



Design and optimisation of a reel mechanism for mechanical harvesting of lentil (*Lens culinaris*) crop using bending theory

PRIYANSHU KUMAR¹, SUBHASH CHANDRA¹, SANJAY KUMAR PATEL¹, SANJAY KUMAR¹, ABHISHEK UPADHYAY^{1*} and ADITYANSHU TRIPATHI¹

College of Agricultural Engineering and Technology, Dr Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar 848 125, India

Received: 29 January 2026; Accepted: 30 June 2026

ABSTRACT

Lentil (*Lens culinaris* Medik.) harvesting in general is associated with low plant height and high pod shattering leading to the significant crop loss during harvesting. The present study was aimed to develop the specialised reel mechanism to optimise the mechanical reel relation according to the crop status. Reel was developed by using mechanical crop modelling based on bending theory. While applying the bending theory, lentil stems were treated as elastic beams for study of the deflection angle (ϕ) at variable deflection force. The flexural rigidity of stem (D), ear weight of crop (W), reel force (P), loading height (h_p) and reel kinematics were taken into account for deriving the mathematical expressions by using MATLAB within the selected crop parameters range. The crop deflection angle was optimised by using Response Surface Methodology (RSM) optimal (custom) design. The developed reel mechanism was evaluated for its parameter in relation to the angular displacement between successive tine bars (α), number of tine bars (n), reel rotational velocity (ω) and header advancement/radian of reel rotation (R_o). Measured mechanical and physical properties of lentil plants were taken as design inputs to achieve adequate stem deflection for cutting lentil crop while minimising shattering losses. The analysis showed that increasing the flexural rigidity of lentil stems decreased deflection, while reel force and pod weight increased the deflection angle. Loading point height significantly influenced crop position at the cutter bar, which guided the selection of reel radius (R), position and speed of reel. An appropriate lentil reel mechanism was designed using mathematical models with optimum parameters of $R=35$ cm, $\phi = 83.79^\circ$, $Z_r = 16$ cm, $\alpha = 45.74^\circ$, $n = 8$ and $R_o = 28$ cm. The developed machine recorded a reel loss of 2.92% which was minimal in comparison to the reported value of 9% for pulse crops harvested using conventional cereal-based headers.

Keywords: MATLAB simulation, Mechanical harvesting, Reel-crop interaction, Reel design, Stem deflection

Lentil (*Lens culinaris* Medik.), a major Indian pulse cultivated on 1.48 mha with 1.03 mt production (Tripathi and Chisi 2024), ranks first in area and second in production (Yadav *et al.* 2020) and is nutritionally valuable. Its low first-pod height (5–15 cm) (Sobko *et al.* 2022) necessitates manual harvesting at 64 man-h/ha (Golpira *et al.* 2013).

Conventional reel mechanisms often fail to lift lodged crops, causing flattening and shattering losses from suboptimal tine-to-crop kinematics (Marini and Romano 2009, Oduori *et al.* 2012). Effective harvesting requires flexible cutter bars, proper reel adjustment (Yang *et al.* 2021) and precise crop-lifter positioning (Barker 2025). A kinematic index of 1.5–1.7 minimises header losses

(Bawatharani *et al.* 2013), similar to the 1.6–2.4 pulse-crop range (Golpira *et al.* 2013; 2021), improving stem lifting (Srivastava *et al.* 2006).

Lentil's short canopy (≤ 450 mm) and low first-pod height (65 ± 41 mm) cause seed losses up to 55%, and cereal combines add header losses of 7.9–8.7% (Gharakhani *et al.* 2017, Demirel and Sessiz 2023). Optimised kinematic index, bat configuration, reel speed, height and stem-bending deflection raise feeding efficiency beyond 98% (Chaab *et al.* 2020, Dula *et al.* 2020, Li *et al.* 2024), guided by bending-behaviour models (Shah *et al.* 2017, Al-Zube *et al.* 2018, Martin-Nelson *et al.* 2021, Gangwar *et al.* 2023, Liang *et al.* 2025) and MATLAB-RSM optimisation (Myers *et al.* 2016).

This absence of a bending theory-based optimised reel mechanism is a critical gap for smallholder lentil systems facing labour scarcity and cost constraints (Yang *et al.* 2021, Kuzbakova *et al.* 2022). The study, thus, aimed to

¹College of Agricultural Engineering and Technology, Dr Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar. *Corresponding author email: abhiupadhyay7798@gmail.com

design, optimise and develop a reel mechanism for efficient mechanical lentil harvesting.

MATERIALS AND METHODS

The research was carried out during 2024–25 at Dr Rajendra Prasad Central Agricultural University, Pusa, Samastipur (25°59'10"N, 85°40'31"E), Bihar. HUL 57 lentil variety samples were randomly selected from mature field crops for the data collection. Firstly, the crop physical parameters like crop length, pod height, weight of ear and center length of an ear of the plant were measured and noted.

Physical parameters were integrated into mathematical equations and optimised using Response Surface Methodology (RSM) which involves statistically designed experiments, regression analysis, optimisation of response variables, and interpretation of response surfaces and contour profiles. The RSM enables simultaneous development of empirical and mathematical models. Optimal (custom) design can be employed for multi-response surface analysis (Witek-Krowiak *et al.* 2014, Yusri *et al.* 2018). It establishes an experimental framework enabling estimation of response surfaces using a limited number of observations while accommodating multiple independent variables. Multi-response optimisation was carried out in two sequential stages: model development and optimisation.

