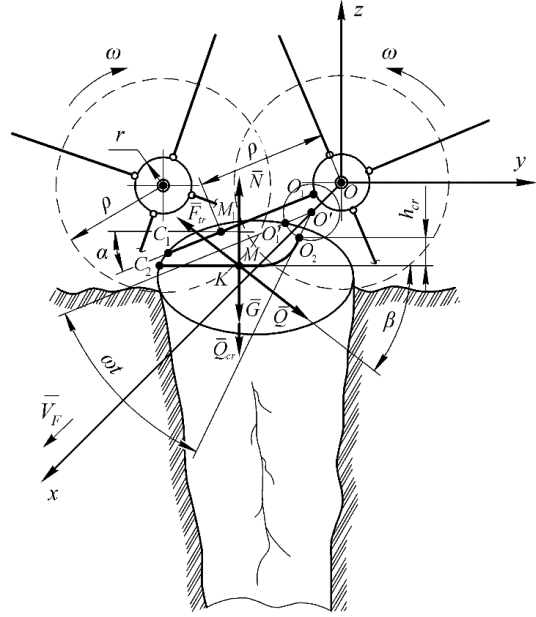


Figure 1. Calculation scheme of interaction between a flexible cleaning blade and the carrot root crown (Budzanivskyi, 2023).

increasing distance from the neck zone upward, the stems partially deviate from each other. Gaps appear between adjacent stems and the bunch begins to take a cone shape. Therefore, at the cutting height the bunch resembles a frustum (a truncated cone): the lower base diameter equals the neck diameter, whereas the upper base diameter depends on the cutting height and will, of course, be larger than the neck diameter. Since we do not know how the gap between adjacent stems increases with bunch height on the carrot crown, and hence the ratio between the upper and lower bunch diameters, we notionally compress the bunch from all sides, eliminating all gaps between stems and transforming it into a solid cylinder with the diameter equal to the neck diameter, because in the neck zone the bunch is already not compressible.

The volume of such a cylinder equals:

$$V_u = \frac{\pi \cdot d_n^2}{4} \cdot h_b, \quad (14)$$

where d_n is the root neck diameter, m; h_b is the bunch height, m.

Then the mass M_b of this bunch equals:

$$M_b = \gamma_s \cdot V_s = \gamma_s \cdot \frac{\pi \cdot d_n^2}{4} \cdot h_b, \quad (15)$$

where γ_s is the density of the stem tissue of carrot top residues before impact contact with the cleaning blade, $\text{kg} \cdot \text{m}^{-3}$.

According to Rykhlivskyi (2021), the carrot root neck diameter is $d_n = 2 \dots 4$ cm.

The mass M_{rem} of top residues remaining on the carrot root crown after one cleaning blade pass is determined by the following expression:

$$M_{rem} = M_b - M_{cr}, \quad (16)$$

where M_{cr} is the mass of top residues removed by the blade in one pass, kg.

According to the theoretical model of blade motion along the carrot crown, the angular velocity of the cleaner shafts can vary within $5\text{--}58 \text{ rad s}^{-1}$, the blade length within $0.07\text{--}0.15$ m, and the blade fastening point relative to the shaft axis within $0.03\text{--}0.08$ m (Bulgakov et al., 2024b). For constructing the response surfaces, a practical range $\omega = 10\text{--}50 \text{ rad s}^{-1}$ was adopted. The impact radius ρ was varied within $0.06\text{--}0.12$ m as a realistic interval within the design range of the cleaner. The blade width range $b = 0.03\text{--}0.06$ m was selected based on two considerations: the mean diameter of the top bunch at the upper part of carrot is about 3.72 cm (Gaadhe et al., 2023), whereas for similar elastic crown cleaners blade widths of $5\text{--}6$ cm were used (Bulgakov et al., 2018).

