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Design and parametric optimization of a deep-loosening cultivator working body for cotton inter-row tillage

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ABSTRACT

Efficient soil tillage is essential for sustainable cotton production and resource-saving agriculture. Conventional inter-row cultivation requires multiple passes, leading to increased fuel consumption, soil compaction, and operational costs. This study presents the design, analytical modeling, and experimental optimization of a deep-loosening working body integrated into an inter-row cultivator for cotton cultivation. The proposed tool improves soil aeration, water infiltration, and root development while reducing energy consumption. Mathematical models were developed to determine optimal tool geometry considering soil mechanical properties, plant root protection zones, and operational parameters. Experimental investigations evaluated the effects of working width, penetration angle, and tool length on soil fragmentation, loosened layer width, and draft resistance. Regression models were established to determine optimal parameter combinations ensuring maximum agro-technical performance with minimal energy consumption. Field tests confirmed reliable operation and compliance with agronomic requirements. The developed cultivator reduced labor costs by 51% and operational expenses by 32%, while improving soil structure and moisture retention. The proposed design contributes to sustainable and energy-efficient cotton production systems.

Keywords: Cotton cultivation, Deep loosening, Inter-row tillage, Energy-efficient machinery, Soil aeration, Sustainable agriculture.
Article type: Research Article.

INTRODUCTION

Sustainable agricultural production increasingly depends on technologies that improve soil health while minimizing energy consumption and environmental impact. Population growth, climate variability, and land degradation have intensified the need for resource-efficient farming practices worldwide. Soil compaction, declining organic matter, and reduced water infiltration are among the major constraints limiting crop productivity and long-term soil sustainability. Consequently, modern agricultural engineering emphasizes conservation-oriented tillage technologies that enhance soil structure while reducing energy inputs and ecological disturbance. Cotton is cultivated on millions of hectares globally and remains a strategic industrial crop in many regions. Optimal soil conditions are essential for cotton growth, particularly during early vegetative development and root system formation. Adequate soil aeration, moisture retention, and nutrient availability directly influence plant health and yield potential. However, intensive mechanization and repeated shallow tillage often lead to the

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formation of compacted subsurface layers that restrict root penetration, reduce water infiltration, and impair soil respiration (Zhang *et al.* 2022; Li *et al.* 2023; Wang *et al.* 2023). Inter-row tillage is a key agronomic operation in cotton production systems, contributing to weed control, soil aeration, moisture conservation, and nutrient availability. Conventional inter-row cultivation typically requires separate passes for shallow cultivation and deep loosening. While shallow cultivation disrupts surface crust and controls weeds, deep loosening is necessary to break compacted soil layers and improve subsoil permeability. Performing these operations separately increases fuel consumption, soil compaction from repeated machinery traffic, greenhouse gas emissions, labor demand, and production costs. In addition, multiple passes may disturb soil structure and accelerate moisture loss, particularly in arid and semi-arid environments. Deep loosening plays an essential role in improving soil physical properties by disrupting compacted layers, enhancing porosity, improving water infiltration, and promoting deeper root penetration. Improved soil structure also stimulates microbial activity and supports long-term soil fertility. However, conventional subsoilers are primarily designed for pre-plant operations and cannot safely operate between crop rows during the growing season, as they may damage roots and destabilize plants (Battiato & Diserens 2022; Spoor & Tijink 2022; Khodjayeva *et al.* 2025). Recent studies have focused on optimizing soil-engaging tool geometry, reducing draft resistance, improving soil fragmentation, and enhancing energy efficiency. Advances in conservation tillage and precision agriculture emphasize minimizing soil disturbance while maintaining agronomic effectiveness. Nevertheless, integrated cultivator systems capable of simultaneously performing inter-row cultivation and deep loosening in a single pass remain insufficiently investigated. Therefore, the development of a deep-loosening working body capable of safe inter-row operation represents both a scientific and practical challenge. Such a system must ensure effective subsoil loosening, protect crop roots, minimize draft resistance, and reduce energy consumption while meeting agronomic requirements. This study aims to design and optimize a deep-loosening working body integrated into an inter-row cultivator to improve soil physical properties, enhance root development, and reduce energy consumption and operational costs. The proposed solution contributes to sustainable cotton production by improving soil structure, increasing resource-use efficiency, and supporting environmentally responsible agricultural practices.