Mechanical model of a crop stalk with identical cross-section and effect of an ear: Lentil stalks follow structural engineering principles applicable to other pulse crops, adapted for short plant height, thin fibrous stem diameter, and low flexural rigidity. Stalks are modelled as simply supported or cantilever beams, with reel action idealised as a concentrated horizontal force at reel trajectory height (Leblicq *et al.* 2015, Hou *et al.* 2025).

The predominant deflecting force is horizontal, applied laterally by reel bats to erect plants toward the cutter bar. While the stress-strain relationship is linearly elastic, the small-deflection assumption is not applied, as lentil stems undergo large elastic deformations prior to fracture or pod shattering, necessitating non-linear geometric deflection analysis (Song and Muliana 2019).

For reel loading analysis, the lentil stem was idealised into two regions: the lower stem (greater diameter, higher rigidity, greater resistance to bending and lodging) and the upper stem (smaller diameter, lower flexural stiffness, more susceptible to deformation). Prior studies confirmed that stem diameter, wall thickness, and tissue structure vary along stem length, significantly affecting bending response and stiffness (Shah *et al.* 2017, Amirian *et al.* 2018). In lentil, similar trends were noted, meaning stem stiffness and those basal stem traits act as key drivers of lodging resistance (Ball *et al.* 2006). The stem was split into lower and upper sections for bending moment analysis to capture different mechanical behaviours during reel-crop interaction. Two common bending moment formulae were applied to the respective parts of the lentil stalk i.e. lower structural part, and upper section. This approach of dual-section bending representation enhances the precision of analysis

for predicting stem displacement and pod movement due to reel forces (Zhang *et al.* 2024).

An advanced mechanical model originally developed for cereal and pulse stalks has been extended to lentils, wherein the pod cluster mass is represented as a concentrated load at the midpoint of the grain-bearing stem section, contributing additional bending moment during lateral displacement. Although pod mass is lower than that of cereal ears, it measurably influences tip deflection due to height-dependent variation in stem linear density, increasing susceptibility to bending (Nelson *et al.* 2021).

Self-weight-induced deflection in lentil stalks is negligible compared to that caused by pod mass and reel loading. Consequently, a simplified model omitting distributed stem weight is sufficiently accurate for lentil posture analysis, allowing focus on the principal loading interactions reel force, pod mass and stem flexibility without considerable loss of predictive accuracy (Speck and Burgert 2011). These mechanical models are fundamental to analysing reel-plant interaction, optimising reel position and speed, and minimising harvesting losses in lentil. They enable detailed examination of postural changes, deflections, and stem displacement paths directly influencing crop feeding and shattering during combine operations.

The deflection equation (model) is formulated as follows:

$$0 \leq y \leq h_p \text{ or } y \leq h_p$$

$$\frac{d^2x}{d^2y} = \frac{p(h_p - y) + W(l_e \sin^{\theta_t}/2 + x_t - x)}{EI} \quad (1)$$

$$h_p \leq y \leq h_t \text{ or } y \leq h_p$$

$$\frac{d^2x}{d^2y} = \frac{W(l_e \sin^{\theta_t}/2 + x_t - x)}{EI} \quad (2)$$

The mechanical model shown in Fig. 1(A) was used to derive the stalk deflection equation. The ear's weight was considered as a point load at the stalk tip. Flexural rigidity (D) was treated as a single parameter, and the deflection angle represented the stalk's deviation from the vertical position.

$$\phi = \frac{dx}{dy} = \frac{p(h_p y - y^2/2) + W(l_e - x)y}{EI} \quad (3)$$

At the ground level, the deflected stalk has no slope, so the boundary condition is zero. Under this condition, the constant in the equation becomes zero.

$$l_e = l_e \sin^{\theta_t}/2 + x_t \text{ and } (x, y) = (x_p, h_p)$$

$$\phi = \frac{dx}{dy} = \frac{ph_p^2/2 + W(l_e - x_p)h_p}{EI} = \frac{h_p[ph_p + 2W(l_e - x_p)]}{2EI} \quad (4)$$

Crop stems were modeled as elastic cantilever beams fixed at the base. The relationship between applied reel force and lateral deflection was obtained using classical Euler–Bernoulli beam theory, which has been widely applied for agricultural crop stems (Mohsenin 1986, O'Dogherty 1989).

$$X_p = \frac{ph_p^3}{3EI} \quad (5)$$

Where p, Deflection force applied to the lentil stalk

at height h_p ; h_p , Height at which the deflection force p is applied; y , Vertical coordinate along the stalk; W , Weight acting on the stalk and pod; l_c , Length of the pod; θ_t , Deflection angle at the tip of a stalk at time t ; x_t , x-coordinate of the stalk position at time t ; x , Horizontal coordinate of the stalk; E , Young's modulus of the stalk material; I , Moment of inertia of the stalk cross-section; EI , Flexural rigidity of the stalk; h_t , Height of the stalk position at time t ; t , Time after reel engagement;

Interaction between deflection of crop stalk and reel operation: Fig. 1(B) describes reel-stalk interaction. Kinematic behaviour is governed by forward speed (V_m) and angular velocity (ω), with (x_i , y_i) as reference coordinates and x_s as the x-coordinate of first reel tine-stalk contact. The reel moves forward at V_m and rotates at ω , producing a tangential velocity V .

$$V = \omega R \quad (6)$$

Where ω , Angular velocity of the reel; R , Radius of the reel.

