OPTIMIZATION OF SHEARING PARAMETERS OF CORN STALKS BASED ON DESIRABILITY FUNCTION APPROACH

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基于满意度函数法的玉米秸秆剪切工艺参数优化

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ABSTRACT

To determine the parameters of the whole corn stalks shearing, single factor and multi factor tests were carried out by using node and internode critical shearing strength as the evaluation indexes and the moisture content, sampling location and shearing speed as the influencing factors. The results showed that the moisture content, sampling location and shearing speed had significant effects on the critical shearing strength of internodes and nodes ($F > F_{0.05}$), the order of the influencing factors on the internode and node critical shearing strength were: moisture content >sampling location >shearing speed and sampling location >moisture content >shearing speed. By using Design-Expert and Desirability Function Approach, the optimization problem of three response values, including difference value of critical shearing strength between node and internode at the same segment (DV), the node and internode critical shearing strength, was transformed into a single response value optimization. The corn stalks with a moisture content of 15% had lower shearing strength and higher shearing stability at the shearing speed of 25 mm/min.

摘要

为确定玉米秸秆的整秆剪切工艺参数,本文以含水率、取样部位、剪切速度为试验因素，节间和节部临界剪切强度为试验指标进行单因素和多因素试验。试验结果表明：含水率、取样部位、剪切速度对节间和节部临界剪切强度均影响显著，节间临界剪切强度影响的因素主次顺序为含水率>取样部位>剪切速度，节部临界剪切强度影响因素主次顺序为取样部位>含水率>剪切速度。利用满意度函数法和 Design-Expert 数据分析软件，将节间、节部临界剪切强度及节部节间临剪切强度差值三个响应值优化转化成单一响应值优化。优化结果表明，使用 25mm/min 的速度剪切含水率为 15%的玉米秸秆，玉米秸秆的整秆剪切强度低，剪切平稳性高。

INTRODUCTION

Corn stalk is biomass resource that can be developed and utilized. Its comprehensive utilization can achieve ecological balance of agriculture and ease the pressure on energy and the environment (*Zhang et al., 2017*). Among the numerous and varied recycling modes of corn stalks, the three main approaches are as follows: using smashed corn stalks to make fodder, sprinkling crushed corn stalks back into the field, and directly harvesting entire corn stalks (*Han et al., 2002*). These approaches are inseparable from shearing components, which are the core components of the recycling machinery for corn stalks (*Wu, 2013*).

Chen Chaoke et al. studied the effects of test factors such as moisture content and sampling location on the shearing force of sugarcane stalks, and compared the shearing properties between its nodes and internodes (*Chen et al., 2016*). *Wang Yan* summarized the cutting force required for different harvest periods using the corn stalk harvest period as the influencing factor (*Wang, 2012*). Some researchers also carried out tensile and shearing characteristics tests on the rind of corn stalks, and discussed the effects of moisture content, sampling locations, and shearing speed on the tensile and shearing characteristics (*Chen, et al., 2012*). Numerous studies on the shearing characteristics of corn stalks had been investigated (*Igathinathane et al., 2010; Li et al., 2010; Zhang et al., 2018; Zhang et al., 2020*).

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However, the research about studying the effects of moisture content, sampling location and shearing speed on the shearing stability of corn stalks was not searched by author. Corn stalks having different moisture contents, sampling locations, and parts had different mechanical properties and required different shearing strength (*Zhang et al., 2016*). The difference may cause an imbalance in the workload of the corn stalk processing machine (*Chen et al., 2016*). Therefore, reducing the shearing strength of corn stalks and shearing strength difference of the whole stalk is an urgent problem to solve.

This study aimed to obtain the relatively stable parameters of the whole corn stalks shearing. Single-factor and multi-factor tests were carried out to study the significance of factors and establish regression models. Furthermore, by using the Design-Expert and Desirability Function Approach, the optimization problem of three response values was transformed into a single response value optimization to obtain the relatively stable shearing parameters. This study is of practical significance in prolonging the life-span of shearing tools and developing and designing shearing components.

