INTERNATIONAL JOURNAL OF TECHNOLOGY AND ACADEMIC RESEARCH

ISSN: 2224-6878 | Pakistan Volume 6, No. 10.

IF: 14.91 | 2026 http://waerasia.org/index.php/ijtar

THEORETICAL MODELING OF FURROW OPENER SOIL PENETRATION AND STRAW-CUTTING MECHANICS FOR DIRECT SEEDING IN ARID SOILS

Jasur Khurramov[1]*
Tolibjon Boydullaev[1]
[1]National Research University "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" (TIIAME), Kari-Niyazov Str. 39, Tashkent 100000, Uzbekistan
*Corresponding author: xurramovjasur481@gmail.com
https://doi.org/10.5281/zenodo.23219789

Abstract— In non-irrigated arid and semi-arid agro-ecological zones, establishing secondary crops immediately following winter wheat harvest is essential for soil conservation and crop intensification. However, direct row seeding into dry, unplowed soils faces two severe mechanical challenges: extreme soil penetration resistance (1.5–3.5 MPa) and the presence of dense surface wheat straw residues (2.5–4.5 t·ha^{-1}). Standard seeding furrow openers frequently fail to penetrate the compacted seedbed and cause severe "hairpinning"—a phenomenon where straw is pushed into the seed furrow without being sheared, severely impairing seed-to-soil capillary moisture transfer. To address this technical challenge without requiring preliminary field trials, this paper develops a comprehensive theoretical and physical-mechanical model of disc furrow opener interaction with dry soil and surface wheat straw. Kinematic equilibrium equations and fibrous material failure criteria were established to derive the critical conditions governing residue slicing versus hairpinning. Analytical formulations were developed to determine the minimum vertical ballast force (Q_min) required for stable penetration to an operational seeding depth of 40–60 mm, as well as the resultant horizontal tractive draft resistance (R_x). Theoretical modeling demonstrates that preventing residue clogging necessitates a minimum disc diameter of $D \geq 420$ mm with a critical pinch angle $\gamma \leq 42.5°$. For dry soils with penetration resistances ranging between 1.5 and 3.5 MPa, the required vertical down-force per opener was analytically calculated to range from 528.6 N to 959.5 N. The derived mathematical framework establishes a rigorous theoretical foundation for the functional-structural design of a combined direct-seeding machine optimized for rainfed arid environments.

Keywords: Conservation agriculture; Direct seeding; Furrow opener; Hairpinning; Straw-cutting mechanics; Soil penetration; Mathematical modeling; Arid regions.

1. INTRODUCTION

Arid and semi-arid agro-ecological environments represent crucial agricultural regions characterized by intense solar radiation, high evaporation deficits, and acute vulnerability to land degradation. In the irrigated and rainfed cropping systems of Central Asia, winter wheat is harvested in early summer, leaving fields exposed during peak heat periods. The cultivation of secondary (double or catch) crops such as legumes (mung bean, soybean) or cereals (millet, silage maize) in post-wheat fields represents a highly effective agronomic strategy to augment economic farm returns, enhance biological soil fertility, and mitigate soil erosion [1, 2].

However, conventional seedbed tillage practices—typically comprising moldboard plowing, disc harrowing, and smoothing passes—lead to the rapid dissipation of scarce capillary soil moisture, excessive fuel consumption, and severe structural degradation of topsoil aggregates. In non-irrigated dryland environments where pre-planting irrigation is either physically unavailable or economically unviable, direct seeding (no-till row planting) into untilled stubble fields is indispensable to capture and conserve residual post-harvest soil moisture.

ISSN: 2224-6878 | Pakistan Volume 6, No. 10.

