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Article

OPTIMIZATION OF BLADE ROLLER PARAMETERS FOR SLIDING CUTTING

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Abstract: This study advances a rigorous theoretical framework for the sliding cutting mechanism executed by a blade mounted on a rotating roller, with the objective of intensifying the efficiency of soil clod comminution in agricultural systems. Particular emphasis is placed on the kinematic coupling between tangential and angular velocity components of the cutting edge, alongside a detailed examination of contact-point dynamics and the nonlinear influence of a variable cutting radius. The investigation further elucidates the kinematic transformation of the effective sharpening (rake) angle under sliding cutting conditions and its consequent impact on stress-strain localization, fracture initiation, and the evolution of cutting resistance. It is theoretically substantiated that the superposition of a tangential velocity component induces a transition from predominantly compressive loading to shear-dominated failure mechanisms. This transition significantly reduces the effective tool-material contact interface, amplifies stress concentration, and promotes microcrack nucleation and propagation in low-moisture, brittle soil aggregates. Through analytical modeling and parametric optimization, the study establishes the optimal geometric and kinematic configurations of the blade-roller system, including blade inclination, roller diameter, and translational velocity regimes. The results demonstrate that the rational coordination of these parameters yields a pronounced decrease in cutting resistance, enhanced fragmentation uniformity, and a measurable reduction in specific energy consumption. Overall, the findings provide a mechanistically grounded and quantitatively substantiated basis for the design and optimization of energy-efficient soil tillage implements, thereby contributing to the advancement of sustainable and high-performance agricultural processing technologies.

Keyword: soil clod comminution, sliding cutting mechanism, cutting resistance.

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Introduction

Efficient size reduction of solid materials with low moisture content remains a critical challenge in agricultural processing and related industries. Such materials typically exhibit brittle behavior, low plasticity, and high resistance to deformation, which complicates conventional cutting and crushing processes. As a result, traditional impact-based or compression-based methods often lead to excessive energy consumption, non-uniform particle size distribution, and increased wear of working elements [1–4].

In recent years, sliding cutting (shear-dominated cutting with tangential motion) has been recognized as a more energy-efficient and quality-oriented approach for processing brittle and low-moisture materials. Unlike direct cutting, sliding cutting reduces the contact area between the cutting edge and the material, thereby increasing local stress concentration and facilitating crack initiation at lower applied forces. This mechanism significantly improves cutting efficiency while minimizing unnecessary deformation of the material [5–7].

According to studies in material cutting mechanics, the introduction of a tangential velocity component along the cutting edge reduces cutting forces and energy consumption due to the transformation of normal stresses into shear stresses. This effect is particularly important for dry and brittle materials, where fracture propagation dominates over plastic deformation [8–10].

Research in tribology and cutting mechanics has shown that frictional interaction at the tool-material interface plays a crucial role in sliding cutting processes. A reduction in the effective friction coefficient during sliding leads to improved cutting conditions, lower resistance forces, and enhanced tool performance. Furthermore, the transformation of the effective sharpening angle under sliding conditions contributes to optimizing the stress distribution along the cutting edge [11–13].

Experimental and theoretical studies indicate that combining rotational motion with translational or tangential motion (as in drum-mounted cutting systems) provides favorable kinematic conditions for sliding cutting. In such systems, the cutting edge interacts with the material progressively, allowing gradual stress buildup and controlled fracture. This results in improved product quality and reduced energy requirements [14,15].

Therefore, the development and optimization of cutting parameters for sliding cutting systems are essential for improving process efficiency. Particular attention should be given to the relationship between tangential velocity, rotational speed, cutting radius, and tool geometry. These parameters directly influence cutting dynamics, resistance forces, and energy consumption [16].

In agriculture and processing industries, the size reduction of solid materials with low moisture content is one of the important technological processes [17]. Conventional cutting methods are often characterized by high energy consumption and low efficiency. Therefore, improving cutting quality and reducing energy consumption through the application of sliding cutting methods is considered a relevant and important task [18,19].

Problem Statement. During the process of cutting soil clods using a blade mounted on a rotating drum, the motion of the blade consists of both rotational and tangential components. Variations in velocity at the contact points, the increase in radius, and the transformation of the sharpening angle significantly influence the cutting process. From this perspective, determining the kinematic and geometric parameters that characterize the cutting process, as well as establishing their optimal values, is considered the main problem.