Experimental design for optimisation: Shattering is influenced by lentil stalk deflection, with reel force, ear weight and flexural rigidity as input parameters. MATLAB simulations of the developed models were used to analyse their effects on stalk deflection. A design matrix was generated in Design-Expert v13 (student trial version) and RSM was applied to four-level datasets to determine the optimum deflection angle for minimising shattering loss.

Evaluation of reel stagger and tine bar configuration: Crop stem deflection determines reel stagger in harvester design. Stems should be cut when the rising tine bar's velocity becomes tangent to the bent stem curve—Equation 4.9 was developed based on this principle (Kassa and Abdi 2014). The vertical distance R_o corresponds to the reel's

forward advance per radian of rotation and is expressed as

$$R_o = \frac{V_m}{\omega} \quad (7)$$

Where R_o , Reel's forward advance per radian of rotation; V_m , Forward speed of the harvester; ω , Angular velocity of the reel.

R_o (m/radian) has dimensions of length since radians are dimensionless. Therefore, R and R_o can be treated as quantities of the same type without violating dimensional consistency.

$$\omega = \sin^{-1}\left(\frac{R_o}{R} \sin \phi\right) + \frac{\pi}{2} - \phi \quad (8)$$

Another potential application of reel-induced stem deflection is to estimate the optimal number of tine bars (n) required on the reel mechanism. After the leading tine bar delivers stalks to the cutter bar, the trailing tine bar must engage the next row of stems, preventing cut material from moving forward and being lost. Stems incompletely cut between successive tine bars are acknowledged but neglected in determining the required number of tine bars.

$$\alpha = \omega t - \cos^{-1}\left(\frac{Z_r}{R} + \cos \omega t\right) \quad (9)$$

Where α , Angular displacement between successive tine bars; ω , Angular velocity of the reel; t , Time after reel engagement; Z_r , Horizontal distance between successive tine bars; R , Radius of reel.

Furthermore, the required number of tine bars on the reel can be calculated as follows:

$$n = \frac{2\pi}{\alpha} \quad (10)$$

Where n , Number of tine bars; α , Angular displacement between successive tine bars.

RESULTS AND DISCUSSION

In this developmental study, a total of 64 data sets, generated through four replications of the equations, were employed to formulate acceptable deflection angle.

RSM model: The outputs obtained from the mathematical models were subjected to analysis using the student trial version of design-expert Version 13 for optimisation of the deflection angle. The equation expressed in coded variables can be used to predict the response at given factor levels. By convention, high factor levels

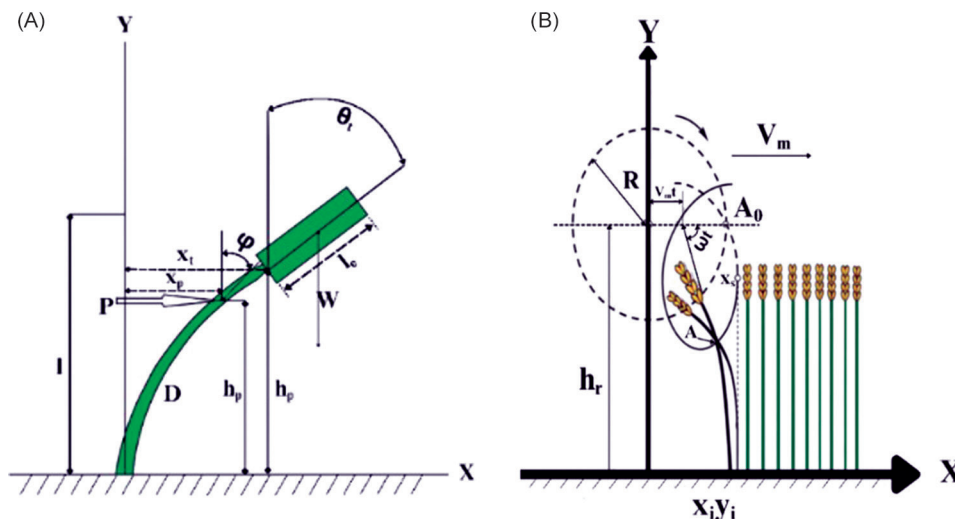


Fig. 1 Schematic view of (A) Influence of deflection force (P) applied at height (h_p) on a lentil stalk with ear, and (B) Reel trajectory dynamics and crop stalk deflection at the operating point A.

Where A_o , Initial stalk position; h_r , Reel axis height; R , Reel radius; t , Deflected position at time t due to reel engagement; V_m , Forward speed; ω , Angular velocity; x_i and y_i , Reference coordinates; x_s , x-coordinate of first reel tine-stalk contact.

are coded as +1 and low levels as -1. The coded form of the equation enables direct comparison of coefficients to determine relative factor impact. The final coded-factor equation for the deflection angle (ϕ) is presented in Equation (11).

$$\phi = 1.11 - 0.7226A - 0.0157B + 0.8098C + 0.0365AB - 0.4309AC + 0.0351BC + 0.4019A^2 - 0.1016B^2 + 0.0205C^2 \quad (11)$$

Where A, Flexural rigidity; B, Weight of ear; C, Reel force; ‘-’, Antagonistic effects; ‘+’, Synergistic effects.

The equation expressed in actual factors can be used to predict the response at specified factor levels using their original units. However, it is not appropriate for evaluating the relative influence of individual factors, as the coefficients depend on factor units and the intercept does not represent the center of the design space. The final empirical equations for the deflection angle, expressed in terms of real-world units, are as follows:

$$\phi = 1.21964 - 1.13148D + 29.04753W + 3.38066P + 2.16145DW - 0.638405DP + 6.93691WP + 0.178634D^2 - 802.41416W^2 + 0.101316P^2 \quad (12)$$

Where D, Flexural rigidity; W, Weight of ear; P, Reel force; ‘-’, Antagonistic effects; ‘+’, Synergistic effects.