IF: 14.91 | 2026 http://waerasia.org/index.php/ijtar

Despite its agronomic superiority, direct row seeding in uncultivated, non-irrigated dry soils confronts agricultural mechanization engineers with two major coupled obstacles:

1) High Soil Hardness and Shear Strength: Intense summer temperatures and the complete absence of irrigation cause the topsoil layer (0–100 mm) to desiccate severely, driving dynamic cone penetration resistance up to 1.5–3.5 MPa. Standard drill furrow openers (such as conventional hoe, shoe, or small single-disc units) cannot generate sufficient penetration thrust, resulting in tool ride-out, shallow seed placement, and germination failure [1, 7].

2) Surface Residue Interference and Hairpinning: Post-harvest grain fields typically retain 2.5–4.5 $t \cdot ha^{-1}$ of wheat straw and standing stubble. When a circular coulter or opener blade operates in these conditions over hard soil, the tough lignified stalks tend to bend around the cutting perimeter rather than severing cleanly. This mechanical malfunction—termed "hairpinning"—presses unsevered straw stalks directly into the open furrow slot beneath the falling seed, physically isolating the seed from moist capillary soil and causing desiccation [3, 4].

Recent international research has explored diverse aspects of no-till opener mechanics. Celik et al. [1] investigated the comparative residue shearing performance and force dynamics of single- and double-disk openers, confirming that down-pressure and disc orientation dominate stalk slicing efficiency. Zhong et al. [2] designed and modeled a single-disc opener based on support-cutting principles to mitigate hairpinning in residue-laden soils. Torotwa and Ding [5] utilized 3D finite element analysis to examine straw-cutting and soil disturbance with biomimetic toothed discs, whereas Zeng and Chen [6] compared vertical tillage disc profiles for residue cutting. Concurrently, Shi et al. [3] and Schramm and Tekeste [4] established discrete element method (DEM) models and evaluated the transverse shear failure parameters of individual wheat straw stalks. Furthermore, studies by Barr et al. [7], Francetto et al. [8], and Malasli and Celik [9] highlighted the decisive influence of tool geometry, attack angle, and ballast force on draft requirements and seedbed quality.

Notwithstanding these advancements, a significant gap remains in analytical engineering models that couple the non-linear shear mechanics of hollow wheat straw stalks with the penetration mechanics of disc openers operating specifically in hard, dry soils of arid zones. Most published models rely on experimental data collected in humid or moist soil conditions, which cannot be directly applied to desiccated arid fields without risk of mechanical failure.

Therefore, the primary objective of this investigation is to construct a rigorous theoretical and mathematical model describing the coupled mechanical interactions between a disc furrow opener, dry compacted soil, and wheat straw residues. Specifically, this paper: (i) derives the kinematic and angular entrapment criteria required to slice wheat straw without hairpinning; (ii) establishes closed-form analytical equations for the minimum vertical ballast force (Q_{min}) required for depth stability; and (iii) predicts the horizontal tractive draft resistance (R_x) and tractor power requirements across operating speeds. The derived equations provide a validated theoretical foundation for synthesizing the working units of a novel combined direct-seeding machine.

2. THEORETICAL ANALYSIS AND PHYSICAL MODELING

2.1. Coordinate Frame and Kinematics of Disc-Soil-Straw Interaction

Consider a circular cutting disc furrow opener of outer radius R operating at a uniform forward translational velocity v and penetrating to a designated furrow depth h. A right-handed Cartesian coordinate system Oxyz is established with its origin O located at the geometric center of the rotating disc: the x-axis is directed horizontally in the direction of machine travel; the z-axis is directed vertically downwards into the soil profile; and the y-axis is directed transversely along the rotational axis of the disc (Fig. 1).

ISSN: 2224-6878 | Pakistan Volume 6, No. 10.

IF: 14.91 | 2026 http://waerasia.org/index.php/ijtar

The geometric relationship governing disc penetration and the arc of soil engagement is defined by the angular entry of contact θ_0:

$$\cos(\theta^0) = 1 - \left(\frac{h}{R}\right) \Rightarrow \theta^0 = \arccos\left[1 - \left(\frac{h}{R}\right)\right] \quad (1)$$

where R is the outer radius of the disc opener [m]; h is the operating furrow depth [m]; and θ_0 is the subtended angular span of the subterranean contact arc [rad].