Materials and Methods

The drum, which is part of the working unit, moves along the furrow profile between cotton rows and serves to crush soil layers and clods while also performing the function of a support wheel.The main parameters of the drum include its width, minimum and maximum diameters, blade height, sharpening angle, and inclination angle. According to agrotechnical requirements, the working width of the drum must correspond to the spacing between cotton rows; the minimum diameter should ensure the preservation of the protective zone; the maximum diameter should align with the center of the furrow; and the blades must effectively cut and crush soil clods and weeds (Fig. 1 (1 – ridge former; 2 – handle; 3 – drum; 4 – blade)).

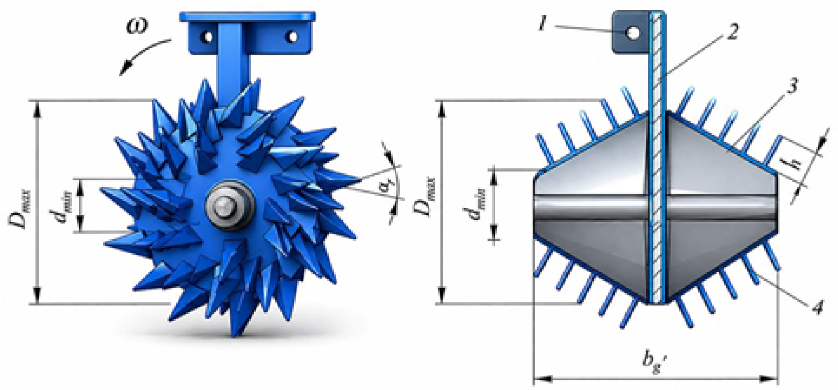

Figure 1. Scheme of a drum with blades

Results

In substantiating the parameters of the drum, it is assumed that its shape and dimensions correspond to the furrow profile between cotton rows, and that the conditions for crushing the soil layer and clods are uniform across the entire working width. It is also assumed that the blades act perpendicularly on soil particles and clods. According to these assumptions, the drum should roll easily over the clods, crush them effectively, and penetrate the soil to ensure high-quality fragmentation. For the bladed drum to operate efficiently, the clods must undergo sliding cutting, crushing, and disintegration along its surface. Using the scheme (Fig. 2), the radius of the minimum diameter of the drum can be expressed by the following relation:

$$r_{\min}(1-\cos\delta) - h_1 = r_k(1+\cos\delta) + h_1 - h_2, \tag{1}$$

where r_k – is the radius of the soil clod, m; h_1 – is the penetration depth of the drum into the soil, m; h_2 – is the penetration depth of the clod into the soil, m; δ – is the angle between the arc from the soil support point of the drum to the first contact point of the clod, in degrees.

From expression (3), the following result is obtained:

$$r_{\min} = \frac{r_k(1+\cos\delta) + h_1 - h_2}{1-\cos\delta}, \tag{2}$$

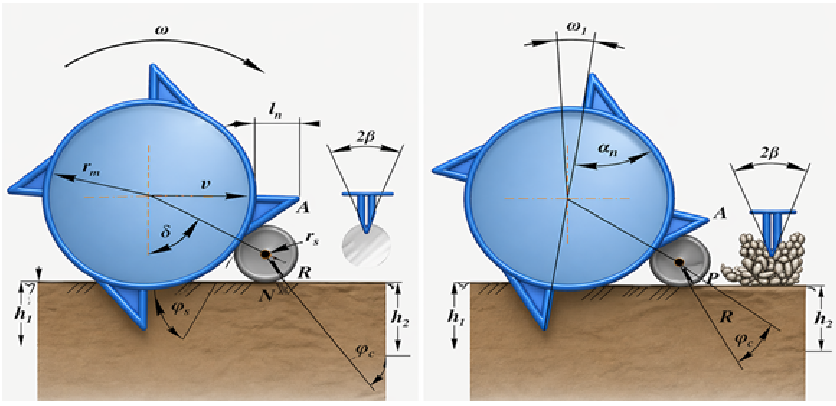

Figure 2. Schematic diagram for determining the drum diameter

$$r_{\min}(1-\cos\delta) - h_1 = r_k(1+\cos\delta) + h_1 - h_2, \tag{3}$$

where r_k is the radius of the soil clod (m); h_1 is the penetration depth of the drum into the soil (m); h_2 is the penetration depth of the clod into the soil (m); and δ is the angle between the arc from the soil support point of the drum to the first contact point of the clod (degrees).