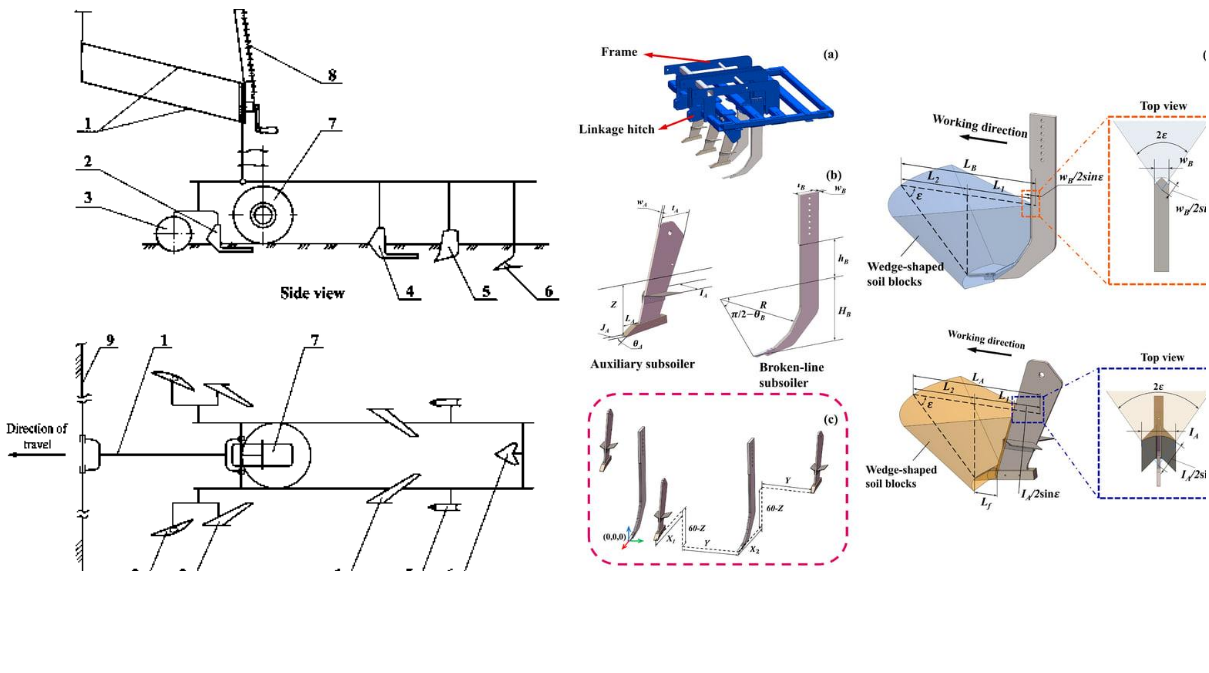
Literature review

Soil tillage technologies play a vital role in maintaining soil structure, improving water infiltration, and ensuring favorable conditions for root development. In recent years, sustainable soil management has become a global priority due to soil degradation, climate change, and the need to reduce energy consumption in agricultural production systems (Abrorov 2019; Keesstra *et al.* 2021; Jabro *et al.* 2022; Faizrakhmanova *et al.* 2025; Mohammad *et al.* 2026). Deep tillage and subsoiling are widely recognized as effective methods for alleviating soil compaction and improving soil physical properties. Recent studies indicate that breaking compacted subsurface layers enhances root penetration, increases oxygen diffusion, and improves water movement within the soil profile, ultimately contributing to improved crop productivity and resilience under water stress conditions (Colombi & Keller, 2019; Keller *et al.* 2019). Soil-tool interaction remains a key factor influencing tillage efficiency and energy consumption. Modern research highlights that tool geometry, rake angle, and operating depth strongly affect soil fracture mechanisms and draft requirements (Ucgul *et al.* 2018). Numerical modeling and discrete element methods have increasingly been used to study soil disturbance patterns and optimize tillage tool design (Zhang *et al.* 2020). Energy-efficient tillage systems have gained significant attention due to rising fuel costs and environmental concerns. Conservation and reduced tillage practices aim to minimize soil disturbance while maintaining productivity (Lal 2020). Optimized tool geometry and reduced draft resistance have been shown to significantly decrease fuel consumption and greenhouse gas emissions during field operations (Hanna *et al.* 2020). Inter-row cultivation is essential in row crop production systems such as cotton, maize, and soybean. Modern inter-row cultivators improve weed control, soil aeration, and moisture conservation; however, most conventional designs focus on shallow soil disturbance and do not address subsoil compaction (Tullberg *et al.* 2018). To improve soil structure and operational efficiency, researchers have investigated strip-tillage and zone tillage technologies. These systems loosen soil in targeted zones, improving root growth and water infiltration while reducing field passes and soil disturbance (Reicosky & Allmaras 2020). Nevertheless, their adoption is often constrained by high machinery complexity and limited adaptability to different field conditions (Al-Suhaibani & Ghaly 2021; Martínez *et al.* 2022; Gao *et al.* 2023). Recent studies have also examined the optimization of subsoiler shank geometry to improve soil disturbance efficiency and reduce draft force. Narrow shank designs and modified tool angles have been shown to decrease energy requirements while maintaining effective loosening

(Abo-Elnor *et al.* 2021). Similarly, field experiments demonstrate that optimized penetration angles can improve soil fragmentation and reduce power demand (Tagar *et al.* 2020). Despite these advancements, the application of deep loosening during the growing season remains limited due to the risk of root damage and crop instability. Existing subsoilers are primarily designed for pre-plant operations and are unsuitable for safe inter-row use in standing crops. Moreover, research addressing the combined effects of tool geometry, penetration angle, working width, and operational speed on soil fragmentation and energy efficiency under inter-row conditions remains insufficient (Baskar *et al.* 2025; Fakhriddin *et al.* 2025; Mamadiyarov *et al.* 2026). Therefore, the development of an optimized deep-loosening working body specifically designed for inter-row cultivation represents an important research direction. Such a system must ensure effective loosening, protect crop roots, minimize energy consumption, and improve soil physical properties. Addressing these challenges will contribute to sustainable agricultural mechanization and resource-efficient cotton production systems.

MATERIALS AND METHODS

Designing concept and structural configuration. The developed cultivator integrates shallow inter-row cultivation with deep loosening, enabling simultaneous surface soil treatment and subsoil loosening within a single field pass. This combined operation eliminates the need for multiple tillage passes, thereby reducing fuel consumption, minimizing soil compaction caused by repeated machinery traffic, and improving overall field efficiency. The design concept is grounded in agronomic requirements for cotton cultivation, ensuring effective weed control, soil aeration, and moisture conservation while maintaining the structural stability of crop rows. Particular attention was given to soil mechanical properties, including soil density, moisture content, and resistance to deformation, to ensure efficient soil fracture and reduced draft resistance. The working body geometry and placement were optimized to promote soil loosening beneath the root zone without disturbing plant anchorage. In addition, the configuration was designed to protect the crop root system by maintaining a safe protective zone, preventing root damage during operation. By integrating shallow cultivation and deep loosening functions into a single implement, the developed cultivator improves soil structure, enhances water infiltration, and promotes deeper root penetration. This integrated approach contributes to improved crop growth conditions while supporting energy-efficient and resource-saving agricultural practices.