MATERIALS AND METHODS

Test materials and equipment

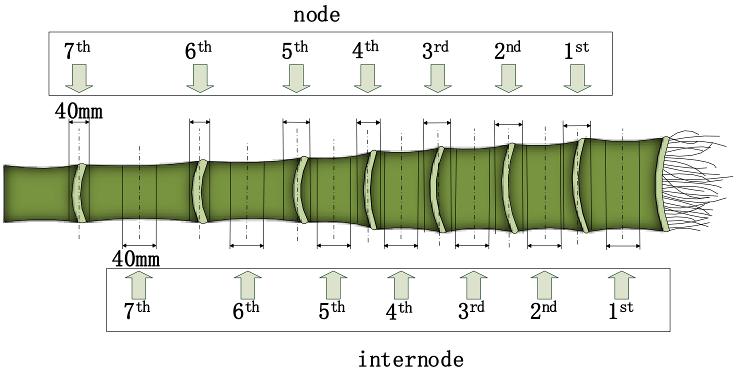


Fig. 1 - Sampling diagram

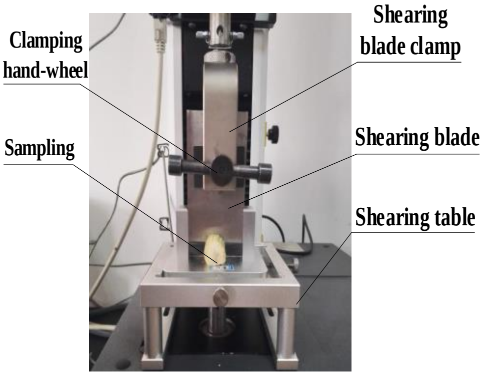


Fig. 2 - Measuring device for shearing strength

The test materials used in this study were corn stalks with a plant height range of 1.60-2.00m and a moisture content of 15%-75%. First, internode and node sections of the whole stalk from the prop root above the soil surface were marked with 1 to 7, as shown in Fig. **1**. Samples of 40 mm from each internode and node section were cut symmetrically taking the dotted line as the centre, as shown in Fig. 1.

Test equipment and instrument mainly include an universal testing machine (INSTRON-3344), as shown in Fig. **2**, a drying oven under forced convection (GuangMing 101), an electronic balance (JJ523BC, precision 1mg), and a Vernier calliper (precision 0.01 mm).

Test factors and indexes

In this study, the node and internode critical shearing strength, DV were selected as the evaluation indexes because the critical shearing strength is affected by the internal structure difference of the nodes and internodes of corn stalks. The moisture content of the corn stalks, sampling location, and shearing speed were selected as the influencing factors by reviewing the related literature and mechanical design requirements (*Zhang et al., 2016; Yu et al., 2012*).

The shearing strength–displacement curve was obtained from a corn stalk shearing test as shown in Fig. 3. It is clearly observed that the shearing strength linearly increased with the variation in the displacement during the initial stages; however, as the displacement increased further, the shearing strength increased faster after the turning point of the curve. The anti-shear ability became stronger and the shearing strength increased dramatically when the upper and bottom skin of the corn stalks was cut out and rind of corn stalks was compacted successively. The shearing strength immediately decreased, until the corn stalk was cut off. The peak value resulting from the shearing strength dramatically decreasing is called the critical shearing strength, which is considered as the test index in this study (*Xing, 2017*).

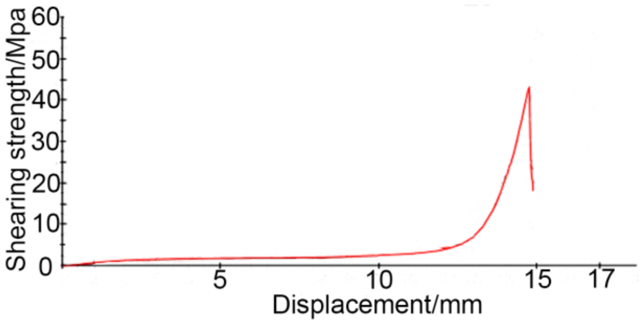


Fig. 3 - The curve of shearing strength-displacement for shearing test

Test design of single factor tests

The 4th nodes and internodes of the samples were selected, and the effect of the moisture content of samples on the critical shearing strength was examined at a shearing speed of 15 mm/min. Samples from different sections of the whole stalk were selected, and the moisture content of each sample was adjusted to 45%±2%, and the effect of the sampling location on the critical shearing strength was examined at a peeling speed of 15 mm/min. The moisture content of the sample in the 4th nodes and internodes were adjusted to 45%±2% to study the influence of the shearing speed on the critical shearing strength. The test was repeated 5 times at each test level, and the *F* value tests were performed at the level of P=0.05.