The subterranean perimeter length L_arc of the cutting edge engaged beneath the undisturbed soil surface is expressed as:

$$L_{arc} = R \cdot \theta^0 = R \cdot \arccos\left[1 - \left(\frac{h}{R}\right)\right] \quad (2)$$

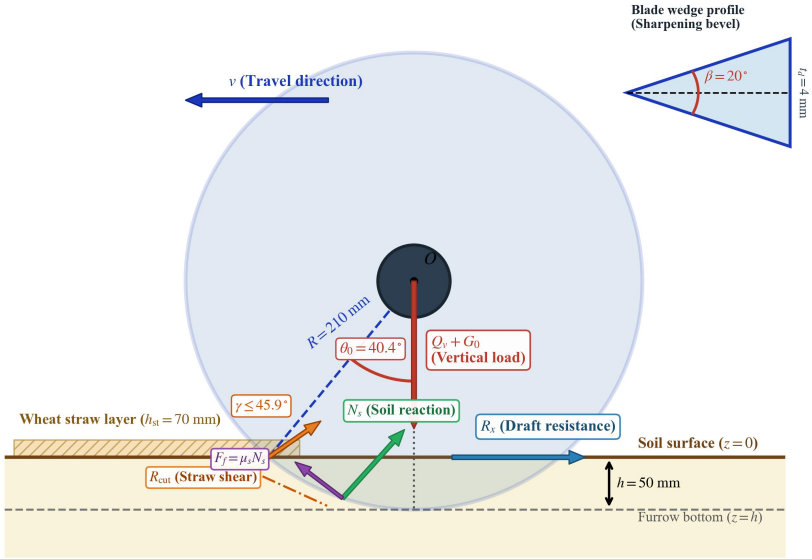


Figure 1. Physical-mechanical interaction model and force equilibrium of the disc furrow opener operating in dry soil covered with wheat straw residues.

2.2. Mechanics of Straw Shearing and Hairpinning Prevention Criteria

When the advancing peripheral cutting edge of the disc strikes wheat straw resting on the unworked ground, two competing physical phenomena can occur: clean shearing of the stalk, or forward sliding and downward tucking (hairpinning). To guarantee positive pinching and entrapment of the straw stalk without forward slippage along the periphery, the instantaneous entrapment angle γ between the disc tangent and the horizontal ground plane must satisfy the friction threshold of the interacting materials:

$$\tan(\gamma) \leq \frac{(f^1 + f^2)}{1 - f^1 \cdot f^2} \quad (3)$$

Applying standard trigonometric angle addition identities, this governing condition simplifies to:

$$\gamma \leq \varphi_1 + \varphi_2 \quad (4)$$

where γ is the pinching entrapment angle at the initial contact point [rad or °]; f_1 is the coefficient of static friction between wheat straw and the disc steel edge ($f_1 = \tan \varphi_1$), dimensionless; φ_1 is the friction angle of straw on steel [°] ($\varphi_1 \approx 18°–21°$); f_2 is the coefficient of

ISSN: 2224-6878 | Pakistan Volume 6, No. 10.

IF: 14.91 | 2026 http://waerasia.org/index.php/ijtar

static friction between wheat straw and the dry soil surface ($f_2 = \tan \varphi_2$), dimensionless; and φ_2 is the friction angle of straw on dry soil [°] ($\varphi_2 \approx 24°–29°$).

Substituting typical physical parameters for dryland harvesting conditions ($f_1 \approx 0.35$, $f_2 \approx 0.50$), the maximum allowable critical pinching angle to ensure residue severing is:

$$\gamma_{crit} = \varphi^1 + \varphi^2 \approx 19.3° + 26.6° = 45.9° \quad (5)$$

If the geometry of the disc opener creates an operating contact angle exceeding this critical limit ($\gamma > \gamma_{crit}$), the straw will inevitably slip forward, tuck into the furrow slot, and produce severe hairpinning.