No direct published values of the effective bulk density of the compacted carrot top-residue layer and its thickness after impact were found. Therefore, $\rho_h = 0.85 \text{ g cm}^{-3}$ was adopted as an effective density, which is lower than the true density of fresh carrot tissue, reported by Jahanbakhshi et al. (2018) as about 1.04 g cm^{-3} , because the residue bunch contains inter-stem voids. The impact duration was assumed as $t_{imp} = 0.008$ s according to the engineering recommendations of Pogorelyi & Tatianko (2004). The thickness of the flattened layer was varied within $\delta_{cr} = 0.002\text{--}0.005$ m. This interval was considered an engineering assumption consistent with crown geometry, since the carrot crown protrudes above the soil surface by about 0.015 m (Nath et al., 2019) and therefore the flattened residue layer should be smaller than the height of the cut bunch. For the base-case calculation, $\omega = 30 \text{ rad} \cdot \text{s}^{-1}$, $\rho = 0.10$ m, $b = 0.04$ m and $\delta_{cr} = 0.004$ m were used.

Blade durability considerations. Blade service life is not an output of Eqs (1–16), and no fatigue or wear experiment was performed in this study. The model therefore assumes that blade properties remain unchanged during a single contact. In service, durability can be governed by cyclic bending strain near the suspension, impact frequency and load sequence, stress concentrations at holes and edges, temperature-dependent hysteresis, oxidation or ozone exposure, manufacturing defects and abrasive contact with soil or mineral particles. Progressive cracking or tip wear can change blade mass and geometry, the coefficient of restitution and the effective contact area. Quantitative replacement criteria will therefore require cyclic-fatigue and soil-abrasion tests (Mars & Fatemi, 2004; Gehling et al., 2023).

RESULTS AND DISCUSSION

Substituting the initial values into Eq. (13) yields $M_{cr} = 0.003264$ kg, or 3.264 g in one blade pass. The corresponding initial residue mass estimated from Eqs (14) and (15) is $M_b = 0.01386$ kg, or 13.86 g. Hence, the nominal mass remaining after one pass equals $M_{rem} = 10.59$ g. In relative terms, one pass removes about 23.5% of the nominal residue load. This result indicates the need for a multi-blade cleaning arrangement.

The first response surface was constructed at fixed values $b = 0.04$ m and $\delta_{cr} = 0.004$ m. As shown in Fig. 2, the removed mass monotonically increases both with increasing angular velocity ω and with increasing impact radius ρ . Within the selected range, M_{cr} varies from 0.65 to 6.53 g. This trend is explained by the increase in tangential velocity and, consequently, the swept area during the post-impact phase. This agrees with the results of Bulgakov et al. (2024b), who showed that increasing angular velocity increases the post-impact velocity of the blade–crown contact point.

The second response surface was obtained at fixed $\omega = 30$ rad·s^{−1} and $\rho = 0.10$ m. Fig. 3 shows that the removed mass monotonically increases both with increasing blade width b and with increasing thickness of the flattened layer δ_{cr} , varying from 1.22 to 6.12 g. The effect of b is a design factor directly related to the cleaner layout, because a wider blade covers a larger strip of the crown surface. The effect of δ_{cr} is significant because it represents the portion of the flattened residue layer that is actually available for removal after the impact phase. In practice, δ_{cr} depends on the residue height after cutting, the local bunch density and the intensity of the impact interaction.

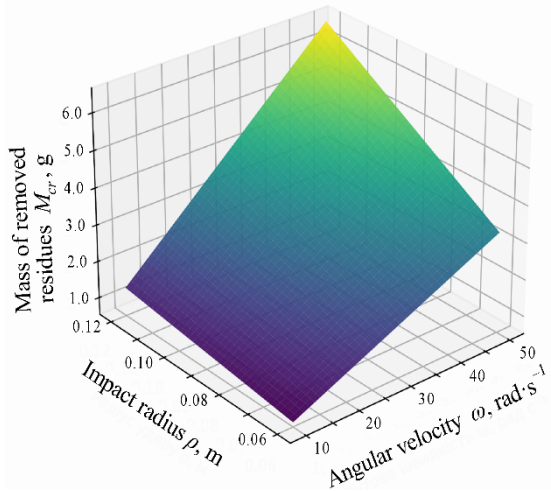


Figure 2. Response surface for the mass of removed residues M_{cr} as a function of angular velocity ω and impact radius ρ at $b = 0.04$ m, $\delta_{cr} = 0.004$ m, $\rho_h = 850$ kg m^{−3} and $t_{imp} = 0.008$ s.