Test design of ternary quadratic regression orthogonal combination

Ternary quadratic orthogonal regression tests were carried out by using internode and node critical shearing strength ($Y_1$and Y_2) as the evaluation indexes and the moisture content (X_1), sampling location (X_2) and shearing speed (X_3) as the influencing factors. The test was repeated 5 times for each group and then the average values were calculated and recorded. The factor level coding table of the tests is shown in

Table **1**.

Table 1

Factor level coding table of the tests

Levels	**Moisture content** X_1 **[%]**	**Sampling location** X_2 **[node or internode]**	**Shearing speed** X_3 **[mm/min]**
+1.525	75	7	25
+1	65	6	59.67
0	45	4	15
-1	25	2	20.33
-1.525	15	1	5

Non-linear multi-objective optimization

The optimization of stable shearing parameters of corn stalks should be based on the following principles: the lower internode and node critical shearing strength, and DV. The DV Y_3 can be obtained from Equation (1):

$$Y_3 = Y_2 - Y_1 \tag{1}$$

By using Desirability Function Approach, the optimization problem of three response values, including DV, the node and internode critical shearing strength, was transformed into a single response value optimization, and then the whole corn stalk relatively stable shearing parameters were obtained. It could be known that the desirability degree would be high if the response values of node critical shearing strength, internode critical shearing strength and DV were low. The desirability function is calculated by Equation (2) (*Xu et al., 2020*).

$$d_i\left(Y_i\right) = \begin{cases} 1 & if\ \ Y_i < L_i \\ \dfrac{U_i - Y_i}{U_i - L_i} & if\ \ L_i \le Y_i \le U_i \\ 0 & if\ \ Y_i > U_i \end{cases} \tag{2}$$

where: d_i is the desirability function of the response surface; Y_i is the response value; L_i is the specification lower limit of the response value; U_i is the specification higher limit of the response value.

The overall desirability function D is shown in Equation (3) (*Xu et al., 2020*).

$$D = \left(\prod_{i=1}^{3} d_i^{r_i} \right)^{\frac{1}{\sum r^i}} \tag{3}$$

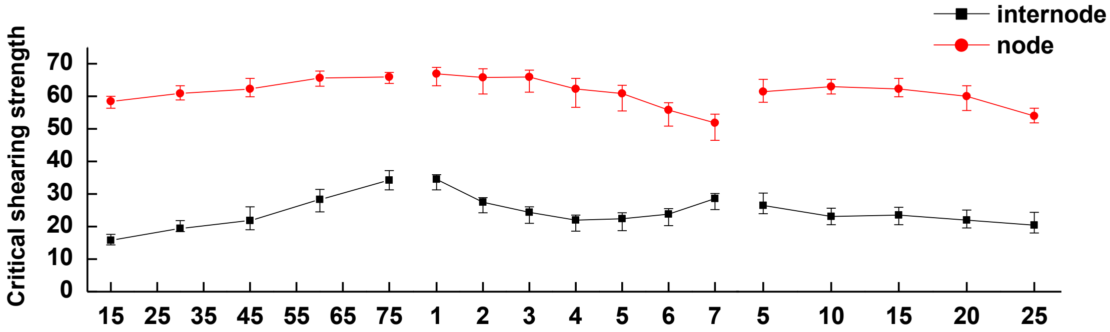
In the Equation (3), r_i is the weight coefficient, which depends on the importance of each response surface in the optimization design of stable shearing process parameters of corn stalks. In this paper, the importance of each response surface regression model was assumed to be the same, which is $r_1 = r_2 = r_3$. Putting $r_1 = r_2 = r_3$ into Equation (3) to get:

$$D = \sqrt[3]{d_1 \, d_2 \, d_3} \tag{4}$$

The overall desirability function D is the function of moisture content, sampling location and shearing speed, which can be used as the basis for the optimization of stable shearing parameters of corn stalks.