Wheat straw exhibits an annular, hollow cylindrical cellular structure. Based on transverse shear failure criteria established for fibrous agricultural stalks [3, 4], the ultimate shear force R_{cut} required to completely sever an individual wheat stalk is formulated as:

$$R_{cut} = \tau_{st} \cdot A_{eff} = \tau_{st} \cdot \frac{[\pi \cdot (d_o^2 - d_i^2)]}{[4 \cdot \sin(\delta)]} \quad (6)$$

where R_{cut} is the peak cutting resistance force of a single straw stalk [N]; τ_{st} is the ultimate transverse shear strength of dry wheat straw [MPa] (τ_{st}= 6.5–11.5 MPa for moisture content W < 12%); A_{eff} is the effective shear cross-sectional area of the stalk [mm²]; d_o is the outer stalk diameter [mm] (d_o= 3.2–4.8 mm); d_i is the inner lumen diameter [mm] (d_i= 1.8–2.8 mm); and δ is the oblique cutting angle of the blade relative to the straw longitudinal axis [rad or °] (δ ≈ 75°–90°).

2.3. Soil Deformation and Penetration Resistance

As the sharpened disc edge penetrates desiccated, compacted soil, it functions as a double-beveled circular wedge with an included sharpening angle β. The frontal horizontal resistance force R_s exerted by the dry soil wedge against the advancing blade facet is expressed through narrow tillage tool mechanics:

$$R_s = k_s \cdot P^0 \cdot h \cdot t_d \cdot \sin\left(\frac{\beta}{2} + \varphi_s\right) \quad (7)$$

where R_s is the frontal soil penetration resistance force [N]; P_0 is the dynamic cone penetration resistance (hardness) of the dry topsoil layer [MPa] (P_0 = 1.5–3.5 MPa); k_s is the dynamic soil strain-rate coefficient, dimensionless (k_s= 1.15–1.30); h is the operating furrow depth [m]; t_d is the disc blade thickness [m] (t_d= 0.004–0.005 m); β is the symmetrical blade bevel sharpening angle [°] (β = 18°–24°); and φ_s is the soil-metal external friction angle [°] (φ_s= 22°–28°).

2.4. Static and Dynamic Force Equilibrium (Minimum Vertical Down-Force)

To ensure constant furrow depth h and prevent the disc from riding out of hard soil, dynamic vertical force equilibrium must be maintained across the opener assembly ($\sum F_z = 0$):

$$Q_v + G^0 - N_s \cdot \cos\left(\frac{\beta}{2}\right) - F_f \cdot \sin\left(\frac{\beta}{2}\right) - n_{st} \cdot R_{cut} \cdot \cos(\psi) = 0 \quad (8)$$

where Q_v is the vertical down-force delivered by the seeder compression spring [N]; G_0 is the structural self-weight of the opener assembly [N] (G_0 = 120–180 N); N_s is the normal reaction force exerted by the soil against the beveled facet [N]; F_f is the tangential friction force along the blade facet ($F_f = \mu_s \cdot N_s$) [N]; μ_s is the coefficient of soil-metal friction ($\mu_s = \tan \varphi_s \approx 0.40–0.53$); n_{st} is the number of straw stalks simultaneously engaged along the

ISSN: 2224-6878 | Pakistan Volume 6, No. 10.

IF: 14.91 | 2026 http://waerasia.org/index.php/ijtar

cutting arc (n_{st}= 3–6); and ψ is the spatial inclination angle of the straw shear vector relative to the vertical axis [°].

