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3D FINITE ELEMENT ANALYSIS OF THE TILLAGE AND STRAW CUTTING PERFORMANCE OF A CURVED-EDGED TOOTHED DISC

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KEYWORDS

tillage resistance forces, straw-cutting efficiency, curved-toothed disc, Finite Element Analysis (FEA), conservation tillage.

ABSTRACT

The management of crop residues together with compacted soil under intensive farming systems requires highly efficient and well-adapted tools. The performance assessment of such tools requires proper definition of their technical designs as well as the tool-induced soil-straw dynamic interactions. Few studies have characterized the performance of toothed discs based on their design considerations and mechanical responses. This study evaluated the tillage forces, structural strength, straw-cutting performance, and tillage-depth uniformity of a curved-edged toothed disc in comparison to a straight-edged toothed disc. The design of the curved-toothed disc was inspired by the arc-shaped structure of the mole-rat's claw. 3D finite element analysis (FEA) was used to simulate the discs' interactions with soil and straw. Field experiments were conducted to validate the FEA results. It was revealed that the curved disc reduced the tillage forces by up to 22.8%, and significantly reduced the stresses on the tool. The disc also achieved uniform tillage depths and improved the straw-cutting efficacy by up to 26.31%. Bionic curved cutting-profiles on toothed discs thus provide a structurally enhanced, energy-efficient option for effectively managing crop residues and improving seeding performance in no-till conservation farming.

INTRODUCTION

Tillage discs play a key role in mechanized conservation farming by facilitating smooth sowing in the presence of crop-residue cover (Zeng & Chen, 2018). However, conventional disc designs perform poorly when working in the compacted soils and dense crop-residue conditions that are commonly observed in intensive farming systems (Ahmad et al., 2017). The thick layers of straw often induce high resistance forces on the discs, causing them to bounce off the ground and drag or fold the straw in furrows (Zeng & Chen, 2019). Besides the impacts of soil and crop residues, the geometry of the cutting blade significantly affects the performance of tillage discs (Zhao et al., 2020; Armin et al., 2014). This has led to the development of several disc configurations, with the commonly available designs being: plain, notched (toothed), fluted, bubble, corrugated and wavy (ASABE, 2013). Generally, toothed discs have been shown to have better soil penetration, lower resistance forces, and improved crop-

residues cutting performance compared to smooth-edged discs (Magalhães et al., 2007; Ahmad et al., 2017). Various configurations of toothed discs have been developed to optimize their performance and adaptability. In particular, toothed discs with curved cutting profiles have been proposed to further improve the shearing capability and minimize tillage resistance (Zhao et al., 2020; Li et al., 2013).

To achieve high-efficiency and well-adapted toothed discs, it is important to understand the technical basis of the adopted design configuration. One of the most viable concepts for design optimization is through biomimetics, where tools are developed by mimicking the well-developed morphologies of living organisms (Jia et al., 2019; Wang et al., 2019). This concept has been proven effective in reducing cutting resistance and improving the working efficiencies of tools (Zhang et al., 2016; Sun et al., 2018). Apart from the technical features of the soil-engaging tools, it is also necessary to consider the mechanical interactions of the tool with the soil and straw

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in specific working environments. This knowledge can be crucial in determining the fundamental tool characteristics for meeting the performance demands of conservation tillage (Zeng et al., 2020). However, defining the intricate non-linear behavior of soil and straw during tillage is challenging (Richards & Peth, 2009). Studies on the soil–tool interaction dynamics have taken three main approaches, namely: experimental, theoretical analyses, and numerical simulations. Numerical simulation methods have shown great advantages over the other two methods because of their ability to solve the problems of complex tool geometries (Ucugul et al., 2018; Karmakar & Kushwaha, 2006).

The Finite Element Method (FEM) is a robust numerical approach that has been widely used to study soil–tool interactions due to its relative ease in model formulation (Zhang et al., 2018). In FEM, materials are treated as continua, while stresses and strains represent forces and displacements within particles (Upadhyaya et al., 2002). With a proper choice of the constitutive laws governing stress–strain relationships, the non-linear soil and straw interactions can be modeled (Tagar et al., 2015; Li et al., 2013). Various researchers have employed FEM to study different agricultural tools. He et al. (2016) examined the effects of the cutting depths of different tine geometries on penetration resistance and soil disturbances using FEM. Their work showed that the cutting resistance increased with the surface area, thickness, and depth. Tagar et al. (2015) simulated the soil failure patterns of a cutting tool in relation to consistency limits and sticky points of soil using FEM. Ibrahim et al. (2015) used FEM to study the effects

of the working depth, speed, cutting angle, and lifting angle of a moldboard plow on tillage forces.

Whereas many studies have focused on the soil-engaging effects of conventional tools, hardly any researcher has empirically defined the design considerations of toothed discs based on the mechanical responses of soil and plant-residue interactions in the context of conservation tillage. The purpose of this study, therefore, was to examine the soil and straw engaging dynamics of a bionic curved-toothed disc in terms of tillage resistance forces, structural strength, straw-cutting performance, and tillage-depth uniformity. Field experimental tests were used to validate the finite element analysis (FEA) predictions.

MATERIAL AND METHODS

Design of the curved-toothed disc

The curved-toothed disc was developed by mimicking the arc-shaped profile of the mole-rat (*Scaptochirus moschatus*) claw. In earlier studies, Li et al. (2013) established that the curved outline of the mole’s claw improves the structural strength and digging performance. The curved claw profile of the mole-rat’s second toe was thus traced from its image using AutoCAD 2017 (Autodesk) software and the longer arc used for reverse-engineering the cutting edges of the bionic curved-toothed disc, as shown in Figure 1a. A straight-edged toothed disc was developed for comparative purposes, as shown in Figure 1b. Both discs had an equivalent mass of 2.7 kg, density of $7.85 \times 10^{-9} \text{ Mg mm}^{-3}$, Young’s modulus of 201 GPa, Poisson’s ratio of 0.3; and were 457 mm in diameter and 3.5 mm in thickness.