RESULTS

Results and analysis of single factor test



(a) Moisture content (b) Sampling location (c) shearing speed

Fig. 4 - The critical shearing strength of internodes and nodes at different levels of factors

Table 2

F value test results

	Moisture content		Sampling location		Shearing speed	
	Internode	**Node**	**Internode**	**Node**	**Internode**	**Node**
***F* value**	36.71	15.21	46.57	38.33	4.40	10.48
$F_{0.05}$ crit	2.87	2.87	2.45	2.45	2.87	2.87

The internode and node critical shearing strength of corn stalks with different moisture contents are shown in Fig. 4, the *F* value test results at the level of P= 0.05 are shown in Table 2.

It can be observed from

Table **2**, $F_{internode}$ = 36.71> F_{node} = 15.21> $F_{0.05}$ (4, 20) = 2.87, indicating that moisture content has significant effects on internode and node critical shearing strength. At the shearing speed of 15 mm/min, the critical shearing strength values of the 4th nodes and internodes gradually increase and DV decreases with the increase of moisture content from 15% to 75%; moreover, the critical shearing strength of the nodes is about 2-3 times that of the internodes with the same moisture content (see Fig. 4(a)).

The higher the moisture content of corn stalks is, the denser the structure will be, the greater the critical shearing strength will be required and the moisture content may have effect on the DV which may be the reasons for the above results.

It can be observed from

Table 2, $F_{internode}$ = 46.57 > F_{node} =38.33 > $F_{0.05}$ (6, 28) = 2.45, indicating that sampling location has significant effects on internode and node critical shearing strength. At the shearing speed of 15 mm/min, for corn stalks with a moisture content of 45 ±2%, with the change of sampling location from 1st to 7th, the critical shearing strength values of nodes gradually decrease, that of internodes decreases overall, and DV first increases and then decreases; moreover, the critical shearing strength of the nodes is about 2-3 times that of the internodes on the same sampling location of the corn stalk (see Fig. 4(b)). The tissue structure at the bottom of corn stalks is denser than that at the top of corn stalks which may be the reason for the above results.

It can be observed from

Table 2, $F_{internode}$ = 4.4> F_{node}= 10.48> $F_{0.05}$ (4, 20) = 2.87, indicating that shearing speed has significant effects on internode and node critical shearing strength. For the 4th nodes and internodes of corn stalks with a moisture content of 45 ±2%, the node and internode shearing strength gradually decreases, with the increase of shearing speed from 5 mm/min to 25mm/min; moreover, the critical shearing strength of the nodes is about 3 times that of the internodes at the same shearing speed (see Fig. 4(c)). The greater the shearing speed is, the easier the corn stalks will be cut, the smaller the critical shearing strength will be required and the shearing speed has less effect on the DV which may be the reason for the above results.

Results and analysis of ternary quadratic regression orthogonal test

The results of the ternary quadratic regression orthogonal combined shearing tests are shown in Table 3. Design-Expert data analysis software was used to establish two regression models of coding values between influencing factors and the critical shearing strength of internodes and nodes of corn stalks, as shown in equations (5) and (6).

Table 3

Test results of shearing strength

Test No.	**Factors and levels**			**Response indexes**	
	Moisture content x_1 **[%]**	**Sampling location** x_2 **[node or internode]**	**shearing speed** x_3 **[mm·min^{-1}]**	**Internode critical shearing strength** Y_1 **[MPa]**	**node critical shearing strength** Y_2 **[MPa]**
1	-1	-1	-1	25.55	50.65
2	1	-1	-1	38.00	62.13
3	-1	1	-1	24.28	44.30
4	1	1	-1	30.08	45.95
5	-1	-1	1	17.70	47.10
6	1	-1	1	35.19	57.75
7	-1	1	1	20.82	42.93
8	1	1	1	27.58	42.10
9	-1.525	0	0	16.88	48.78
10	1.525	0	0	38.00	54.33
11	0	-1.525	0	34.52	53.88
12	0	1.525	0	30.41	41.08
13	0	0	-1.525	25.78	50.73
14	0	0	1.525	25.12	42.80
15	0	0	0	23.01	50.63
16	0	0	0	21.74	54.98
17	0	0	0	21.40	53.23
18	0	0	0	20.22	54.10
19	0	0	0	23.00	54.18
20	0	0	0	24.00	54.93

$$Y_1 = 22.56 + 5.91\ x_1 - 1.58\ x_2 - 1.39\ x_3 + 1.46\ x_1^2 + 3.62\ x_2^2 + 0.61\ x_3^2 - 2.17\ x_1x_2 + 0.75\ x_1x_3 + 0.59\ x_2x_3 \tag{5}$$

$$Y_2 = 53.44 + 2.48\ x_1 - 4.89\ x_2 - 1.99\ x_3 - 0.37\ x_1^2 - 2.12\ x_2^2 - 2.43\ x_3^2 - 2.66\ x_1x_2 - 0.41\ x_1x_3 + 0.34\ x_2x_3 \tag{6}$$