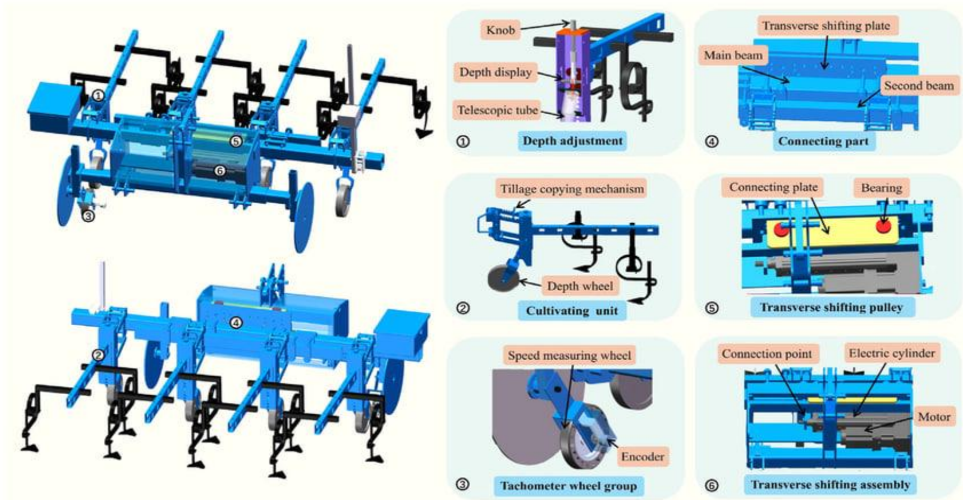


Fig. 1. Structural scheme and operating principle of the deep-loosening working body.

Determination of protective zone width

During inter-row tillage operations performed in the growing season, protecting the crop root system from mechanical damage is a critical agronomic requirement. Cotton plants develop a branched root system that extends laterally into the inter-row space as the plant matures. If tillage tools operate too close to the crop row, root injury may occur, leading to reduced nutrient uptake, plant instability, and potential yield loss. Therefore, determining an appropriate protective zone between the working body and the crop row is essential for safe and effective operation. The protective zone width was established based on the spatial distribution of cotton roots, crop row spacing, and the working geometry of the deep-loosening tool. Field observations and agronomic recommendations indicate that the active root zone expands laterally as plant growth progresses, requiring sufficient clearance to prevent mechanical disturbance.

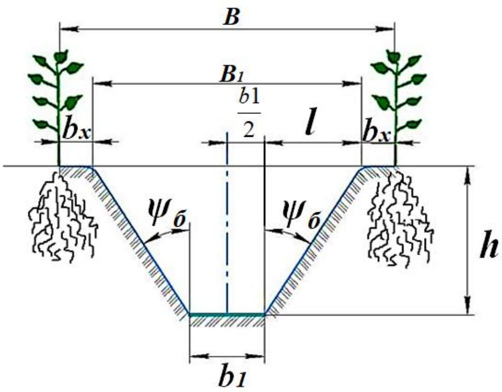


Fig. 2. Diagram for determining the width of the working body's protection zone.

For cotton row spacing of 90 cm, the protective distance from the crop row to the working body was determined using geometric considerations and root safety requirements:

$$B_1 = B - 2b_x,$$

where b_x represents the protective distance from the crop row centerline to the nearest edge of the working body. This protective zone ensures that the deep-loosening tool operates outside the primary root concentration area while still effectively loosening the inter-row soil. Maintaining this clearance prevents root pruning and preserves plant stability, particularly during later growth stages when root systems are fully developed. At the same time, the selected protective width allows the tool to loosen the maximum possible soil volume within the inter-row space, improving soil aeration, moisture infiltration, and root zone development. Thus, the adopted protective zone width represents an optimal balance between agronomic safety and soil loosening efficiency. Accordingly, under a row spacing of 90 cm, the maximum effective loosening width was established within the range of 60–66 cm. This value was determined based on the biological characteristics of cotton root system development and the required protective zone necessary to prevent mechanical damage to plant roots during inter-row cultivation (Khudoyberdiev & Kholdarov 2022; Kholdarov 2025).

Determination of optimal loosening depth

The limiting depth of deep loosening is governed by soil mechanical properties and the geometric configuration of the working body. Soil resistance to deformation, bulk density, moisture content, and the presence of compacted subsurface layers significantly influence the depth at which effective soil fracture can be achieved. In many intensively cultivated fields, repeated machinery traffic and shallow tillage operations lead to the formation of a compacted layer that restricts root penetration and impedes water infiltration. The optimal loosening depth was determined considering row spacing, protective zone width, and furrow geometry to ensure effective soil loosening while preventing root damage.

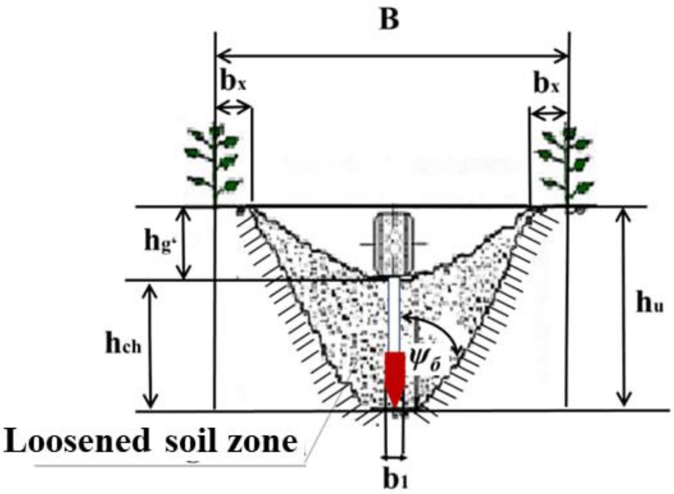


Fig. 3. Scheme for determining the optimal depth of deep loosening in cotton inter-row spacing.

where:

B — row spacing;

$\mathbf{b_x}$ — protective zone width;

$\mathbf{b_1}$ — working body width;

$\mathbf{h_u}$ — working depth;

$\mathbf{h_{g'}}$ — furrow depth;

$\mathbf{h_{(ch)}}$ — loosening depth relative to the furrow bottom.