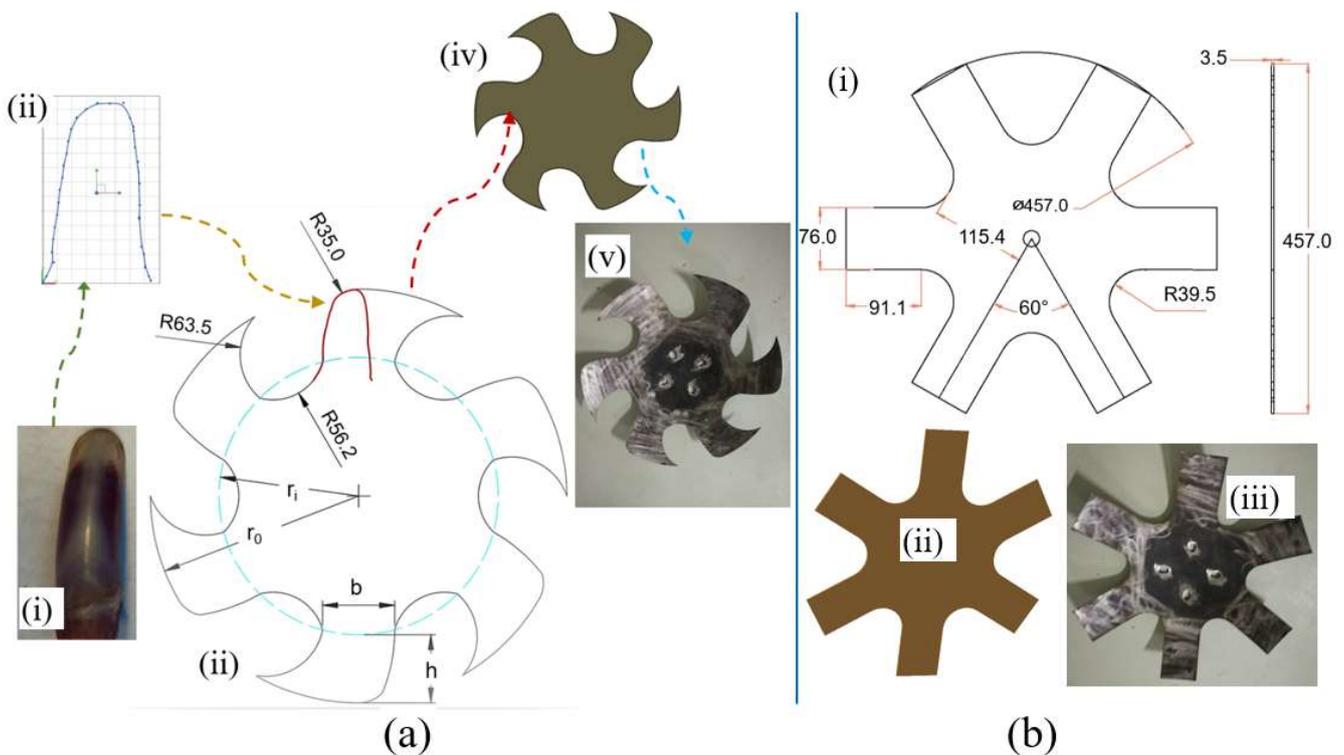


FIGURE 1. (a) (i) Image of a mole-rat’s claw (Li et al., 2013), (ii) traced outline of the mole’s claw, (iii) scaled structure of the proposed disc, (iv) 3D illustration of the curved-toothed disc, (v) curved-toothed disc developed for the study. (b) (i) Configurations of the straight-edged toothed disc, (ii) 3D representation of the straight-edged disc, (iii) mock-up fabricated for the study.

Soil and straw properties

Cylindrical soil cores collected from the experimentation field of Nanjing Agricultural University were weighed before and after oven-drying at 105 °C for 24 h and used to determine the soil bulk density and moisture content. Direct shear tests and triaxial compression tests were used to determine the soil cohesion, internal friction angle, and soil shear properties (Fredlund & Vanapalli, 2002). The soil properties are summarized in Table 1.

TABLE 1. Soil mechanical properties.

Parameter	Value
Soil bulk density (Mg m^{-3})	1.39
Cohesion (kPa)	40.52
Soil moisture content (%)	22.90
Young's modulus (MPa)	2.84
Poisson's ratio	0.43
Flow stress ratio	0.86
Dilatation angle ($^{\circ}$)	0.00
Coefficient of soil-metal friction	0.42
Internal friction angle, Mohr-Coulomb ($^{\circ}$)	12.90

Rice straw was collected from a freshly harvested field and dried in the open air for four weeks to a moisture content of 9–15%. The straw shearing strength and failure characteristics were determined using the TMS-Pro Texture Analyzer (Food Technology Corp., USA). Table 2 lists the straw properties.

TABLE 2. Straw mechanical properties.

Property	Value
Bulk density (Mg m^{-3})	0.18
Average straw length (mm)	370
Straw diameter (mm)	5.00
Straw wall thickness (mm)	0.50
Poisson's ratio	0.025
Yield strength (MPa)	9.25

Finite element analysis

FEM involves pre-processing where the system being studied is divided into finite elements (meshing) together with formulating the material properties of the elements, assembling the parts in the manner in which they interact, and defining the loading and boundary conditions. Also, the degrees of freedom should be established and the field outputs required outlined before running the FEA solver. The post-processing involves preparing the output presentation and interpretation.