The results of the analysis of variance of regression models are shown in Table 4. It can be observed from Table 4 that the regression of the two regression models is extremely significant (p<0.01), the lack of fit is not significant (p>0.05) and R^2 of model 1 and model 2 are 0.9353 and 0.9489 respectively. The above results indicate that both of the regression models have a good and reasonable fit. It can be observed that the influencing factors order of critical shearing strength of the internode is moisture content (x_1) > sampling location (x_2) > shearing speed (x_3) and that of the node is sampling location (x_2) > moisture content (x_1) > shearing speed (x_3) through the comparison of *F* values. Moreover, the interaction term of x_1x_2 has significant effects on the internode and node critical shearing strength.

Table 4

Analysis of variance

Source	**MS**	***F* value**	***P* value**	**Source**	**MS**	***F* value**	***P* value**
Model 1	79.03	16.05	<0.0001**	**Model 2**	67.10	20.65	< 0.0001**
x_1	441.07	89.59	< 0.0001**	**x_1**	78.01	24.01	0.0006**
x_2	31.38	6.37	0.0301*	**x_2**	302.58	93.12	< 0.0001**
x_3	24.61	5.00	0.0494*	**x_3**	50.34	15.49	0.0028**
x_1x_2	37.81	7.68	0.0197*	**x_1x_2**	56.71	17.45	0.0019**
x_1x_3	4.51	0.92	0.3612	**x_1x_3**	1.36	0.42	0.5320
x_2x_3	2.77	0.56	0.4707	**x_2x_3**	0.91	0.28	0.6080
x_1^2	23.13	4.70	0.0554	**x_1^2**	1.48	0.46	0.5145
x_2^2	141.98	28.84	0.0003**	**x_2^2**	48.74	15.00	0.0031**
x_3^2	3.98	0.81	0.3897	**x_3^2**	63.82	19.64	0.0013**
Lake of Fit	7.99	4.31	0.0675	**Lake of Fit**	3.86	1.46	0.3430

*Note: P<0.01(extremely significant**), P<0.05(significant*); Model 1 is variance analysis of internode critical shearing strength. Model 2 is variance analysis of node critical shearing strength.*

Analysis of the effects of the interaction factors on node and internode critical shearing strength

When the shearing speed is set to the level of 0, the response surfaces of the moisture content and sampling location on the critical shearing strength of the internodes and the nodes are shown in Fig. 6.

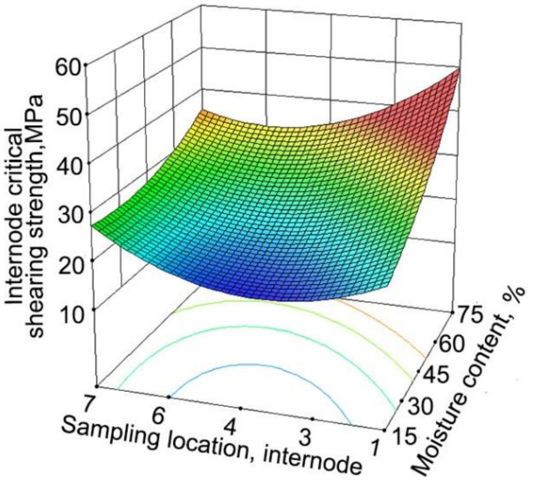


Fig. 5 - Interaction effects of moisture content and sampling location on internode critical shearing strength

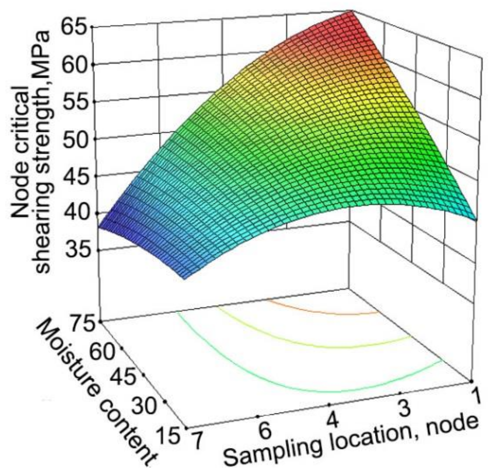


Fig. 6 - Interaction effects of moisture content and sampling location on node critical shearing strength