The obtained relationships should be interpreted as local estimates for a single pass. They do not yet account for the decrease in residue mass after successive contacts, partial overlap of removal zones, or the effect of the translational speed of the cleaner along the row. This is important because field studies of elastic crown cleaners have shown that the residual mass on the crowns is also affected by the machine forward speed and the vertical position of the working element (Bulgakov et al., 2019a; Budzanivskyi, 2023). Therefore, Eq. (13) should be considered as a basic element for further modelling of a multi-blade and two-shaft system.

The selected parameter ranges agree well with published geometric and strength characteristics of carrot. Nath et al. (2019) reported that the carrot crown protrudes above the soil surface by about 1.5 cm, and Gaadhe et al. (2023) reported that the mean diameter of the top bunch in the upper part of carrot is 3.72 cm. Jahanbakhshi et al. (2018) showed that carrot tissue exhibits a considerable resistance to crumpling, bending and shear; therefore, cleaning aggressiveness cannot be increased indefinitely without risk of damaging the root crop. For this reason, increasing ω , ρ or b is beneficial only within a technologically acceptable, non-damaging regime.

The base-case prediction of 3.264 g corresponds to 23.5% of the nominal initial residue mass. This is a local single contact estimate and should not be interpreted as whole machine cleaning efficiency. It nevertheless supports repeated blade contacts: experimental studies of elastic crown cleaners have shown that residual top mass depends on angular velocity, forward speed and the vertical position of the working element (Bulgakov et al., 2019a; Budzanivskyi, 2023), whereas the present model supplies the local mass term required to represent those sequential interactions.

The positive response to ω and ρ follows from the increase in tangential blade speed, but it should not be interpreted as a recommendation to maximise either parameter. Jahanbakhshi et al. (2018) reported maximum forces of 71.90 N for bruising, 48.60 N for bending and 41.14 N for shearing carrot tissue, while Xia et al. (2021) obtained critical impact forces of 45.2 N in simulation and 43.1 N experimentally. These values were obtained under loading configurations different from the present blade–crown contact and therefore cannot be inserted directly into Eq. (6). They nevertheless show why the residue removal response must be evaluated together with a crop damage constraint. Wang et al. (2025) similarly found that carrot damage and missed pulling rates varied with clamping and conveying speed rather than improving monotonically at the highest speed.

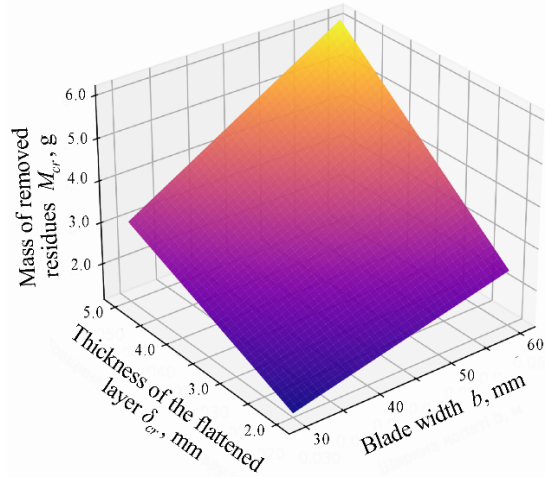


Figure 3. Response surface for the mass of removed residues M_{cr} as a function of blade width b and thickness of the flattened layer δ_{cr} at $\omega = 30 \text{ rad}\cdot\text{s}^{-1}$, $\rho = 0.10 \text{ m}$, $\rho_h = 850 \text{ kg}\cdot\text{m}^{-3}$ and $t_{imp} = 0.008 \text{ s}$.