Fig. 3 illustrates the geometric relationships used to determine the optimal depth of deep loosening within cotton inter-row spacing. The scheme considers row spacing, protective zones, and furrow geometry to ensure effective subsoil loosening while preventing damage to the crop root system. The working depth is defined relative to the furrow bottom to maintain stable tool operation and safe root protection.

To determine the depth at which effective soil failure occurs, an analytical model describing soil–tool interaction was employed. The limiting loosening depth was calculated using the following relationship:

$$h_{ch} = \frac{b_1 \cdot \left[0{,}1 \frac{\sigma_э}{\tau_к} \left(1 + 3 \cdot tg\psi_б\right) - n \right]}{m + ctg\alpha},$$

where:

b_1 — working body width (m);

σ_e — soil compressive strength (Pa);

τ_k — critical shear stress of soil (Pa);

ψ_b — soil internal friction angle (°);
α— installation angle of the working body (°);
n,m — coefficients depending on soil physical-mechanical properties.

Substituting soil parameters obtained under field conditions into the model yielded an optimal loosening depth in the range of 30–35 cm (Khudoyberdiev & Kholdarov 2022; Kholdarov 2025). At this depth, the compacted subsurface layer is effectively disrupted, improving soil porosity and facilitating air–water exchange within the root zone. Enhanced aeration promotes oxygen diffusion and stimulates beneficial microbial activity, while improved permeability allows deeper water infiltration and reduces surface runoff. Furthermore, loosening to a depth of 30–35 cm promotes deeper root penetration, enabling plants to access moisture and nutrients from lower soil horizons. This is particularly important under arid and semi-arid conditions, where deeper rooting improves drought tolerance and crop resilience. The selected depth also represents an optimal balance between agronomic effectiveness and energy efficiency. Increasing the loosening depth beyond this range would significantly increase draft resistance and fuel consumption without providing proportional agronomic benefits. Therefore, the adopted depth ensures effective soil structure improvement while maintaining energy-efficient operation.

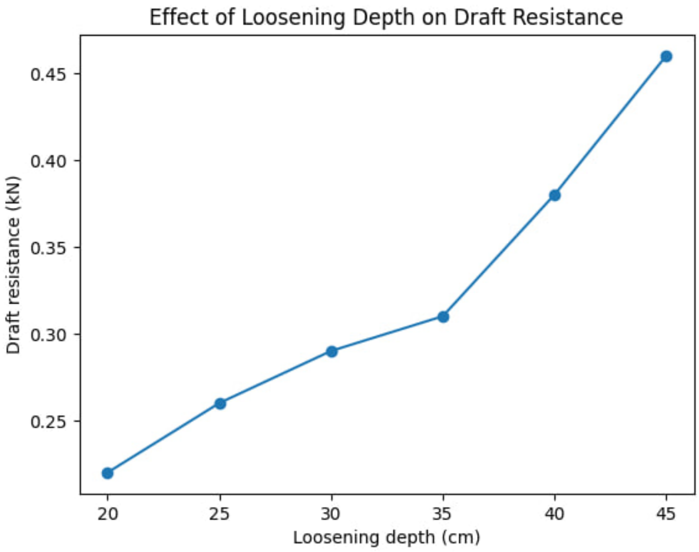


Fig. 4. Relationship between loosening depth and draft resistance.

The graph demonstrates that draft resistance increases by elevating loosening depth. The range of 30–35 cm represents an optimal operational zone where effective soil loosening is achieved without excessive energy consumption.

Working body geometric parameters

The performance of the deep-loosening working body is strongly influenced by its geometric configuration, which determines soil fracture behavior, draft resistance, and the overall quality of soil loosening. The primary parameters affecting tool performance include the installation angle (α), working width (b_1), working surface length (l_u), and sharpening angle (βc). These parameters govern the interaction between the working body and soil, influencing soil disturbance patterns, resistance forces, and energy consumption during operation. (Kholdarov 2025). The installation angle (α) affects the direction and magnitude of soil displacement as well as the penetration ability of the tool. Proper selection of this angle ensures stable soil entry and efficient loosening while minimizing soil compaction and resistance forces. The working width (b_1) determines the volume of soil disturbed during operation. A wider working body increases the loosened soil zone but also raises draft resistance and energy demand. Based on analytical calculations and experimental observations, the optimal working width was determined to be 4–6 cm, providing effective soil loosening while maintaining acceptable energy requirements. The working surface length (l_u) influences the duration of soil–tool interaction and the degree of soil fragmentation. Insufficient length results in incomplete soil fracture, whereas excessive length increases resistance and fuel consumption. Geometric analysis established an optimal working length of approximately 12.3 cm, ensuring adequate soil disruption with minimal energy loss. The sharpening angle (βc) plays a critical role in soil penetration and soil flow along the working surface. An appropriately selected sharpening angle reduces soil adhesion, prevents clogging, and lowers draft resistance. Experimental evaluation indicated that a sharpening angle within the range of 27°–33° provides optimal penetration efficiency and stable soil flow under typical field conditions. (Kholdarov 2025). Together, these optimized geometric parameters ensure efficient soil fracture, reduced draft resistance, and energy-efficient operation while maintaining agronomic safety and soil structure integrity.

Draft resistance modeling

Draft resistance is a key performance indicator that determines the power requirement and energy efficiency of tillage implements. It is influenced by several interacting factors, including soil bulk density, moisture content, tool geometry, operating depth, and forward speed. Denser soils and lower moisture content increase soil strength and resistance to deformation, resulting in higher draft forces. Similarly, greater working depths and larger volumes of disturbed soil increase resistance due to intensified soil–tool interaction. Tool geometry plays a significant role in draft force formation. Parameters such as working width, penetration angle, and sharpening angle affect soil failure patterns and soil flow along the working surface. Proper optimization of these parameters reduces soil adhesion and promotes smooth soil movement, thereby lowering resistance and energy demand.