ANOVA confirmed the quadratic model for deflection statistically significant at 95% confidence level: F-value =

159.14, $p < 0.0001$, $R^2 = 0.9931$. Adjusted R^2 (0.9868) and Predicted R^2 (0.9567) difference of only 0.0301 confirmed no overfitting and strong predictive power. Adequate precision = 42.47 (exceeds threshold of 4), indicating robust signal-to-noise ratio. RSM residual graphs (Fig. 2 A–D) confirmed model accuracy.

Residuals (difference between experimental and model-predicted deflection angles) were analysed via a normal probability plot, showing approximate normal distribution with no significant deviation. The residuals vs. predicted plot showed data points closely aligned along the 45° line, confirming satisfactory predictive capability. The predicted vs. actual plot further demonstrated good agreement, with data points near the reference line and R^2 approaching unity.

Effects of individual factors and their interactions on the responses: The perturbation plot (Fig. 2E) showed combined influence of independent variables on deflection angle. Reel force (C) increased deflection angle, while flexural rigidity (A) decreased it significantly. Ear weight (B) showed negligible effect (nearly horizontal). Deflection angle was most sensitive to flexural rigidity (A), followed by reel force, as higher reel force increases bending moment while higher flexural rigidity increases internal resistance to deformation. A similar trend was previously reported for teff crop (Kassa and Abdi 2014, Dula *et al.* 2020, Langer *et al.* 2021).

The observed behaviour has attributed to the mechanical interaction between the reel and the crop stem. An increase

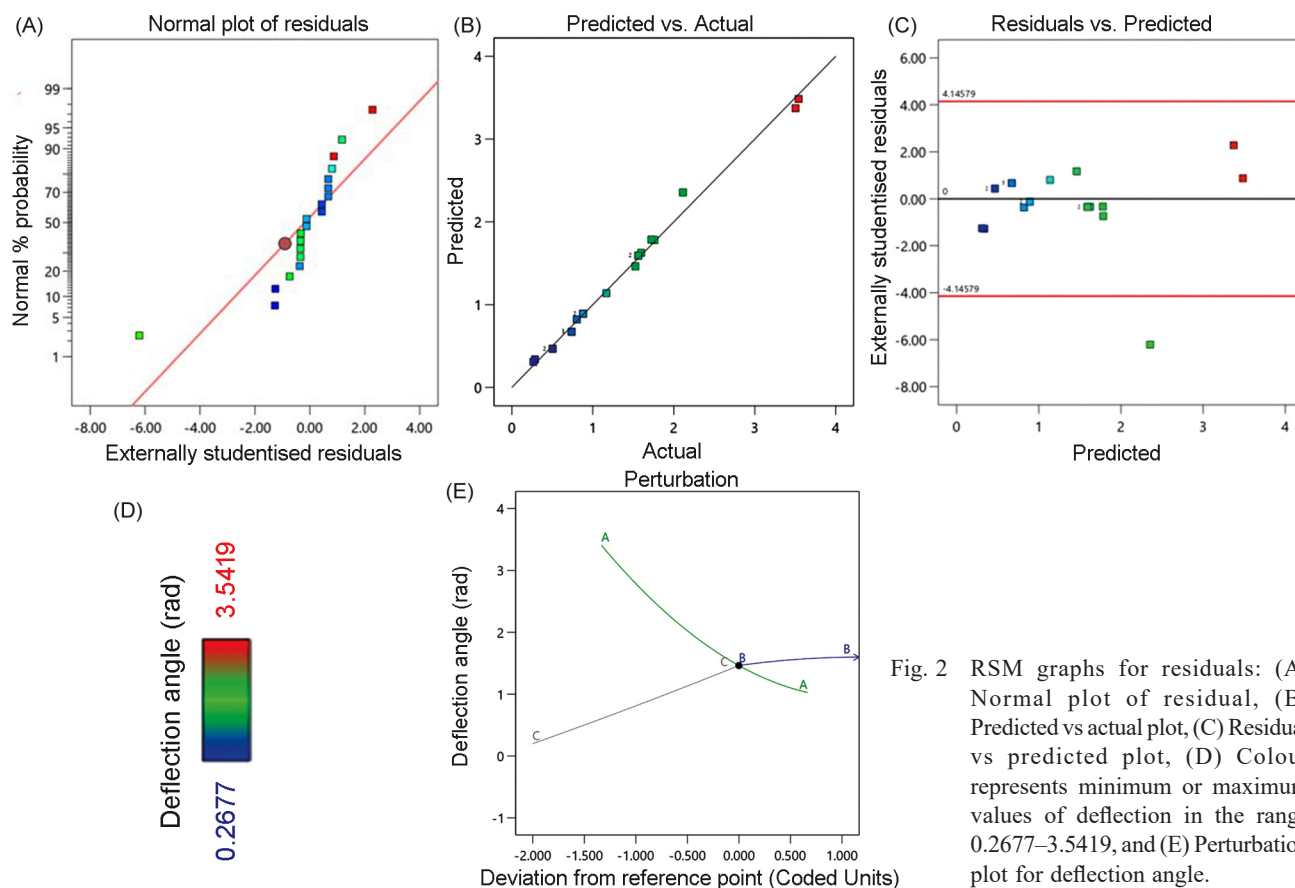


Fig. 2 RSM graphs for residuals: (A) Normal plot of residual, (B) Predicted vs actual plot, (C) Residual vs predicted plot, (D) Colour represents minimum or maximum values of deflection in the range 0.2677–3.5419, and (E) Perturbation plot for deflection angle.