In this study, 3D FEA dynamic explicit models were developed using Abaqus/CAE 6.14 software (Dassault Systèmes Simulia Corp., Vélizy-Villacoublay, France). The soil was modeled as an elastic-plastic material of dimensions 1000 mm length, 500 mm width, and 250 mm depth; and subjected to the extended Drucker-Prager linear yield criterion with hardening during failure. Straws were modeled as thin-walled elastic-plastic shell rods aligned perpendicularly to the direction of tool travel, and experiencing ductile damage with a linear softening displacement during failure. The discs were modeled as discrete rigid parts. Mesh sensitivity analysis was performed to determine the appropriate number of elements that would give consistent prediction accuracy with reasonable computational time. The mesh density on the soil part was gradually increased by changing the seeding size. Tests were then run at different depths, while the forward and rotational speeds remained constant. The maximum principal stresses were recorded against the number of elements used for each tillage depth until the point where, with the addition of more elements, the maximum stresses stabilized and, after some point, started dropping. This range of uniform stresses was assumed as the optimal range for meshing.

The working depths of the discs were adjusted over 40, 70, and 100 mm. The soil was constrained at its bottom face while the discs were allowed to move with a forward velocity of 100 mm s^{-1} and angular velocity of 15.7 rad s^{-1} . The loading and boundary conditions as well as the meshed assembly are shown in Figure 2.

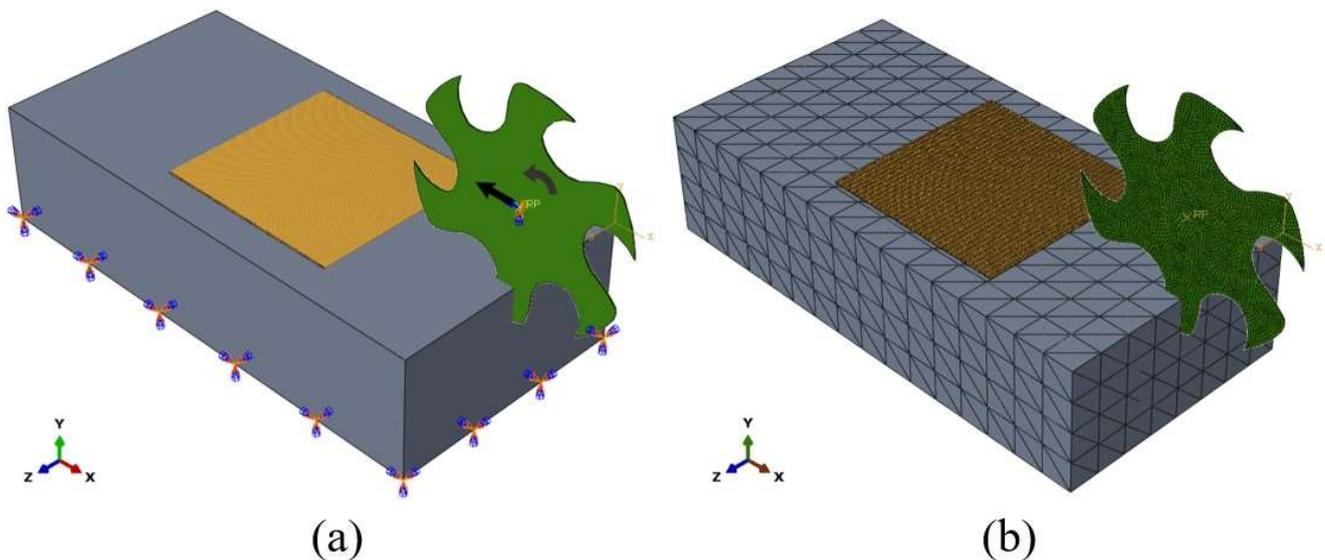


FIGURE 2. (a) FEA boundary and loading conditions, (b) meshed assembly of soil, straw, and disc.

The simulations were set to run for 0.025 s and at the end of each analysis, reaction forces were taken about the reference points. Additionally, the stress distribution contours on the discs due to the maximum reaction forces acting at the initial points of contact were derived.

Field experimental setup

Experiments were performed at the experimentations

farm of Nanjing Agricultural University in December 2020 using an in-situ test-rig facility. The test rig was 8 m long and 1.8 m wide and was powered by a 13.5 kW generator. It consisted of a tool carriage unit, a traction motor, depth adjustment motors, force sensors, and a data acquisition system. The experimental setup is shown in Figure 3.



FIGURE 3. (a) Set-up of the test-rig and straw laid down along the path of tool travel, (b) curved disc cutting through the straw, (c) straight-edged disc cutting through the straw.

A randomly selected site within the experimental field was marked out, cleared of its surface cover, and divided into 18 plots, each of size 2 m × 6 m. The discs were mounted onto the tool carriage in turns while dry straw (2000 grams) was laid perpendicular to the path of tool travel over a 2 m stretch. The discs were then drawn through a 3 m distance, at a constant speed of 100 mm s⁻¹, while the tillage depth was varied over 40, 70, and 100 mm. Each test was replicated three times in a randomized block design.

Resistance forces were measured using calibrated S-type load cells. Data acquisition was done using LabVIEW2010 software (National Instruments Corporation, Austin, TX, USA), interfaced with the Advantech Portable data acquisition module (Advantech Co., Ltd, Taipei, Taiwan).