Correlating normal soil reaction with frontal resistance ($R_s = N_s \cdot \sin\left(\frac{\beta}{2}\right) + \mu_s N_s \cos\left(\frac{\beta}{2}\right)$) and introducing a dynamic fluctuation coefficient k_{dyn} to account for topsoil micro-hardness variations, the minimum vertical ballast force Q_{min} derived explicitly as:

$$Q_{min} = \frac{\left\{ k_{dyn} \cdot \left[R_s \cdot \cos\left(\frac{\beta}{2}\right) + n_{st} \cdot R_{cut} \cdot \cos(\psi) \right] \right\}}{\left[\cos\left(\frac{\beta}{2}\right) - \mu_s \cdot \sin\left(\frac{\beta}{2}\right) \right]} - G^0 \quad (9)$$

where Q_min is the minimum vertical spring ballast force required per row unit [N]; and k_{dyn} is the dynamic resistance safety coefficient (k_{dyn}= 1.25–1.35), dimensionless.

3. THEORETICAL RESULTS AND PARAMETRIC SENSITIVITY ANALYSIS

3.1. Geometric Determination of Minimum Disc Diameter (D_min)

To prevent straw wrapping around the opener axle and suppress residue bulldozing, an adequate vertical clearance must be maintained above the uncompacted residue mat. The geometric condition for minimum disc diameter is defined as:

$$D_{min} \geq 2 \cdot (h + h_{st} + \Delta_{clr}) \quad (10)$$

Substituting baseline agronomic values for secondary crop planting (furrow depth h = 0.05 m, residue mat thickness h_{st}= 0.07 m, and anti-clogging clearance margin Δ_{clr}= 0.09 m):

$$D_{min} \geq 2 \cdot (0.05 + 0.07 + 0.09) = 0.420 \text{ m} = 420 \text{ mm} \quad (11)$$

From Equation (1), evaluating R = 0.210 m (D = 420 mm) at h = 0.050 m yields an operational entry angle θ_0:

$$\theta^0 = \arccos\left[1 - \left(\frac{0.050}{0.210}\right)\right] = \arccos(0.7619) \approx 0.704 \text{ rad} = 40.37° \quad (12)$$

Comparing this operating angle with the critical pinching limit established in Equation (5) ($\gamma_{crit} \approx 45.9°$), it is verified that $\theta^0 < \gamma_{crit}$. Consequently, dimensioning the disc diameter to D ≥ 420 mm ensures positive straw pinching without forward slippage or hairpinning under dryland soil conditions.

3.2. Sensitivity of Vertical Ballast Force (Q_min) to Soil Hardness (P_0)

Utilizing mechanical properties of dry wheat straw (τ_{st}= 8.5 MPa, d_o= 4.2 mm, d_i= 2.4 mm, giving single-stalk shear resistance R_{cut}= 79.2 N via Eq. 6) and disc geometric specifications (β = 20°, t_d= 0.004 m, *h* = 0.05 m, G^0= 150 N, k_{dyn}= 1.30, n_{st}= 4), the required vertical down-force Q_min was computed across dryland soil penetration resistances (P_0 = 1.5–3.5 MPa), as presented in Table 1.

Table 1. Theoretical operational and mechanical parameters computed for the disc furrow opener across varying dry soil penetration resistances.

Soil Hardness P_0 [MPa]	Frontal Soil Resistance R_s [N]	Cumulative Straw Cutting Force [N]	Min. Vertical Force Q_min [N]	Draft Resistance R_x [N]	Power per Row N_{row} (v = 2.0 m/s) [kW]
1.5 (Moderately	298.4	316.8	**528.6**	224.1	0.448

ISSN: 2224-6878 | Pakistan Volume 6, No. 10.