Based on soil–tool interaction theory and the geometric configuration of the working body, draft resistance was analytically determined using the following relationship:

$$R = \kappa_1 \cdot T \cdot t_T \cdot b_T + \left(b_1 \cdot h_{ch} + h_{ch}^2 tg\psi_б\right) \cdot \left\{ \frac{[\tau_\kappa] \cdot \left[\sin\frac{1}{2}(\alpha + \varphi_1 + \varphi_2) + f\cos\frac{1}{2}(\alpha - \varphi_1 - \varphi_2)\right]}{\cos\frac{1}{2}(\alpha + \varphi_1 + \varphi_2)} + \right.$$

$$+ \rho \cdot \left(1 + \frac{W}{100}\right) \cdot \left(g \cdot h_{ch} \frac{f \cdot tg(\alpha + \varphi_1)}{\sin\alpha} \cdot + 2 \cdot \frac{V_a^2 \sin\alpha \cdot \sin(\alpha + \varphi_1)}{\cos\varphi_1}\right) +$$

$$+ \left(h_{ch} - l_u \sin\alpha\right) \cdot \left[q_0 \cdot t_y \cdot (l_u + f \cdot ctg\gamma) + f \cdot q_e \cdot (2 \cdot b_y - t_y \cdot ctg\gamma)\right]$$

where:

k_1 — shape factor of the soil surface interacting with the working body;
T — soil hardness (Pa);
t_t — thickness of the working body blade (m);
b_t — blade width (m), where $b_T = b_1$;
f — coefficient of friction between the soil and tool surface;
ρ — soil bulk density (1370 kg m^{-3});
W — soil moisture content (W = 16%);
V_a — forward operating speed of the aggregate (m s^{-1});
$h_{(ch)}$ — depth of loosening (m);
l_u — length of the working body (m);
q_0, q_e — specific soil pressure acting on the front and side surfaces of the shank (Pa);
t_γ — thickness of the shank (m);
b_γ — width of the shank (m).

The parameters represent the mechanical properties of the soil, geometric characteristics of the working body, soil–tool friction conditions, and operating variables that collectively influence the resistance forces generated during the soil loosening process (Khudoyberdiev & Kholdarov 2022; Kholdarov 2025). Using soil physical properties and operating conditions obtained from field measurements, the calculated draft resistance of the developed deep-loosening working body averaged:

$R = 0.289 kN$

This relatively low draft requirement indicates efficient soil fracture and reduced resistance during operation. The primary factors influencing draft resistance are illustrated in Fig. 5, which demonstrates how soil properties, tool geometry, operating depth, and forward speed collectively determine resistance forces acting on the working body.

Lower draft resistance directly contributes to reduced fuel consumption, decreased tractor load, and improved operational efficiency. Furthermore, reduced energy demand minimizes machinery wear and lowers greenhouse gas emissions associated with fuel use. Overall, the obtained draft resistance value confirms that the optimized working body geometry ensures effective soil loosening while maintaining energy-efficient operation. The analytical model adequately describes resistance forces and aligns with experimental observations under field conditions (Bae *et al.* 2023).

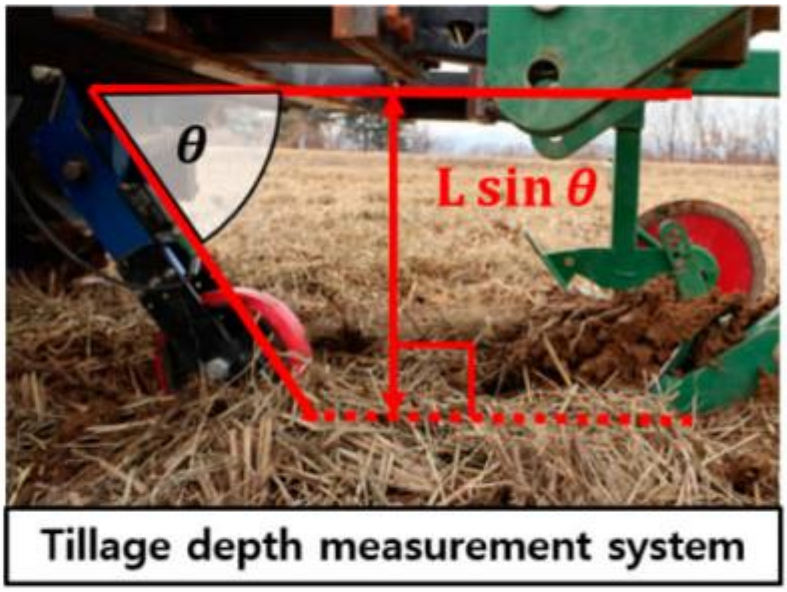


Fig. 5. Geometric principle for determining tillage depth based on the tool position angle ($d = L\sin\theta$).

The geometric principle used to determine tillage depth is illustrated in Fig. 5, where the effective depth is calculated as $d = L\sin\theta$.

Experimental methodology

Field and laboratory experiments were conducted to evaluate the performance of the developed deep-loosening working body under representative soil and operating conditions. The experimental study aimed to determine the influence of geometric and operational parameters on soil disturbance quality and energy requirements.

Performance evaluation focused on three primary indicators:

soil fragmentation quality, which reflects the degree of soil crumbling and suitability for root development;

loosened layer width, indicating the effective soil disturbance zone created by the working body;

draft resistance, representing the force required to pull the tool and a key indicator of energy consumption.

Field experiments were carried out under typical agricultural soil conditions, while controlled laboratory tests were used to ensure measurement accuracy and repeatability. Soil moisture and density were monitored to maintain consistent testing conditions.

To evaluate the influence of tool geometry and operating conditions, the following variables were systematically varied:

penetration angle: 25°–40°

(to determine its effect on soil fracture patterns and resistance forces);

working width variations

(to assess the relationship between soil disturbance volume and draft resistance);

working surface length variations

(to evaluate soil–tool interaction duration and fragmentation efficiency);

forward operating speed: 6–8 km h^{-1}

(representing typical field operating conditions and their effect on soil disturbance and resistance).