From expression (3), the following result is obtained:

$$r_{\min} = \frac{r_k(1+\cos\delta) + h_1 - h_2}{1-\cos\delta}, \tag{4}$$

Since

$$\mathrm{ctg}^2\frac{\delta}{2} = \frac{1+\cos\delta}{1-\cos\delta},$$

and $\delta \le \varphi_p + \varphi_t$, taking this into account, we obtain the following:

$$r_{\min} = r_k\,\mathrm{ctg}^2\left(\frac{\varphi_p+\varphi_t}{2}\right) + \frac{h_1 - h_2}{1-\cos(\varphi_p+\varphi_t)}, \tag{5}$$

For $r_k = 50\,\mathrm{mm}$, $h_1 = 30\,\mathrm{mm}$, $h_2 = 10\,\mathrm{mm}$, $\varphi_p = 33^\circ$, and $\varphi_t = 48^\circ$, the minimum radius of the drum is, on average, equal to 100 mm.

Considering the results of preliminary studies, which show that the depth of cotton row furrows varies in the range of 12.5–17.0 cm with an average value of 15 cm, the maximum radius of the drum is taken as 400 mm. The working width of the drum must be smaller than the inter-row spacing of cotton. Considering that a protective zone of 15 cm is recommended on both the left and right sides for cotton inter-rows of 90 cm, 76 cm, and 60 cm, the working width of the drum is recommended to be 60 cm for 90 cm row spacing, 46 cm for 76 cm row spacing, and 30 cm for 60 cm row spacing. Previous experimental studies have shown that due to low soil moisture, the inter-row area after cultivation with a cultivator before winter wheat sowing contains a significant amount of large soil clods (greater than 50 mm in size) (Fig. 3).

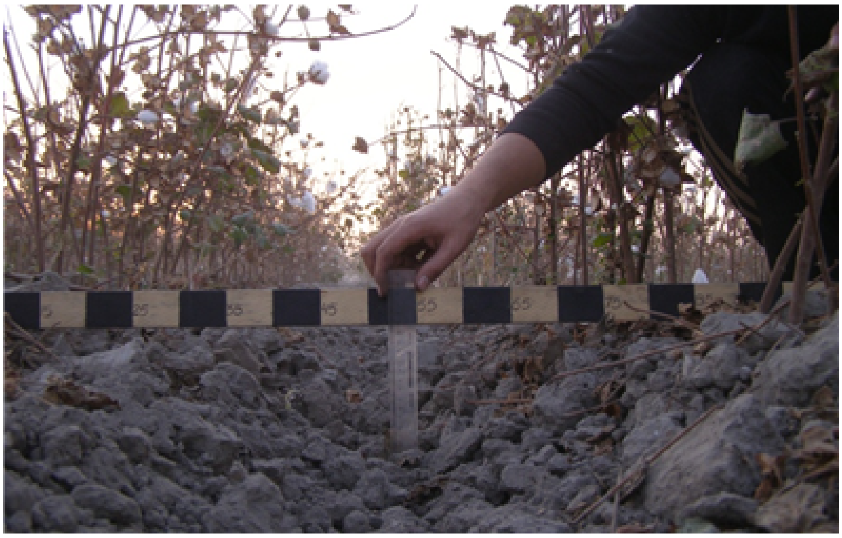

Figure 3. Composition of large clods in cotton inter-row soil after cultivation with a cotton cultivator