To determine the straw-cutting efficiency, the straw along the path of tool travel was carefully collected after the disc had plowed through, separated into ‘cut’ and ‘uncut’ stalks, and then weighed. The straw-cutting efficiency was then calculated using [eq. (1)].

$$\text{Straw – cutting efficiency (\%)} = \frac{\text{Mass of cut straw (g)}}{\text{Initial mass of straw applied (g)}} \times 100\% \quad (1)$$

The uniformity of the achieved tillage depths along the furrows created was measured at 10 equivalent locations using a steel rule.

Data analysis

Statistical analyses were done using IBM-SPSS Statistics 22 software (IBM Corp., Armonk, N.Y., USA) at a 95% confidence interval. Levene’s test was used to determine the homogeneity of variance. Correlated-samples t-tests were used to compare the resistance forces registered from the FEA simulations and experimental tests. Independent-samples t-tests were used to contrast the performances of the two discs. One-way ANOVA with

Least Significant Difference (LSD) was used to examine the effects of the tillage depth. Percentages and average scores of the straw-cutting efficiencies and achieved tillage depths were derived to describe the performance of each disc.

RESULTS AND DISCUSSION

Tillage resistance forces

The FEA simulation models of the curved disc and the straight-edged toothed disc cutting through the soil with straw on the surface, at the three tillage depths, are shown in Figures 4 and 5 respectively.

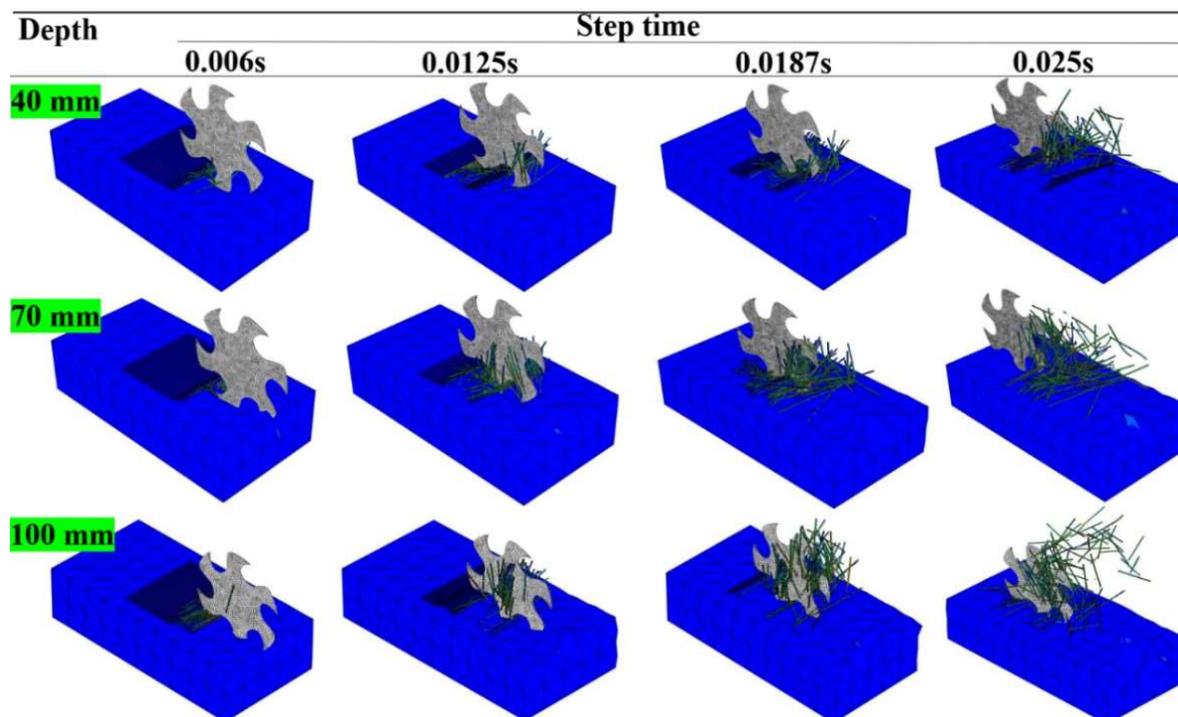


FIGURE 4. FEA models of the curved disc cutting soil with straw on the surface at selected time steps.