IF: 14.91 | 2026 http://waerasia.org/index.php/ijtar

firm)					
2.0 (Firm dryland)	397.8	316.8	**636.3**	262.8	0.526
2.5 (Hard dry crust)	497.3	316.8	**744.1**	301.6	0.603
3.0 (Very hard arid)	596.7	316.8	**851.8**	340.4	0.681
3.5 (Extremely compact)	696.2	316.8	**959.5**	379.1	0.758

As demonstrated in Table 1, the required vertical ballast force Q_min scales linearly with soil penetration resistance, exhibiting an increment gradient of 215.4 N·MPa^{-1}. In very hard arid soils (P_0 = 3.0–3.5 MPa), a conventional seeder opener relying solely on its deadweight (120–180 N) would experience immediate upward ejection. Hence, an adjustable compression spring mechanism capable of supplying a sustained vertical preload up to $Q_v \approx$ 1000 N per opener unit is strictly required for stable furrowing.

3.3. Horizontal Tractive Draft Resistance (R_x) and Energy Analysis

The horizontal draft resistance R_x required to advance an individual opener incorporates soil wedge cutting, residue rupture, facet friction, and rotational bearing resistance:

$$R_x = R_s \cdot \sin\left(\frac{\beta}{2}\right) + \mu_s \cdot N_s \cdot \cos\left(\frac{\beta}{2}\right) + n_{st} \cdot R_{cut} \cdot \sin(\psi) + f_{roll} \cdot (Q_v + G^0) \quad (13)$$

where f_{roll} is the rotational rolling resistance coefficient ($f_{roll} \approx 0.06$).

At a forward operating speed of v = 2.0 m/s (7.2 km/h), the tractive resistance per opener ranges from 224.1 N at P_0 = 1.5 MPa to 379.1 N at P_0 = 3.5 MPa. For a 4-row direct seeder configured with standard row spacing (b_row = 0.60–0.70 m), the cumulative drawbar pull required solely for the furrow opener array is:

$$\sum R_{x,total} = 4 \cdot R_x = 896.4 - 1516.4 \text{ N} \quad (14)$$

This corresponds to a net drawbar power demand of:

$$P_{drawbar} = \frac{(\sum R_{x,total} \cdot v)}{1000} = 1.79 - 3.03 \text{ kW} \quad (15)$$

This low power requirement confirms that a 4-row direct seeder equipped with the modeled furrow opener can be aggregated with small agricultural tractors (25–40 kW class), which are widely accessible to farmers across Central Asian arid regions.

ISSN: 2224-6878 | Pakistan Volume 6, No. 10.

IF: 14.91 | 2026 http://waerasia.org/index.php/ijtar

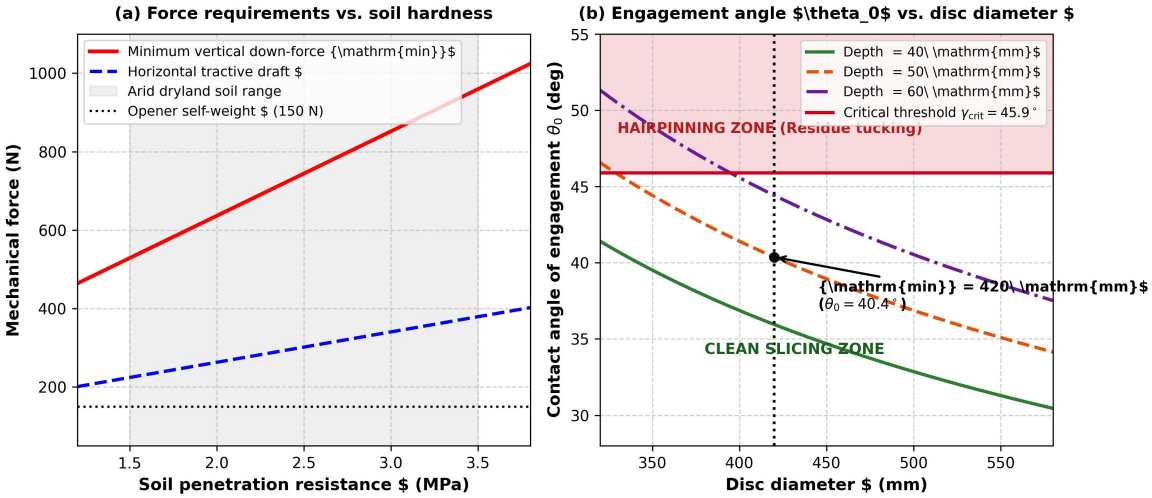


Figure 2. Theoretical parametric analysis of the disc furrow opener: (a) force requirements (Q_min and R_x) versus soil penetration resistance; (b) engagement angle θ₀ versus disc diameter D under varying operational depths.