The main parameters of the drum blades that enable sliding cutting and crushing of soil clods are blade height, sharpening angle, and sliding angle. The drum must cut and crush soil clods, form the furrow between cotton rows, and operate smoothly without forming soil accumulation in front of it. The blade parameters must ensure that, upon contact with soil clods, the clods are crushed, cut through sliding action, and fragmented, while also preventing the drum from slipping or becoming unstable. If these conditions are satisfied, an increase in the pressure exerted by the blades on the soil clods is achieved, resulting in more effective fragmentation of the clods. Analytical studies confirm that sliding cutting with blades ensures better cutting quality, lower deformation of the material, and a cleaner cutting surface [13,14]. The reasons for this are as follows: first, in sliding cutting, the tool acts on a very small and limited contact area with the soil clod, resulting in a scissor-like (sawing) fracture mechanism; second, during sliding cutting, the blade penetrates the material with a transformed cutting angle 2 which is smaller than the actual sharpening angle 2 third, due to the reduced effective cutting length of the blade, the cutting resistance decreases significantly. During the sliding cutting process, the sharpening angle of the blade changes relative to the cutting direction, i.e., the inclination (sliding angle) varies. The transformed angle 2 is related to the sharpening angle 2 and the cutting angle t of the blade [15].

$$\operatorname{tg} 2\beta' = \operatorname{tg} 2\beta \cdot \cos \alpha_m. \tag{6}$$

$$\cos \alpha_m = \frac{1}{\sqrt{1+k^2}} = \frac{S_n}{\sqrt{S_n^2 + S_t^2}} = \frac{V_n}{\sqrt{V_n^2 + V_t^2}}. \tag{7}$$

By substituting expression (7) into expression (6), three formulas are obtained that determine the kinematic transformation of the sharpness angle of a knife with a straight edge:

$$\operatorname{tg} 2\beta' = \frac{\operatorname{tg} 2\beta}{\sqrt{1+k^2}}; \qquad \operatorname{tg} 2\beta' = \frac{S_n}{\sqrt{S_n^2 + S_t^2}} \operatorname{tg} 2\beta; \qquad \operatorname{tg} 2\beta' = \frac{V_n}{\sqrt{V_n^2 + V_t^2}} \operatorname{tg} 2\beta. \tag{8}$$

For each specific case, one of the provided formulas may prove advantageous for calculating the impact on the transformation of the sharpening angle or for establishing the physical relationship between the involved quantities . According to expression (4), the kinematic transformation of the knife's sharpening angle is closely related to the coefficient of friction. A knife set at an angle for helical cutting also provides a certain coefficient of friction in practice. In the case of sliding cutting, there is no chip sliding, meaning that no support is required against cutting. This is because the normal pressure at this contact point does not reach a significantly high value, and the chip is cut due to the combined effects of the advancement of the aggregate and the rotational motion of the roller. The absolute motion of the knife edge consists of rotational motion around the O axis and the translational motion of the aggregate (see Figure 4).

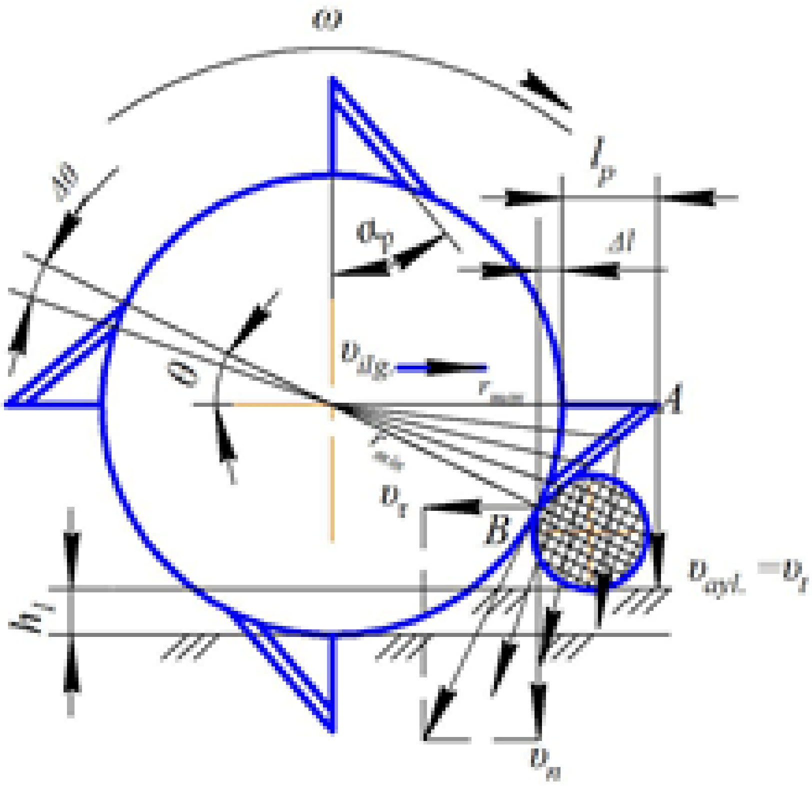

Figure 4. The interaction process of a cylindrical pin with a cut

For point B, the tangential velocity of the knife edge is equal to the circumferential velocity at that point, i.e.,