Table 1 ANOVA and model statistics of quadratic model for deflection

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	16.01	9	1.78	159.14	< 0.0001	significant
A-Flexural Rigidity (D)	5.56	1	5.56	497.90	< 0.0001	significant
B-Weight of Ear (W)	0.0026	1	0.0026	0.2321	0.6404	
C-Reel Force (P)	6.98	1	6.98	624.31	< 0.0001	significant
AB	0.0088	1	0.0088	0.7859	0.3962	
AC	1.22	1	1.22	109.29	< 0.0001	significant
BC	0.0081	1	0.0081	0.7269	0.4139	
A ²	0.5916	1	0.5916	52.93	< 0.0001	significant
B ²	0.0371	1	0.0371	3.32	0.0985	
C ²	0.0015	1	0.0015	0.1347	0.7213	
Residual	0.1118	10	0.0112			
Lack of fit	0.1118	5	0.0224			
Pure error	0.0000	5	0.0000			
Cor total	16.12	19				
SD	0.1057		R ²	0.9931		
Mean	1.32		Adjusted R ²	0.9868		
CV %	8.01		Predicted R ²	0.9567		
			Adequate precision	42.4726		

in reel force generates a higher external bending moment on the stalk, resulting to the greater stem deflection. In contrast, increased flexural rigidity (D), represented as the combined effect of stem material stiffness and geometric resistance to bending, enhances the stalk's ability to withstand deformation and consequently reduces the deflection angle. Similar relationships between bending moment, stem stiffness and deflection behaviour were reported by Martin-Nelson *et al.* (2021) and Stubbs *et al.* (2022), where stem flexural rigidity was identified as a key parameter governing plant response to external loading. Furthermore, recent modelling studies as conducted by Wu *et al.* (2022) and Gangwar *et al.* (2023) revealed that variations in stem geometry and stiffness significantly influenced bending behaviour under applied loads, affecting crop recovery and resistance to lodging. Therefore, the inverse relationship observed between flexural rigidity and deflection angle in the present study is in consistent with established principles of plant biomechanics and stem bending mechanics.

ANOVA (Table 1) and 3D plots (Fig. 3) via Design-Expert 13 determined interaction effects of flexural rigidity (A), reel force (C), and ear weight (B) on deflection angle ($p < 0.05$). Deflection angle increased with reel force (C), showing an increasing slope at greater reel force across tested A and B ranges. Higher deflection results from increased bending moment from reel force (Abolfathi *et al.* 2010), while flexural rigidity is the primary resistance factor against deformation (Berger 2022).

The deflection angle increases as the reel force (C) got higher, and the response surface had a more pronounced slope at those higher reel force levels, across the tested ranges of flexural rigidity (A) and ear weight (B). This kind of behaviour has been explained by the fact that the bending moment acting on the stalk increases when reel force increases, which then drives more stem deformation and so, a bigger deflection angle. Same relation has been reported by Abolfathi *et al.* (2010). On the other hand, flexural rigidity (D) sort of bundles the effect of both material stiffness and stem geometry together, and becomes the main thing that resists the bending and deformation. If stems have greater flexural rigidity, they need a larger external force to reach the same deflection, so under similar loading, the deflection angle drops. Similar findings about applied force, stem stiffness and plant deflection have been reported in work focused on lodging resistance and plant biomechanics, where stem morphology and flexural stiffness were described as main determinants for how crops react to outside mechanical pressures (Shah *et al.* 2017, Martin-Nelson *et al.* 2021). More recent investigations also showed that differences in stem geometry, tissue properties and structural stiffness are really influential for bending behaviour and shape the deformation pattern under dynamic loading (Stubbs *et al.* 2022, Gangwar *et al.* 2023). Also, Jonsson *et al.* (2023) reported in research into plant bending mechanics that stem deflection is controlled by the trade-off between the externally applied bending moment and