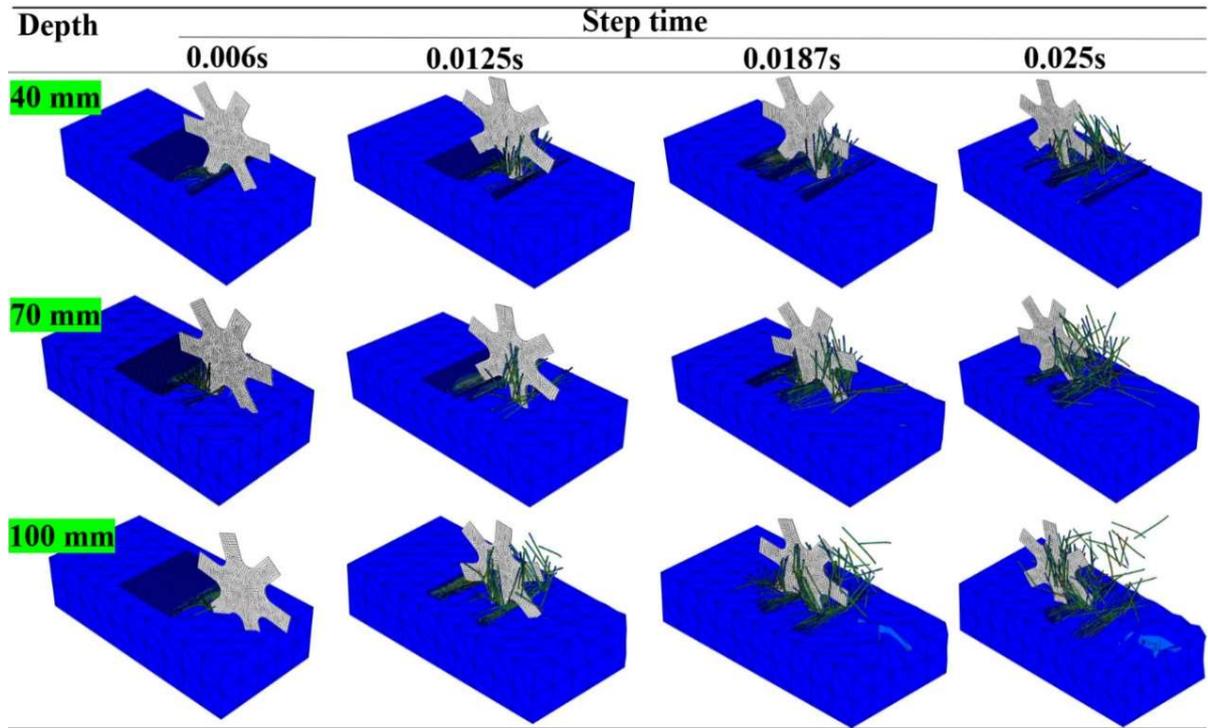


FIGURE 5. FEA models of the straight-edged toothed disc cutting soil with straw on the surface at different time steps.

The vertical reaction forces, F_V , and horizontal (draught) forces, F_H , recorded from both the FEA simulations and experimental tests increased with tillage depth, as seen in Figures 6 and 7.

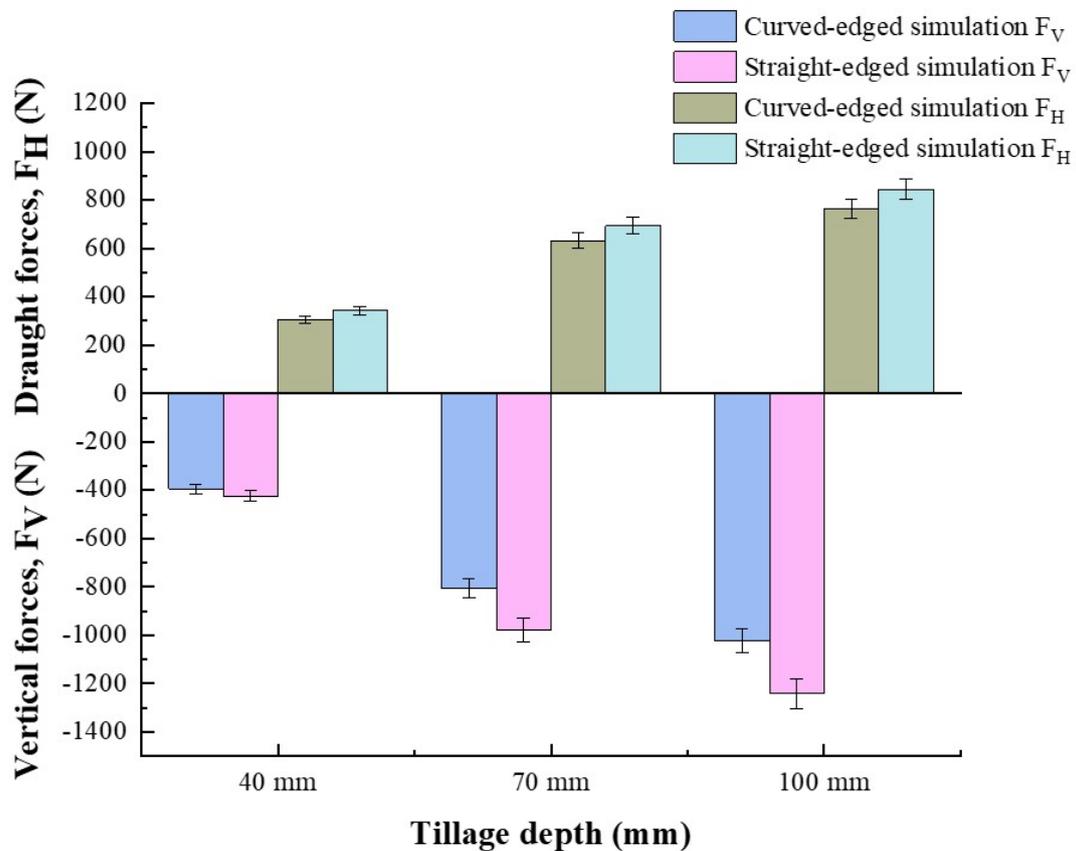


FIGURE 6. Mean vertical resistance and draught forces of the two discs recorded from FEA simulations.