$$v_t = v_{\text{circ.}} = \omega r_{\min}. \tag{9}$$

In this case, $r_{\min}$ is the radius from the O axis of the roller to the outermost cutting point of the knife, in meters.

The working motion consists of the radial penetration of the chip and the rotational motion of the knife together with the roller (see Figure 4).

When the knife fixed to the roller interacts with the chip at contact point B, the circumferential velocity is given by

$$v_{\text{circ.}} = \omega r_{\min}. \tag{10}$$

When the knife mounted on the roller is twisted by an angle $\Delta\theta$ at the contact point B with the chip, a distance Δl is traversed. For this case, the circumferential velocity is

$$v_{\text{circ.}} = \omega(r_{\min} + \Delta l). \tag{11}$$

The value of Δl is related to the angle $\Delta\theta$, and the time for the roller to rotate by an angle $\Delta\theta$ is determined as follows:

$$\Delta t = \frac{\Delta\theta}{\omega}. \quad (12)$$

During the specified time, the minimum radius r_{min} increases as the roller interacts with the chip over a distance Δl with the knife. Subsequently, the cutting process continues until point A. In this case, at each Δl step point, the direction and magnitude of the rotational velocity $v_{\text{circ.}}$ change continuously. Because the rotational velocity changes with each $\Delta\theta$ angular rotation as the step Δl and the radius increases toward r_{max}, the value of the rotational velocity at point A is equal to the following:

$$v_{\text{circ.}} = V_t = \omega r_{\text{max}}. \quad (13)$$

In this case, r_{max} is the distance from the rotation center O of the roller to the outermost point of the blade edge, in mm.

In accordance with expression (6), the transformation of the blade sharpening angle takes the following form:

$$2\beta' = \frac{2\beta}{\sqrt{1 + \left[\frac{(\omega r_{\text{min}} + v_n \Delta\theta)\cos\Delta\theta}{v_n}\right]^2}}. \quad (14)$$

The value of Θ, when it represents the sharpening angle $2\beta = 0$, can be justified by determining the side of the triangle that is equal to the length of the blade.

$$l = \sqrt{r_{\text{max}}^2 + r_{\text{min}}^2 - 2\, r_{\text{max}} r_{\text{min}} \cos\theta}. \quad (15)$$

As noted above, in sliding cutting the quality of cutting the lump improves; that is, the lump undergoes less deformation, and the blade edge acts on a very small, limited contact area. In this case, we assume that the blade height l_p affects the initial contact area, leading to the fracture of the lump. This is because, due to the low moisture content of the lump, it deforms less and has a higher probability of cracking under the initial contact pressure. Taking this into account, the contact area where the blade edge acts on the lump is highly effective under high pressure in the initial stages, while in the subsequent stages the blade slides and cuts through the already fractured material. When the blade approaches an angle θ from the contact point B with the lump, the lump becomes fractured before reaching the contact point A (Fig. 4). In the subsequent phases near point A, the reduction of the friction coefficient from 30° to 0° reduces the transformation of the sharpening angle, and the angle approaches the limiting angle (Fig. 4). In this situation, for sliding cutting, the cutting resistance can be reduced by assuming a smaller effective blade length. Since the lump has already been fractured in this stage, the blade–material interaction is weak, and therefore the cutting resistance is low. In the sliding cutting process, in the initial stage the lump is fractured under high pressure, while in the subsequent stages the blade cuts through it by sliding. This condition leads to a reduction in the contact area and a decrease in cutting resistance.