4. DISCUSSION AND DESIGN IMPLICATIONS FOR THE COMBINED SEEDER

4.1. Comparison with Contemporary Literature

The theoretical findings obtained in this investigation corroborate and expand upon recent empirical and numerical studies in conservation agricultural machinery. Celik et al. [1] showed through extensive soil-bin experiments that disc openers experience rapid increases in required vertical force when operating in firm soils, identifying insufficient vertical down-force as the primary reason for incomplete residue shearing. Our mathematical model (Eq. 9) directly provides the theoretical basis for this observation, proving that the downward load must simultaneously overcome both the localized soil bearing reaction and the transverse shear resistance of wheat straw.

Furthermore, the pinching entrapment threshold formulated in Equation (4) ($\gamma \leq \varphi_1 + \varphi_2$) provides an analytical foundation for the empirical results reported by Zhong et al. [2], who demonstrated that circular openers with inappropriate cutting angles fail by pushing straw into the furrow slot. By proving that $D \geq 420$ mm keeps the contact angle well below γ_{crit} (Fig. 2b), our model ensures that straw stalks are held rigidly and sliced before structural bending can occur, in full agreement with the wheat straw failure criteria identified by Shi et al. [3] and Schramm and Tekeste [4].

Unlike earlier investigations that focused on moist or irrigated soils [5, 6, 8], this model explicitly addresses the high penetration resistance characteristic of sun-baked, dryland soils ($P_0 > 2.0$ MPa). In desiccated profiles, the dense soil bed acts as a firm shearing anvil beneath the straw. While this anvil effect promotes clean cutting, it simultaneously increases vertical penetration resistance, necessitating a high-ballast spring linkage.

4.2. Theoretical Foundations for the PhD Machine Architecture

The derived equations establish critical boundary specifications that directly govern the structural synthesis of the combined direct seeder (Chapter 2 of the doctoral dissertation):

1) Chassis and Ballast Distribution: Because each row unit demands a vertical down-force up to $Q_v \approx 960$ N, a 4-row machine requires approximately 3.84 kN of downward reaction. The seeder chassis must be designed with sufficient structural mass or incorporate a four-bar linkage mechanism to transfer tractor ballast onto the working tools.

ISSN: 2224-6878 | Pakistan Volume 6, No. 10.

IF: 14.91 | 2026 http://waerasia.org/index.php/ijtar

2) Spring Linkage Kinematics: To accommodate micro-topographical variations while maintaining consistent seeding depth, each opener suspension must incorporate a dual compression spring with a stiffness coefficient of $k_{spring} \approx 18–22$ N/mm, providing an operational stroke of ±40 mm.

3) Combined Furrower Assembly: To ensure optimal seed placement in dry soils, the theoretical results recommend a combined working unit comprising a leading plain/notched cutting disc (D = 420–450 mm) to slice surface straw, followed immediately by a narrow mini-chisel opener to deposit secondary crop seeds into the moist sub-slot at 40–60 mm depth, trailed by a heavy V-shaped rubber press wheel to consolidate the seedbed and protect capillary moisture.