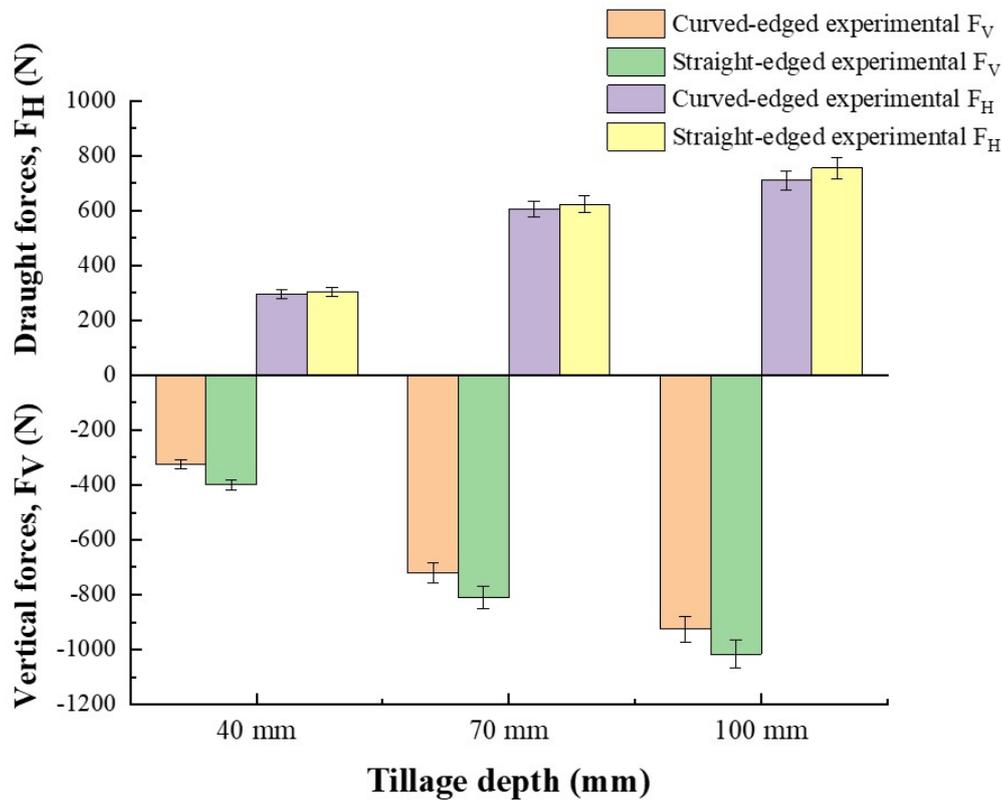


FIGURE 7. Mean draught and vertical resistance forces of the two discs measured from experimental tests.

The straight-edged disc registered higher resistance forces than did the curved design, while the horizontal forces were consistently lower than the vertical forces.

The independent-samples t-tests indicated no significant differences in the mean scores of the resistance forces registered by the discs since they had been standardized to have equivalent mechanical properties. Nonetheless, the experimental tests revealed that the curved disc reduced the resistance forces by 22.8%, 12.3%, and 9.9% at the 40, 70, and 100 mm depths respectively, while the horizontal forces were reduced by 2.9%, 2.8%, and 6.3% at the respective depths. In FEA the curved disc reduced the vertical forces by 7.4%, 21.2%, and 21.3% at the 40, 70, and 100 mm depths respectively, whereas the horizontal forces were reduced by 12.0%, 9.7%, and 10.6%. This points to the advantages of the curved cutting profiles, which mimic the excellent arc shape of the mole-rat's claws (Zhao et al., 2020; Li et al., 2013).

One-way ANOVA revealed that the magnitude of the resistance forces was significantly affected by changes in the tillage depth. The statistics were: $F(2, 60) = 13.695$, $p < .001$ for the vertical forces from field tests by the curved disc; and $F(2, 60) = 13.226$, $p < .001$ for the forces recorded from experimental tests by the straight-edged disc. The statistics of the vertical forces from FEA simulation were: $F(2, 60) = 15.073$, $p < .001$ for the curved disc; and $F(2, 60) = 10.669$, $p < .001$ for the straight-edged disc.

As for the horizontal resistance forces, the statistics from the field experimental tests were: $F(2, 60) = 12.590$, $p < .001$ for the curved-toothed disc; and $F(2, 60) = 16.483$, $p < .001$ for the straight-edged disc. The statistics of the horizontal forces from the FEA simulation were: $F(2, 60) = 12.001$, $p < .001$ for the curved-toothed disc; and $F(2, 60) = 9.571$, $p < .001$ for the straight-edged disc. LSD revealed that the significant difference in the mean resistance forces occurred mainly when the tillage depth was changed from 40 mm depth.

Paired-samples t-tests used to correlate the FEA force estimates with the experimental outcomes indicated that the two approaches had no significant differences ($p > .05$) between their mean scores at all the tillage depths. The FEA models overpredicted the vertical forces by at least 22.11% and draught forces by at least 12.64% across all the depths (Ibrahmi et al., 2015). These differences were acceptably small, thus validating the FEA predictions. FEA can therefore offer reliable predictions of tool performance without having to conduct lengthy, time-consuming, and costly field investigations.

Structural strength of the discs

The stress distribution on the discs when normal reaction forces were applied at the initial points of soil-tool contact is shown in Figure 8.