Discussion:

The research results showed the following:

Cutting quality improves significantly during sliding cutting;

Clod (soil aggregate) deformation decreases, resulting in lower energy consumption;

Due to the smaller contact area, contact pressure increases, promoting more efficient material fracture;

The transformation of the blade sharpening (rake) angle optimizes the cutting process;

An increase in the roller radius changes the circumferential velocity and affects the cutting dynamics.

Based on the theoretical analysis, the following optimal parameters are recommended:

The blade sharpening angle: $2\beta = 30°$;

Average clod diameter: 50 mm;

Minimum roller diameter: $d_{\text{min}} = 100$ mm;

Maximum roller diameter: $D_{\max} = 400\,\mathrm{mm}$;
Forward speed of the implement: $2.5\,\mathrm{m\,s^{-1}}$;
Blade height: $l_p = 80\,\mathrm{mm}$.

These parameters make it possible to reduce cutting resistance and improve the operational efficiency of the machine.

To verify the theoretical results and validate the proposed design parameters, a special field experimental setup was developed (Fig. 5).

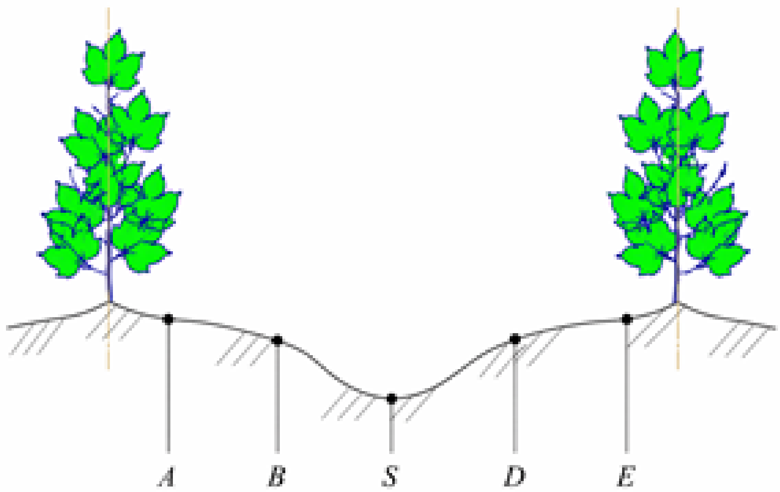

Figure 5. Scheme of a special field experiment for investigating inter-row soil along longitudinal sections

For this purpose, cross-sectional measurements were taken along the central, left, and right parts of the cotton inter-row furrow (sections A, B, S, D, and E). The amount of clods larger than 50 mm was determined, and the measurement accuracy was ±0.5 cm. The obtained data were processed using methods of mathematical statistics, and the mean value M_{mean} and standard deviation $\pm\sigma$ were determined (Fig. 6).

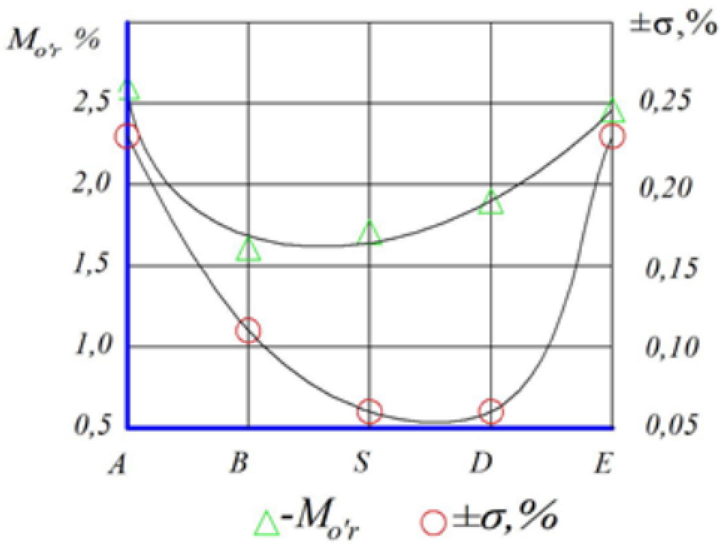

Figure 6. Graphs of variation of the amount of clods larger than 50 mm (M$_{m}ean)andtheirstandarddeviation(\pm\sigma$) along longitudinal sections of the inter-row).