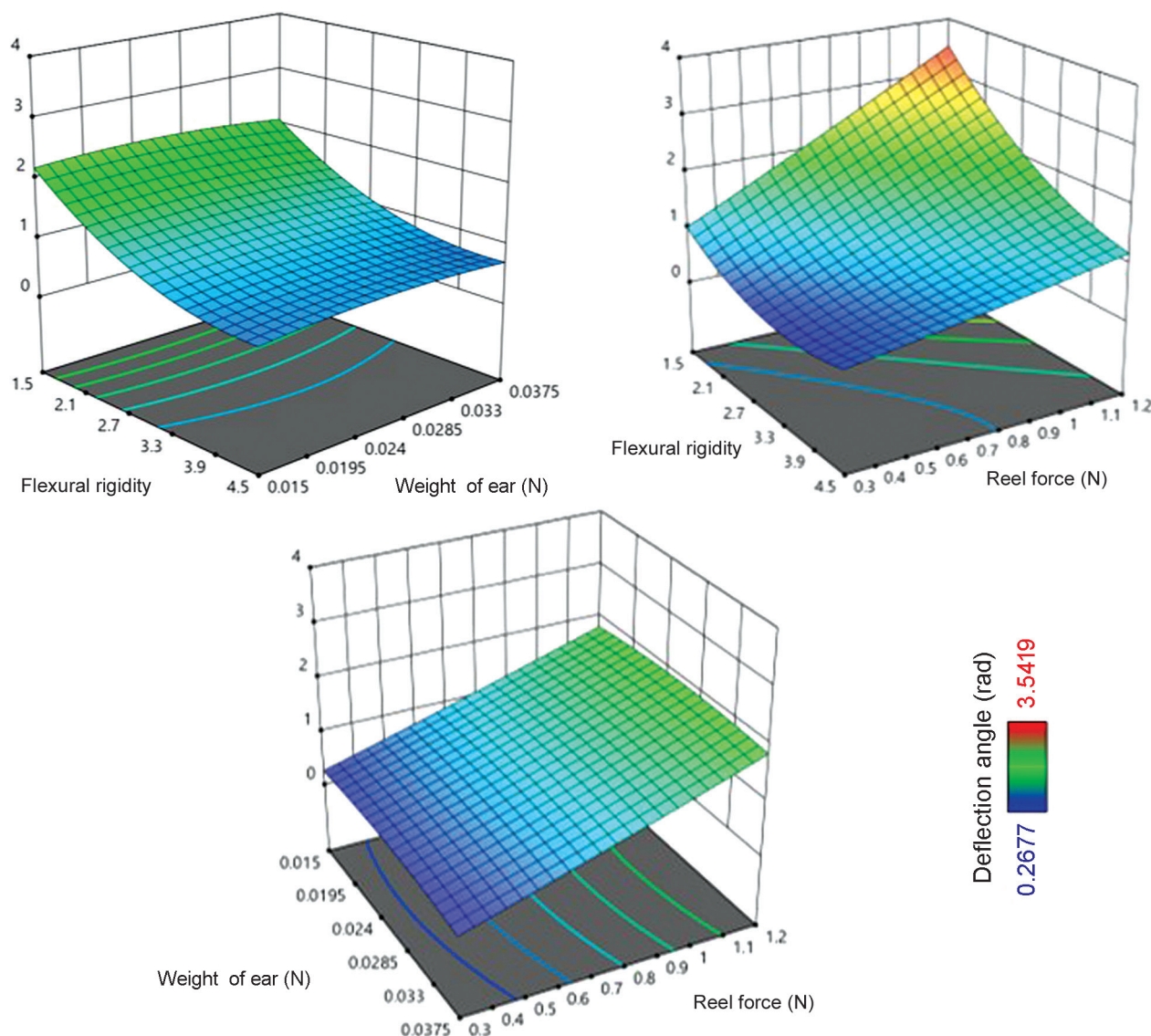


Fig. 3 3D graphs for significant interaction effect of independent parameters on deflection angle. Colour represents minimum or maximum values of deflection angle (rad).

the intrinsic mechanical resistance from the stem tissues. So overall, the increase in deflection angle with reel force and its decrease as flexural rigidity rises, do fit well with the known theories of stem biome.

Design of reel: Mechanical crop modelling used bending theory incorporating flexural rigidity (D), ear weight (W), reel force (P), loading height (h_p) and reel kinematics, plotted via MATLAB. Deflection angles were optimised using RSM optimal (custom) design to determine header advance per radian (R_o), angular displacement (θ), and number of tine bars (n). The optimum deflection angle (ϕ) obtained from RSM is 1.46242 rad (83.79°).

Angular displacement of consecutive tine bars: The angular displacement of consecutive tine bars was determined to estimate the appropriate number of tine bars on the reel, based on the deflection angle and reel stagger. The input data used for the calculation included

an optimised deflection angle (ϕ) of 83.79°, a reel radius (R) of 35 cm, a reel rotational speed (N) of 15 rpm and a reel stagger (Z_r) of 16 cm.

Design parameters of the reel: The key design parameters of the reel mechanism were calculated through a mathematical design to achieve synchronised crop harvesting and efficient cutting of lentil. The reel rotational speed (ω) was 1.57 rad/sec, producing a peripheral speed (V) of 0.5495 m/sec, with the machine operating at a forward speed (V_m) of 0.4396 m/sec. The header advance per radian (R_o) was 28 cm, angular displacement (ωt) was 58.893° and angular spacing (α) between successive tine bars was 45.744°, yielding a total of eight tine bars. Reel loss was 2.92%, compared against 9% reported for pulse crops harvested using conventional cereal-based headers.

A simplified mechanical model was developed to estimate the deflection angle and bending force of lentil

stalks during reel-crop interaction. Response Surface Methodology (RSM) yielded an optimum value of 83.79° with high desirability at a flexural rigidity of 30.1 kN·mm², ear weight of 0.025 N, reel force of 0.5 N and loading height of 10 cm. The number of tine bars and their angular spacing were determined based on the modelled stem bending behaviour and the optimised parameters were incorporated into the developed reel mechanism. Field evaluation of the reel-equipped harvester provided direct validation of the modelling results through satisfactory crop feeding and harvesting efficiency. Reel loss of 2.92% was substantially lower than the reported 9% for pulse crops harvested with conventional cereal-based headers. Given the narrow 10–15 day harvesting window for lentil, the modelling and optimisation approach effectively reduced prototype iterations and field trials, minimising development cost and time. These findings confirm that lentil can be harvested using a combine harvester in a manner analogous to rice and wheat, and that bending theory-based reel design may be a practically viable approach for improving lentil harvesting efficiency.

ACKNOWLEDGEMENT

The authors express sincere gratitude to the Department of Science and Technology (DST), Government of India for financial support under INSPIRE Fellowship reference no. DST/INSPIRE Fellowship/IF240176.