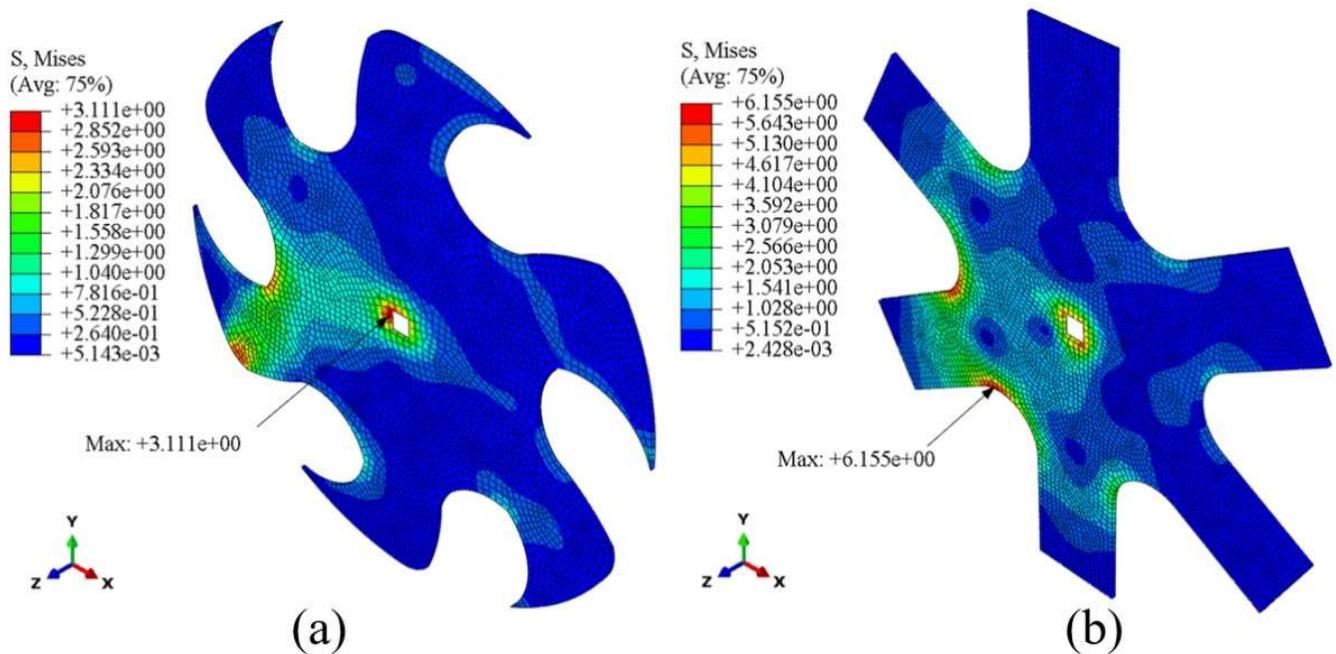


FIGURE 8. Stress distribution due to vertical reaction forces on (a) curved disc and (b) straight-edged disc.

The maximum stress on the straight-edged disc was 6.16 MPa compared to the curved disc's 3.11 MPa. The curved-toothed disc was able to diffuse the pressure on the tooth and the direct maximum loads to the center. Conversely, the conventional straight-edged disc exerted maximum loads on the neck of the tooth. Consequently, the magnitude of maximum stresses registered on the curved disc was substantially reduced, giving it more structural

strength. This would allow it to bear more reaction loads at higher working rates, lengthening the tool's life span. Similar observations were made by Nalavade et al. (2011) and Li et al. (2013).

Straw-cutting forces

The forces used for cutting only straw in the absence of soil were determined using FEA, as shown in Figure 9.

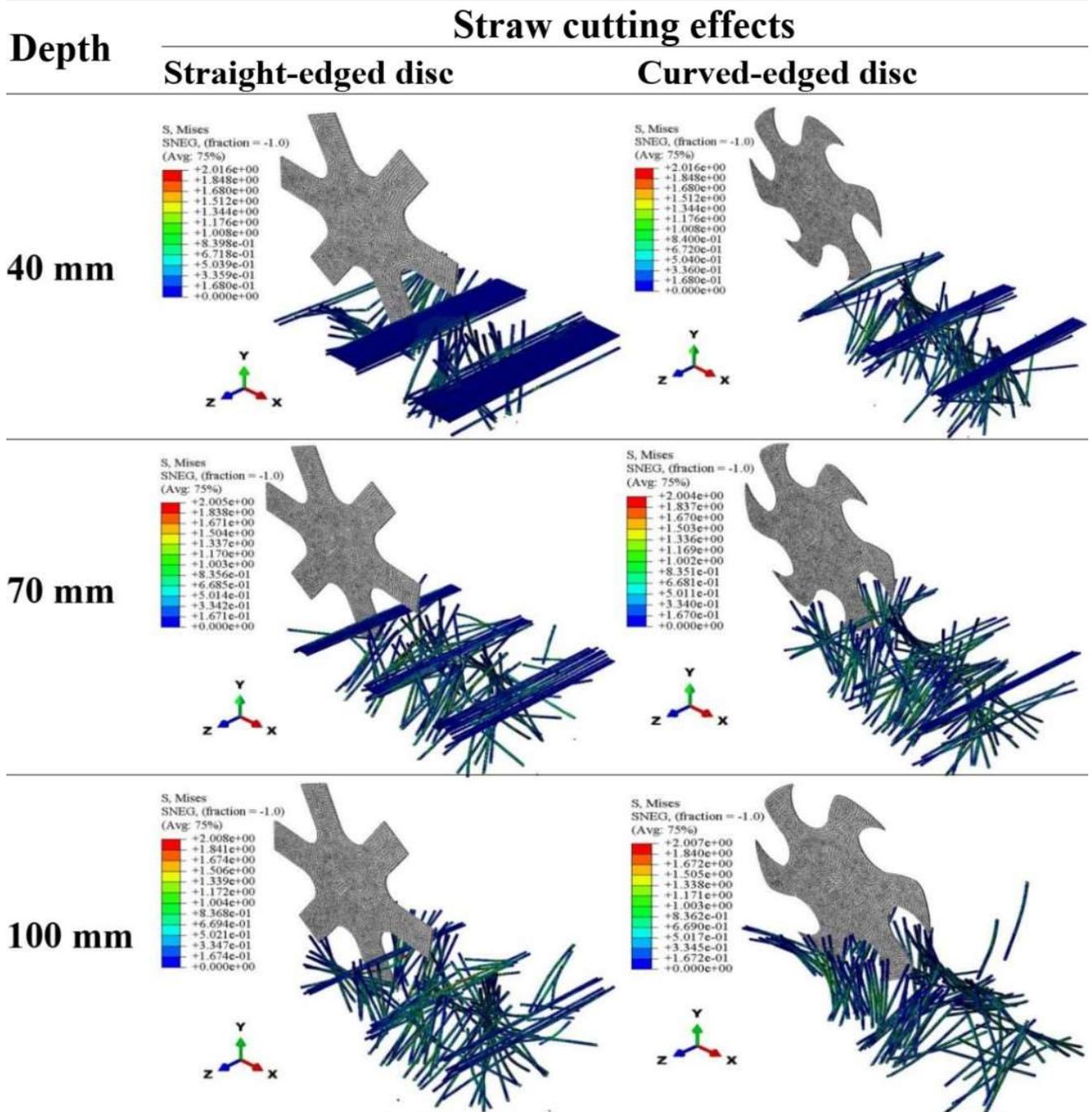


FIGURE 9. FEA straw-cutting effects of the discs when the soil part was isolated from the model.