The effects of blade width and flattened-layer thickness follow directly from Eq. (13), because both parameters scale the effective removed volume. The practical benefit of increasing blade width is limited by crown geometry and overlap between adjacent blade trajectories. Gaadhe et al. (2023) reported a mean upper top bunch diameter of 3.72 cm, which is close to the lower part of the adopted blade-width range. Widths substantially larger than the crown may increase redundant contact rather than useful coverage, whereas insufficient width can leave untreated sectors. In addition, Stopa et al. (2019) showed that the shape of a loading element redistributes pressure on carrot roots, indicating that contact geometry must be considered together with nominal width.

Recent carrot harvesting studies also show the distinction between local contact mechanics and machine level performance. Rybacki et al. (2024) predicted yield losses during mechanical heading from crop and machine variables, and Senthilkumar et al. (2024) evaluated a complete harvesting and detopping unit. The present model instead isolates one blade–crown contact. Its contribution is therefore complementary: it provides a physically interpretable input for a larger multi contact model rather than a direct prediction of field scale cleaning quality.

An additional design trade-off concerns blade durability. Higher angular velocity increases contact frequency, while a larger impact radius raises tangential speed and can increase cyclic strain and local heating. Elastomer fatigue studies identify strain amplitude, mean strain, load sequence, frequency, temperature, oxidation, manufacturing defects and surface damage as major life controlling factors (Mars & Fatemi, 2004; Gehling et al., 2023). Soil contact can add abrasive wear. Because cyclic life and wear tests were outside the scope of this study, the response surfaces describe initial blade behaviour only; a parameter combination that maximises predicted removed mass may not maximise service life or lifecycle efficiency.

The principal limitations are the nominal cylindrical representation of the residue bunch, the assumptions of uniform effective density and flattened layer thickness, the approximate contact point velocity, and the omission of forward speed, crown-to-crown variability, successive pass overlap, moisture dependent petiole properties and blade wear. The model has not yet been validated against directly measured residue mass after individual blade contacts. Future work should combine high speed measurement of impact duration and blade deflection with gravimetric determination of initial and removed residue mass, repeat the tests across cultivars and moisture conditions, and conduct cyclic fatigue and soil abrasion trials. The resulting data would allow calibration of the effective density, flattened layer thickness, coefficient of restitution and post impact velocity approximation, followed by uncertainty analysis and field scale validation of multi blade and two shaft cleaners.

CONCLUSIONS

By linking the impact crumpling criterion to the post-impact swept area, the study establishes a mechanism based estimate of the residue mass removed in one blade pass. This coupling is the main contribution of the work because it converts the principal kinematic and geometric parameters into a mass output that can be used as an element of sequential multi-blade calculations.

For the base case (effective bulk density $\rho_h = 850 \text{ kg}\cdot\text{m}^{-3}$, impact duration $t_{imp} = 0.008 \text{ s}$, angular velocity $\omega = 30 \text{ rad}\cdot\text{s}^{-1}$, impact radius $\rho = 0.10 \text{ m}$, blade width $b = 0.04 \text{ m}$ and flattened-layer thickness $\delta_{cr} = 0.004 \text{ m}$), the model predicts removal of 3.264 g from a nominal initial mass of 13.86 g, or approximately 23.5%. Across the analysed ranges, the predicted mass varied from 0.65 to 6.53 g for the pair (angular velocity, impact radius) and from 1.22 to 6.12 g for the pair (blade width, flattened-layer thickness). These relationships support repeated contacts in a multi-blade, two-shaft cleaner, but the highest parameter values should not be selected without simultaneous crop damage and blade durability checks.

Limitations and future directions. The conclusions are limited to an analytical, single pass model based partly on assumed values of compacted residue density, flattened layer thickness and impact duration. The next stage should measure these quantities directly, validate the mass prediction for individual contacts, incorporate forward speed and overlapping trajectories, quantify cultivar and moisture effects, and determine fatigue and abrasive wear of the flexible blades. Until such validation is completed, the model should be used for preliminary parameter selection and experimental planning rather than as a final field performance predictor.

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