Measurements were recorded using standard soil testing methods and field instrumentation. Each experimental condition was repeated to ensure reliability and minimize random error. Statistical analysis of the experimental data included regression modeling to determine relationships between parameters and performance indicators, analysis of variance (ANOVA) to evaluate factor significance, and adequacy testing to verify model reliability.

The statistical significance of the results was evaluated at a confidence level of $p < 0.05$. This methodology ensured reliable evaluation of the working body performance and enabled identification of optimal parameter ranges for efficient soil loosening and reduced energy consumption.

RESULTS AND DISCUSSION

Effect of working width. The working width of the deep-loosening working body significantly influences soil disturbance characteristics and energy requirements. Experimental results showed that increasing the working width resulted in a corresponding increase in the width of the loosened soil layer. This occurs because a wider tool engages a larger soil volume, producing greater lateral soil displacement and expanding the disturbed zone within the inter-row space. An increase in the loosened layer width improves soil aeration, enhances moisture infiltration, and promotes better root development by enlarging the effective soil treatment zone. From an agronomic perspective, a wider disturbed zone can improve soil structure and reduce surface crust formation. However, increasing the working width also led to a noticeable rise in draft resistance. This is attributed to the greater soil mass being displaced and the increased soil–tool contact area, which intensifies frictional forces and resistance to deformation. As the working width increases, the energy required to overcome soil resistance also rises, resulting in higher fuel consumption and tractor load. The experimental observations indicate that excessively large working widths do not proportionally improve soil loosening effectiveness but significantly increase energy demand. Therefore, an optimal working width must balance soil disturbance efficiency with energy consumption. Within the tested range, the working width of 4–6 cm provided the most favorable balance, ensuring sufficient soil loosening while maintaining moderate draft resistance and energy-efficient operation. These findings confirm that proper selection of working width is essential for achieving effective soil disturbance, reduced energy consumption, and improved operational efficiency in inter-row deep loosening.

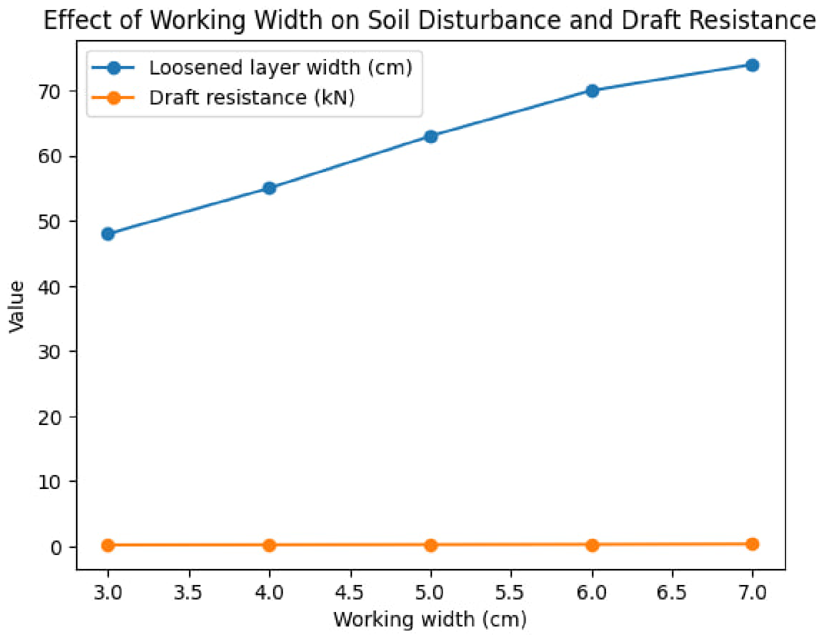


Fig. 6. Effect of working width on loosened layer width and draft resistance.

Fig. 6 illustrates the relationship between working width and both the loosened layer width and draft resistance. As the working width increases, the width of the disturbed soil zone expands due to greater soil displacement. At the same time, draft resistance increases because of the larger soil volume engaged and the increased soil–tool contact area. The results indicate that although increasing working width improves soil disturbance, excessive width significantly upraises energy demand. The optimal working width range of 4–6 cm provides an effective balance between soil loosening efficiency and draft resistance.

Effect of penetration angle

The penetration angle of the working body significantly influences soil fracture patterns, loosening efficiency, and draft resistance. Experimental results showed that soil fragmentation improved as the penetration angle increased from 25° to approximately 35°. Within this range, the tool effectively penetrated the soil and generated favorable soil failure patterns, resulting in improved crumbling and loosening quality. As the penetration angle increased, the soil experienced enhanced shear deformation, which promoted the formation of stable fracture planes and improved soil breakup. This contributed to better aeration and improved soil structure in the root zone. However, when the penetration angle exceeded 40°, soil fragmentation quality declined and draft resistance increased. At steeper angles, the tool tended to push soil forward rather than fracture it effectively, resulting in increased resistance and reduced loosening efficiency. The optimal penetration angle was therefore determined to be within the range of: 30°–35°. This range provides efficient soil fracture, stable tool penetration, and energy-efficient operation.

Effect of working surface length

The length of the working surface plays an important role in determining soil fragmentation quality and resistance forces. Experimental observations indicated that increasing the tool length improved soil fragmentation by increasing the duration of soil–tool interaction and enhancing the formation of fracture zones. A longer working surface allows progressive soil failure and promotes more uniform soil crumbling, which improves soil aeration and root development conditions. However, excessive tool length increased draft resistance due to greater soil contact area and frictional forces. Increased resistance leads to higher energy consumption and reduced operational efficiency.