REFERENCES

- Abolfathi A, Brennan M J and Waters T P. 2010. *Large Deflection of a Simply Supported Beam*. ISVR Technical Memorandum No. 988. University of Southampton, Southampton, UK. 28 pp.
- Al-Zube L, Sun W, Robertson D and Cook D. 2018. The elastic modulus for maize stems. *Plant Methods* **14**: 11. <https://doi.org/10.1186/s13007-018-0279-6>
- Amirian F, Shahbazi F and Taheri Garavand A. 2018. Effects of moisture content and stem region on the bending characteristics of chickpea stem. *Agricultural Engineering International: CIGR Journal* **20**(2): 190–96.
- Ball R A, Hanlan T G and Vandenberg A. 2006. Stem and canopy attributes that affect lodging resistance in lentil. *Canadian Journal of Plant Science* **86**(1): 71–81. <https://doi.org/10.4141/P05-037>
- Barker B. 2025. *Managing Harvest Losses in Pulses and Soybeans*. Saskatchewan Pulse Growers, Canada.
- Bawatharani R, Jayatissa D N, Dharmasena D A N and Bandara M H M A. 2013. Impact of reel index on header losses of paddy and performance of combine harvesters. *Tropical Agricultural Research* **25**(1): 1–13. <https://doi.org/10.4038/tar.v25i1.8025>
- Berger J. 2022. Effects of flexural stiffness on constraints of imposed deformations in reinforced concrete structures. *Engineering Structures* **272**: 114973. <https://doi.org/10.1016/j.engstruct.2022.114973>
- Chaab R K, Karparvarfard S H, Rahmanian-Koushkaki H, Mortezaei A and Mohammadi M. 2020. Predicting header wheat loss in a combine harvester: A new approach. *Journal of the Saudi Society of Agricultural Sciences* **19**(2): 179–84. <https://doi.org/10.1016/j.jssas.2018.09.002>
- Demirel İ and Sessiz A. 2023. Effects of harvest-threshing methods used in lentil harvesting on fuel consumption, grain losses and machine field capacity. *ISPEC Journal of Agricultural Sciences* **7**(3): 670–80. <https://doi.org/10.5281/zenodo.8361917>
- Dula M W, Kereyu S L, Keneni M T and Tadele C. 2020. Design and fabrication of teff threshing machine. *Nanoscience and Nanometrology* **6**(2): 10–18. <https://doi.org/10.11648/j.nsnm.20200602.11>
- Gangwar T, Susko A Q, Baranova S, Guala M, Smith K P and Heuschele D J. 2023. Multi-scale modelling predicts plant stem bending behaviour in response to wind to inform lodging resistance. *Royal Society Open Science* **10**(1): 221410. <https://doi.org/10.1098/rsos.221410>
- Gharakhani H, Alimardani R and Jafari A. 2017. Design a new cutter-bar mechanism with flexible blades and its evaluation on harvesting of lentil. *Engineering in Agriculture, Environment and Food* **10**(3): 198–207. <https://doi.org/10.1016/j.eaef.2017.03.001>
- Golpira H, Rovira-Mas F, Golpira H and Saiz-Rubio V. 2021. Mathematical model-based redesign of chickpea harvester reel. *Spanish Journal of Agricultural Research* **19**(1): e0203. <https://doi.org/10.5424/sjar/2021191-16391>
- Golpira H, Tavakoli T and De Baerdemaeker J. 2013. Design and development of a chickpea stripper harvester. *Spanish Journal of Agricultural Research* **11**(4): 929–34. <https://doi.org/10.5424/sjar/2013114-3393>
- Hou J, Li Z, Ma Y, Xu Y, Hao D, Li C, Li C, Tang Q and Liu M. 2025. Mechanical properties of corn stalks and behavior of particles during compression process based on discrete element method. *Agriculture* **15**(17): 1824. <https://doi.org/10.3390/agriculture15171824>
- Jonsson K, Ma Y, Routier-Kierzkowska A L and Bhalerao R P. 2023. Multiple mechanisms behind plant bending. *Nat Plant* **9**(1): 13–21. DOI: 10.1038/s41477-022-01310-y
- Kassa E Z and Abdi Z. 2014. Design and modification of appropriate reel mechanism to harvest teff crop. *International Journal of Research in Mechanical Engineering* **2**(1): 15–25. https://iaeme.com/Home/article_id/IJRME_02_01_002
- Kuzbakova M, Khassanova G, Oshergina I, Ten E, Jatayev S, Yezhebayeva R, Bulatova K, Khalbayeva S, Schramm C, Anderson P, Sweetman C, Jenkins C L D, Soole K L and Shavrukov Y. 2022. Height to first pod: A review of genetic and breeding approaches to improve combine harvesting in legume crops. *Frontiers in Plant Science* **13**: 948099. <https://doi.org/10.3389/fpls.2022.948099>
- Langer M, Kelbel M C, Speck T, Muller C and Speck O. 2021. Twist-to-bend ratios and safety factors of petioles having various geometries, sizes and shapes. *Frontiers in Plant Science* **12**: 765605. <https://doi.org/10.3389/fpls.2021.765605>
- Leblicq T, Vanmaercke S, Ramon H and Saeys W. 2015. Mechanical analysis of the bending behaviour of plant stems. *Biosystems Engineering* **129**: 87–99. <https://doi.org/10.1016/j.biosystemseng.2014.09.016>
- Li Y H, Li C, Liu L P, Zhou K and Hou J L. 2024. Design and test of the plant-correcting reel for harvesting lodging garlic plants. *International Journal of Agricultural and Biological Engineering* **17**(1): 59–68. <https://doi.org/10.25165/j.ijabe.20241701.7784>
- Liang Z, Liu J, Yang D and Ouyang K. 2025. Modeling and simulation of reel motion in a foxtail millet combine harvester. *Agriculture* **15**(1): 19. <https://doi.org/10.3390/agriculture15010019>
- Marini V K and Romano L N. 2009. Influencing factors in