The straw-cutting forces of the straight-edged disc were 21.72 N, 70.84 N, and 87.95 N at 40, 70, and 100 mm depths respectively, while the curved disc registered considerably lower resistance forces of 18.36 N, 54.71 N, and 68.13 N at the respective tillage depths. Adopting bionic curved cutting profiles in toothed disc designs would thus provide an energy-efficient option for managing straw in conservation farming (Zhang et al., 2016).

Straw-cutting efficiency

The straw-cutting efficiencies of the two discs increased with the tillage depth as shown in Figure 10. The curved-toothed disc had efficiencies of 27.49%, 50.16%, and 71.97% at the 40, 70, and 100 mm depths respectively, compared to the straight-edged disc, which had 9.67%, 24.28%, and 45.48%.

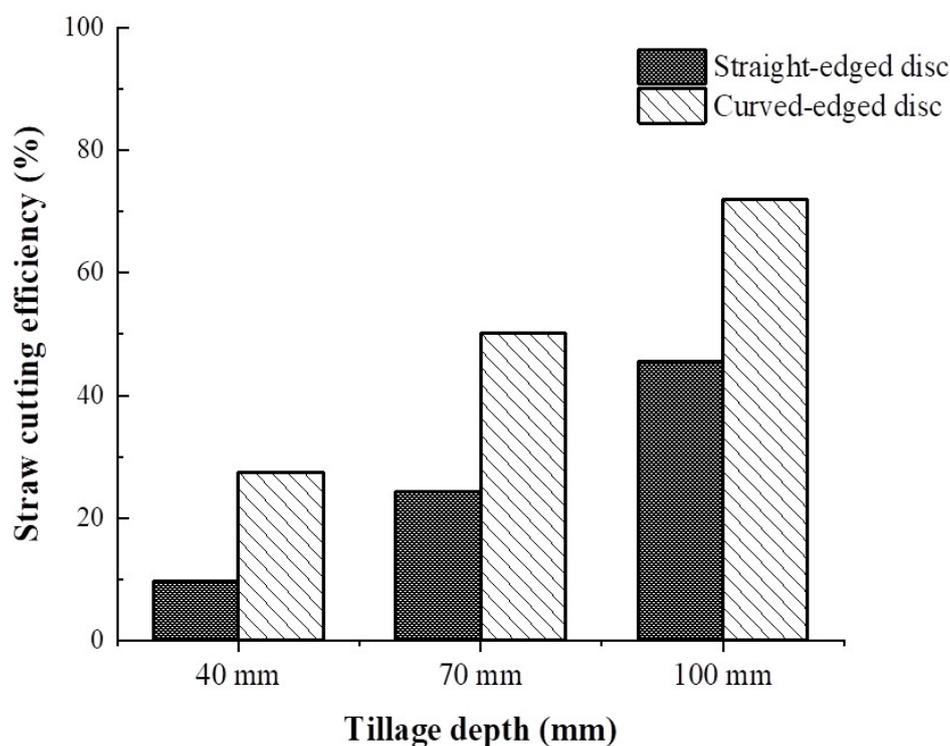


FIGURE 10. Straw-cutting efficiencies of the discs at the three tillage depths.

Straw shearing by the curved disc occurred mainly at the arched tip of the cutting profile, while the elongated curved profile ensured that more straw was in contact with the tool. On the contrary, the straight-edged disc had sharp corners which caused it to stride over sections of the ground. The better cutting efficiency of the curved-toothed discs will increase the utility of the straw, improve furrow opening, and achieve smooth operation of machines in conservation farming.

Uniformity of tillage depth

The curved disc achieved more consistent depths, with averages of 35, 64, and 89 mm, which were 87.5%, 91.43%, and 89% of the targeted 40, 70, and 100 mm respectively. The straight-edged disc achieved depths of 23, 53, and 70 mm, which were 57.5%, 75.71%, and 70% of the respective targeted depths. The bionic curved-toothed profile is thus able to improve the terramechanical efficiency of toothed discs and achieve uniform sowing depths (Matin et al., 2014; Zhao et al., 2020). This will improve seed and fertilizer placement accuracy, enhance seed germination rates, boost root development, and improve the crop stand.

CONCLUSIONS

In this study, 3D Finite Element Analysis (FEA) models and field experimental tests were used to study the working performance of a curved-toothed disc in comparison to a conventional straight-edged toothed disc. The bionic curved-toothed disc significantly reduced stresses on the tool, reduced the resistance forces by up to 22.8%, improved the straw-cutting efficiency by up to 26.31%, and produced more uniform tillage depths. The design presents a structurally enhanced and energy-efficient tool that improves seeding performance while ensuring maximum retention of crop residues on the surface.

Furthermore, the Finite Element Method (FEM) has been shown to be a reliable numerical technique for predicting the performance of tillage tools and is useful for advancing the understanding of the tools' non-linear mechanical interactions with soil and straw during tillage. This knowledge can be useful in defining machine performance parameters for optimal operations, and inform the design and development of more adaptable high-efficiency tools for conservation farming.

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