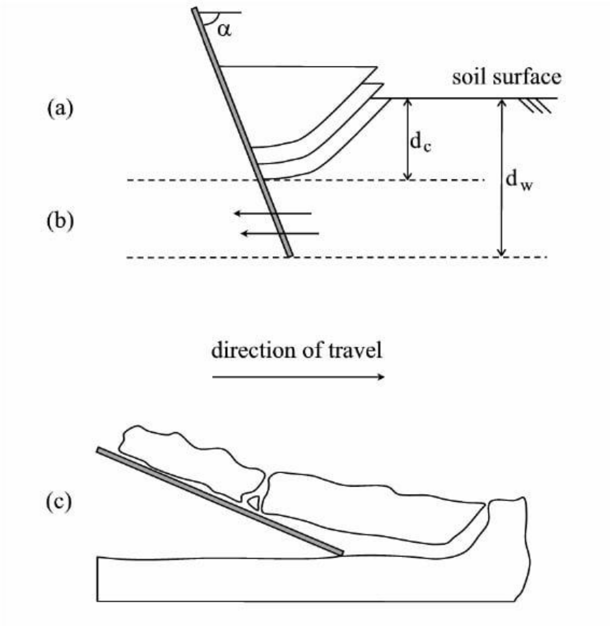


Fig. 7. Soil fracture mechanism and disturbance zone generated by the tillage tool at a penetration angle α.

The optimal working surface length was determined to be:
100–125 mm
Within this range, effective soil fragmentation was achieved while maintaining acceptable energy requirements.

Regression analysis and optimization

Regression analysis was performed to evaluate the combined influence of geometric and operational parameters on soil disturbance quality and draft resistance. The developed regression models demonstrated strong relationships between tool parameters and performance indicators.
Optimization results indicated that the following parameter combinations ensured the best operational performance:
soil fragmentation exceeding 80%,
loosened layer width of 60–70 cm,
minimal draft resistance,
stable and energy-efficient operation.

Analysis of variance (ANOVA) confirmed the statistical significance of the investigated factors, while adequacy testing verified the reliability of the regression models. The obtained models were statistically significant at a confidence level of $p < 0.05$, indicating strong predictive capability. These results confirm that parameter optimization plays a crucial role in improving soil loosening efficiency while minimizing energy consumption.

Econometric analysis of operational and energy efficiency

To quantitatively evaluate the performance of the developed deep-loosening working body, an econometric approach was applied to analyze the relationships between operational parameters, soil disturbance quality, and energy consumption. Regression-based models were developed using experimental data to determine the influence of key design and operational factors, including working width, penetration angle, working surface length, and forward speed, on draft resistance and soil fragmentation efficiency. The obtained regression equations describe the functional relationships between tool parameters and performance indicators, enabling prediction and optimization of operational outcomes. The econometric analysis revealed that draft resistance is significantly influenced by tool geometry and operating depth, while soil fragmentation efficiency is primarily governed by penetration angle and working surface length (Naderi-Boldaji & Keller 2021; Khudoyberdiev & Kholdarov 2022a,b). The combined regression models allowed identification of parameter ranges that ensure high soil loosening quality with minimal energy consumption.

Optimization results indicate that the optimal parameter combination provides:

Soil fragmentation efficiency exceeding 80%;

Loosened layer width of 60–70 cm;

Reduced draft resistance and fuel consumption;

Improved operational efficiency.

The statistical adequacy of the regression models was confirmed through variance analysis and significance testing ($p < 0.05$), indicating reliable predictive capability. Furthermore, the econometric evaluation of field performance demonstrated that the use of the developed working body reduces labor requirements by approximately 51% and operational costs by about 32%, confirming its economic feasibility and resource-saving potential. Overall, the econometric analysis verifies that optimization of working body parameters significantly improves energy efficiency, reduces operating costs, and enhances the sustainability of inter-row cultivation practices.

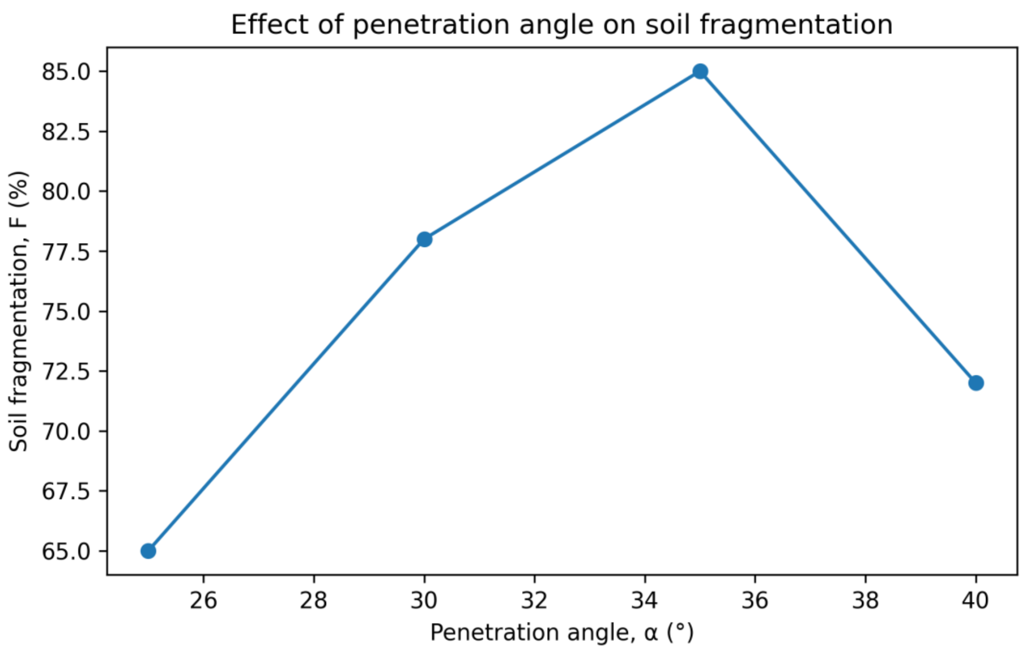


Fig. 8. Effect of penetration angle on soil fragmentation efficiency.