- agricultural machinery design. *Product: Management and Development* 7(2): 111–30.
- Martin-Nelson N, Sutherland B, Yancey M, Liao C S, Stubbs C J and Cook D D. 2021. Axial variation in flexural stiffness of plant stem segments: Measurement methods and the influence of measurement uncertainty. *Plant Methods* 17: 101. <https://doi.org/10.1186/s13007-021-00793-8>
- Mohsenin N N. 1986. *Physical Properties of Plant and Animal Materials*, 2nd edn. Gordon and Breach Science Publishers, New York.
- Myers R H, Montgomery D C and Anderson-Cook C M. 2016. *Response Surface Methodology: Process and Product Optimisation Using Designed Experiments*, 4th edn. Wiley.
- Nelson K L, Davis J E and Corbett C F. 2022. Sleep quality: An evolutionary concept analysis. *Nursing Forum* 57(1): 144–51. <https://doi.org/10.1111/nuf.12659>
- O'Dogherty M J. 1989. A review of mechanical behaviour of cereal straw. *Journal of Agricultural Engineering Research* 44: 1–18. [https://doi.org/10.1016/S0021-8634\(89\)90086-1](https://doi.org/10.1016/S0021-8634(89)90086-1)
- Oduori M F, Mbuya T O, Sakai J and Inoue E. 2012a. Modeling of crop stem deflection in the context of combine harvester reel design and operation. *Agricultural Engineering International: CIGR Journal* 14(2): 21–28. <http://cigrjournal.org/index.php/Ejournal/article/view/1575>
- Oduori M F, Mbuya T O, Sakai J and Inoue E. 2012b. Kinematics of the tined combine harvester reel. *Agricultural Engineering International: CIGR Journal* 14(3): 53–60. <http://cigrjournal.org/index.php/Ejournal/article/view/1577>
- Shah D U, Reynolds T P S and Ramage M H. 2017. The strength of plants: Theory and experimental methods to measure the mechanical properties of stems. *Journal of Experimental Botany* 68(16): 4497–4516. <https://doi.org/10.1093/jxb/erx245>
- Song R and Muliana A. 2019. Modeling mechanical behaviors of plant stems undergoing microstructural changes. *Mechanics of Materials* 139: 103175. <https://doi.org/10.1016/j.mechmat.2019.103175>
- Speck T and Burgert I. 2011. Plant stems: Functional design and mechanics. *Annual Review of Materials Research* 41: 169–193. DOI: 10.1146/annurev-matsci-062910-100425
- Srivastava A K, Goering C E, Rohrbach R P and Buckmaster D R. 2006. Grain Harvesting. (In) *Engineering Principles of Agricultural Machines*, 2nd edn, pp. 403–36. American Society of Agricultural and Biological Engineers, St. Joseph, Michigan. <https://doi.org/10.13031/2013.41474>.
- Stubbs C J, Larson R and Cook D D. 2022. Maize stalk stiffness and strength are primarily determined by morphological factors. *Scientific Reports* 12: 720. <https://doi.org/10.1038/s41598-021-04114-w>
- Tripathi V and Chisi N. 2024. Enhancing the yield of lentils (*Lens culinaris*) in Greater Noida (U.P.) through improved irrigation frequency, nutrient management and mulching. *International Journal of Current Microbiology and Applied Sciences* 13(11): 51–62. <https://doi.org/10.20546/ijcmas.2024.1311.007>
- Witek-Krowiak A, Chojnacka K, Podstawczyk D, Dawiec A and Bubata K. 2014. Application of response surface methodology and artificial neural network methods in modelling and optimisation of biosorption process. *Bioresource Technology* 160: 150–60. <https://doi.org/10.1016/j.biortech.2014.01.021>
- Wu W, Hu Y and Jiang Z. 2022. Investigation on the bending behavior of tea stalks based on a non-prismatic beam with virtual internodes. *Agriculture* 12(3): 370. <https://doi.org/10.3390/agriculture12030370>
- Yadav A K, Singh K M, Singh R K, Singh R P and Nayak R. 2020. Production and productivity enhancement in lentil through cluster front line demonstrations in Azamgarh district. *The Journal of Rural and Agricultural Research* 20(1): 65–68. <https://jraragra.in/Journals/2020Vol1/15.pdf>
- Yang T, Liu K, Poppy L, Mulenga A and Gampe C. 2021. Minimising lentil harvest loss through improved agronomic practices in sustainable agro-systems. *Sustainability* 13(4): 1896. <https://doi.org/10.3390/su13041896>
- Yusri I M, Abdul Majeed A P P, Mamat R, Ghazali M F, Awad O I and Azmi W H. 2018. A review on the application of response surface methodology and artificial neural network in engine performance and exhaust emissions characteristics using alternative fuels. *Renewable and Sustainable Energy Reviews* 90: 665–86. <https://doi.org/10.1016/j.rser.2018.03.095>
- Zhang J, Xie J, Du Y, Li Y, Yue Y and Cao S. 2024. Discrete element modeling and experimental study of biomechanical properties of cotton stalks in machine-harvested film stalk mixtures. *Scientific Reports* 14: 12933. <https://doi.org/10.1038/s41598-024-62390-8>