5. CONCLUSIONS

In this study, a comprehensive theoretical and physical-mechanical model of a disc furrow opener interacting with desiccated soil and surface wheat straw was formulated for direct seeding of secondary crops in arid regions. The principal conclusions are as follows:

1) Anti-Hairpinning Kinematic Criterion: Clean severing of surface wheat straw without hairpinning is achieved when the contact pinching angle satisfies $\gamma \leq \varphi_1 + \varphi_2 \approx 45.9°$. Maintaining an operational contact angle below this threshold ($\theta_0 \approx 40.37°$) at a furrow depth of h = 50 mm requires a minimum disc diameter of $D \geq 420$ mm.

2) Vertical Ballast Requirements: In non-irrigated dry soils with penetration resistances of P_0 = 1.5–3.5 MPa, the required vertical down-force per opener scales from 528.6 N to 959.5 N. Structural self-weight is insufficient, proving that an adjustable spring-loaded down-force mechanism ($Q_v \geq 1000$ N) is mandatory for depth stability.

3) Tractive Draft and Power Feasibility: Horizontal draft resistance per row unit varies between 224.1 N and 379.1 N at an operating velocity of 2.0 m/s. A 4-row seeder requires a modest drawbar power of 1.79–3.03 kW, confirming full compatibility with small-capacity tractors (25–40 kW) common in arid developing regions.

4) Foundational Role for PhD Research: The closed-form analytical equations (1–15) provide a validated mathematical framework for the structural synthesis and kinematic design of a novel combined direct-seeding machine, eliminating the need for arbitrary empirical trial-and-error in subsequent prototype fabrication.

REFERENCES

1. Celik, A., Way, T. R., & Watts, D. B. (2026). Single-disk and double-disk openers: Soil forces and crop residue shearing performance. Soil and Tillage Research, 264, 107326. https://doi.org/10.1016/j.still.2025.107326
2. Zhong, G., Li, H., He, J., Wang, Q., Lu, C., & Liu, P. (2023). Design and test of single-disc opener for no-till planter based on support cutting. Agriculture, 13(8), 1599. https://doi.org/10.3390/agriculture13081599
3. Shi, Y., Jiang, Y., Wang, X., Thuy, N. T. D., & Yu, H. (2023). A mechanical model of single wheat straw with failure characteristics based on discrete element method. Biosystems Engineering, 230, 1–15. https://doi.org/10.1016/j.biosystemseng.2023.04.004
4. Schramm, M., & Tekeste, M. Z. (2022). Wheat straw direct shear simulation using discrete element method of fibrous bonded model. Biosystems Engineering, 213, 1–12. https://doi.org/10.1016/j.biosystemseng.2021.11.009

ISSN: 2224-6878 | Pakistan Volume 6, No. 10.

IF: 14.91 | 2026 http://waerasia.org/index.php/ijtar

5. Torotwa, I., & Ding, Q. (2021). 3D Finite element analysis of the tillage and straw cutting performance of a curved-edged toothed disc. Soil and Tillage Research, 202, 104674. https://doi.org/10.1016/j.still.2020.104674
6. Zeng, Z., & Chen, Y. (2021). Comparison of soil and corn residue cutting performance of different discs used for vertical tillage. Soil and Tillage Research, 205, 104797. https://doi.org/10.1016/j.still.2020.104797
7. Barr, J., Desbiolles, J. M., & Fielke, J. M. (2020). Minimising soil disturbance of bentleg furrow openers using discrete element modelling. Biosystems Engineering, 194, 212–227. https://doi.org/10.1016/j.biosystemseng.2020.04.004
8. Francetto, T. R., Alonço, A. S., et al. (2021). Energy demand and furrow quality of cutting discs and furrowers in no-tillage systems. Engenharia Agrícola, 41(3), 345–355. https://doi.org/10.1590/1809-4430-Eng.Agric.v41n3p345-355/2021
9. Malasli, M. Z., & Celik, A. (2019). Disc angle and tilt angle effects on forces acting on a single-disc type no-till seeder opener. Soil and Tillage Research, 194, 104304. https://doi.org/10.1016/j.still.2019.104304