As shown in Fig. 5, with the decrease of moisture content, the critical shearing strength of the1st internodes decreased gradually, and that of the 7th internodes first decreased and then increased. The main reasons for these results are as follows: the internode samples near the solid surface have the characteristics of thicker fibre bundles and stronger supporting force. With the decrease of moisture content, the volume of internode samples shrank less and the tissues became sparse, so that the internode critical shearing strength decreased. The internode samples far from the solid surface have the characteristics of thinner fibre bundles and weaker supporting force. When the moisture content was high, with the decrease of moisture content, the supporting force of fibre bundles could restrain the volume shrink and the tissues became sparse, so that the internode critical shearing strength decreased; however, when the moisture content was low, with the decrease of moisture content, the supporting force of fibre bundles was insufficient, the volume of internode samples decreased sharply and the tissues became dense, so that the internode critical shearing strength increased.

As shown in Fig. 6, the higher the sampling location was, the lower the node critical shearing strength would be. The main reason for this result is as follows: The tissues of the node samples at different sampling locations were relatively dense. The higher the sampling location was, the thinner the fibre bundles and the lower the critical shearing strength of the node samples would be.

Non-linear multi-objective optimization

Design-expert software was used to optimize the parameters, in order to obtain the optimal parameter combination with small differenc in critical shearing strengths between nodes and internodes of corn stalks, and the weaker critical shearing strengths of the whole stalk. DV Y_3 (see Equation (7)) was derived from simultaneous equations (4), (5), and (6).

$$Y_3 = 30.88 - 3.42x_1 - 3.32x_2 - 0.6x_3 - 1.83x_1^2 - 5.75x_2^2 - 3.04x_3^2 - 0.49x_1x_2 - 1.16x_1x_3 + 0.25x_2x_3 \qquad (7)$$

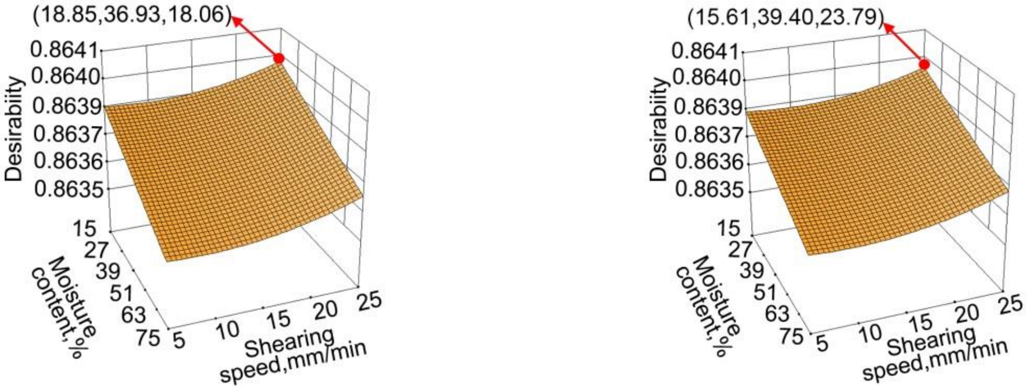
The optimization target ranges of response values were obtained by using Design-expert software, as shown in Table 5.

Table 5

Response optimization target range

Response	**Internode critical shearing strength [MPa]**	**Node critical shearing strength [MPa]**	**DV [MPa]**
Optimization target range	$14.14<Y_1<53.28$	$29.39<Y_2<65.88$	$0<Y_3<32.85$