The presented diagrams confirm the reliability of the econometric analysis and clearly demonstrate the relationships between operational parameters, soil disturbance quality, and economic performance. The results indicate that optimization of tool geometry and operating parameters not only improves soil loosening efficiency but also significantly reduces energy consumption and operational costs. These findings validate the practical applicability of the developed working body and support its use as a resource-efficient solution for sustainable inter-row cultivation.

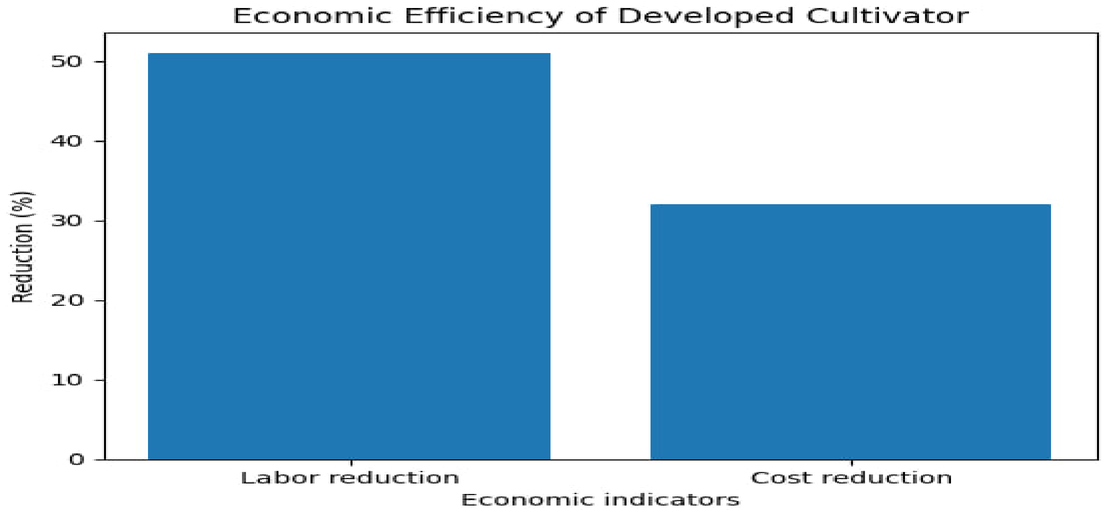


Fig. 9. Economic efficiency achieved using the developed cultivator.

Comparison with conventional systems

The performance of the developed cultivator was compared with traditional multi-pass tillage systems commonly used in cotton cultivation.

Parameter	Conventional Systems	Developed Tool
Passes required	2–3	1
Fuel consumption	High	Reduced
Soil compaction	Increased	Reduced
Root protection	Limited	Improved
Energy efficiency	Moderate	High

The developed tool significantly improves operational efficiency by combining multiple soil treatment operations into a single pass. Reduced machinery traffic decreases soil compaction and improves long-term soil structure stability.

Environmental and energy efficiency benefits

The developed cultivator contributes to sustainable agricultural production by improving soil health and reducing environmental impact (Ucgul *et al.* 2021; Chen *et al.* 2022; Abrorov *et al.* 2025).

The primary environmental benefits include:

Reduced fuel consumption and energy demand,

Lower greenhouse gas emissions,

Minimized soil compaction,

Improved soil moisture retention,

Enhanced soil aeration and biological activity.

Improved soil structure promotes long-term soil fertility and resilience to climate variability. Reduced machinery passes also help conserve soil moisture and reduce erosion risk.

Field performance and economic efficiency

Field tests confirmed reliable operation of the developed cultivator under typical agricultural conditions. The working body performed consistently and met agronomic requirements for soil loosening and root protection.

Operational evaluation demonstrated:

✓ reliable and stable performance

✓ compliance with agronomic standards

✓ improved soil structure and aeration

Economic analysis showed significant benefits:

labor reduction: 51%;

Operational cost reduction: 32%;
Increased field productivity;
Reduced machinery wear and maintenance costs;
The ability to perform multiple operations in a single pass significantly improves field efficiency and reduces total production costs.

CONCLUSION

This study presented the design, analytical modeling, and experimental evaluation of a deep-loosening working body integrated into an inter-row cultivator for cotton cultivation. The developed solution enables simultaneous shallow cultivation and deep loosening in a single pass, improving soil physical properties while reducing energy consumption and operational costs. Analytical modeling and experimental investigations established the optimal geometric and operational parameters of the working body. The protective zone was defined to ensure root safety, while the optimal loosening depth of 30–35 cm was identified to effectively disrupt compacted soil layers and improve air–water exchange within the root zone. The optimal penetration angle of 30°–35° ensured efficient soil fracture and stable tool penetration. A working width of 4–6 cm and a working surface length of 100–125 mm provided the best balance between soil disturbance efficiency and draft resistance. The analytically determined draft resistance averaged 0.289 kN, confirming the energy-efficient performance of the optimized working body geometry. Experimental results demonstrated that proper parameter selection ensures soil fragmentation exceeding 80%, a loosened layer width of 60–70 cm, and stable operation under field conditions. Compared to conventional multi-pass tillage systems, the developed cultivator significantly improves operational efficiency by reducing the number of passes, minimizing soil compaction, and lowering fuel consumption. Field evaluation indicated labor savings of up to 51% and operational cost reductions of 32%, demonstrating substantial economic advantages. In addition to economic benefits, the proposed solution contributes to sustainable agricultural practices by improving soil structure, enhancing moisture retention, reducing greenhouse gas emissions, and promoting soil biological activity. Improved root development conditions increase crop resilience, particularly under water-limited conditions. Overall, the developed deep-loosening working body represents an energy-efficient and resource-saving solution for modern cotton cultivation systems. The results of this study contribute to the advancement of sustainable agricultural mechanization and provide a scientific basis for further development of integrated tillage technologies. Future research should focus on long-term field evaluation under varying soil and climatic conditions, integration with precision agriculture systems, and adaptation of the design for other row crops.

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