The research results showed that the occurrence of large clods varied in both the transverse and longitudinal sections of the cotton inter-row profile. The amount of clods larger than 50 mm was highest in sections A and E and lower in the central section S, indicating differences in soil fragmentation efficiency across the working width. The experimental results confirmed the theoretical assumptions regarding the effectiveness of the sliding cutting mechanism for soil clod fragmentation. The distribution of clods larger than 50 mm along the longitudinal sections of the cotton inter-row showed that the central section (S) contained a lower percentage of large clods compared with the edge sections (A and E). This indicates that the blade-roller system provided more intensive soil fragmentation in the central working zone.

The observed tendency can be explained by the kinematic characteristics of the proposed blade-roller mechanism. During operation, the cutting edge simultaneously performs rotational and translational motion, creating a tangential velocity component along the cutting direction. As demonstrated in the theoretical analysis, such a motion transforms the cutting process from predominantly compressive loading to shear-dominated fracture. As a result, stress concentration near the cutting edge increases, facilitating crack initiation and propagation in brittle, low-moisture soil aggregates. Consequently, soil clods are fragmented with lower resistance and reduced energy consumption.

Another important factor influencing the process is the kinematic transformation of the blade sharpening angle. The analytical model showed that under sliding cutting conditions the effective sharpening angle becomes smaller than the geometric sharpening angle. This effect improves penetration of the blade into the soil clod and decreases the effective contact area between the blade and the material. Similar conclusions have been reported in studies devoted to sliding and oblique cutting processes, where reduced contact area and increased shear stress resulted in lower cutting forces and improved fragmentation efficiency [5, 8, 12].

The field experiment further demonstrated that the variability of clod distribution was lowest in the central section of the inter-row, where the standard deviation reached minimum values. This indicates a more stable fragmentation process and confirms the adequacy of the selected geometric and kinematic parameters. The increased amount of large clods observed in the edge zones can be attributed to reduced interaction intensity between the blades and the soil in areas adjacent to the crop protection zone.

The recommended parameters of the blade-roller system (blade sharpening angle $2\beta = 30^\circ$, minimum roller diameter $d_{\min} = 100$ mm, maximum roller diameter $D_{\max} = 400$ mm, blade height $l_p = 80$ mm, and forward speed $v = 2.5$ m/s) provided favorable cutting conditions and ensured effective soil fragmentation. The obtained results indicate that proper coordination of blade geometry and roller kinematics significantly enhances the performance of the soil-crushing process while reducing cutting resistance.

Conclusions

This study shows that slip cutting is an effective method for breaking up low-moisture, brittle soil particles in agricultural tillage processes. The integration of tangential and rotational motion significantly improves the cutting efficiency by strengthening the shear-dominated fractures and reducing the cutting resistance.

The analysis confirms that the kinematic change of the blade sharpening angle and the change of the cutting radius play an important role in determining the stress distribution and contact conditions during cutting. The proper coordination of these factors enhances the formation and propagation of cracks, resulting in improved quality of cutting and reduced energy consumption.

The optimal values of the blade-roller system parameters, including blade angle, roller diameter, blade height and forward speed, were determined. These parameters ensure efficient operation, low mechanical resistance and stable operation under operating conditions.

Overall, the findings provide a theoretical basis for the design and optimization of energy-efficient soil tillage tools.

Authors' contribution

Conceptualization, A. Igamberdiyev and G. Usmanova; methodology, A. Igamberdiyev and G. Usmanova; software, S. Saidov; validation, A. Igamberdiyev, G. Usmanova and S. Saidov; formal analysis, A. Igamberdiyev; investigation, G. Usmanova and S. Saidov; resources, A. Igamberdiyev; data curation, G. Usmanova; writing original draft preparation, G. Usmanova; writing review and editing, A. Igamberdiyev; visualization, S. Saidov; supervision, A. Igamberdiyev; project administration, A. Igamberdiyev. All authors have read and agreed to the published version of the manuscript.

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Ethics approval

Not applicable.

Consent for publication.

Not applicable.

Data Availability Statement

Not applicable.

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Conflict of interest

The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

UDC	WUniversal Decimal Classification
SD	DStandard Deviation
D_{max}	Maximum drum diameter
d_{min}	LMinimum drum diameter

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