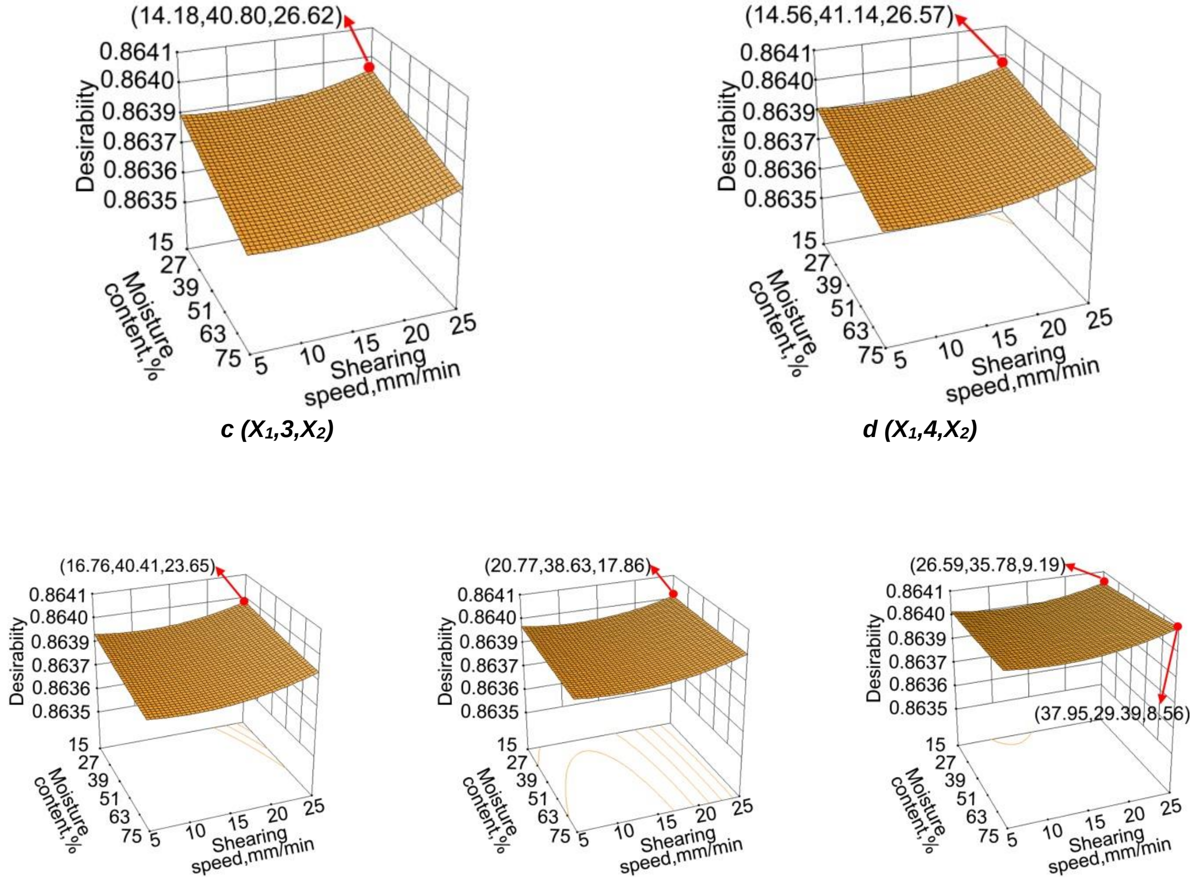
When the sampling locations were different, the moisture content and shearing speed were optimized and analysed. Based on the Design-Expert software and equations 4, 5, 6, and 7, the response surfaces of the overall desirability function were obtained when the sampling location X_2=1, 2, 3, 4, 5, 6 and 7 as shown in Fig. 7.



a (X_1,1,X_2) ***b (X_1,2,X_2)***

a) ***b)***

Fig. 7 a,b - Response surfaces of the desirability function of each sampling location



c (X$_1$,3,X$_2$) *d (X$_1$,4,X$_2$)*

e (X$_1$,5,X$_2$) *f (X$_1$,6,X$_2$)* *g (X$_1$,7,X$_2$)*

Fig. 7 c,d,e,f,g - Response surfaces of the desirability function of each sampling location

The maximum values of the desirability function at different sampling locations are shown in Table 6. When the shearing speed was 25 mm/min, the desirability function of the 7th stalk section with a moisture content of 75% achieved the maximum value, which was similar to the 7th stalk section with a moisture content of 15%. Therefore, it is best relatively stable shearing technics to cut corn stalks with a moisture content of 15% at shearing speed of 25 mm/min. Using this shearing parameter to cut stalks has the characteristics of lower shearing strength of the whole stalk and higher shearing stability.

Table 6

Maximum values of the desirability function for each sampling location

Sampling location X_2 [node or internode]	Moisture content X_1 [%]	shearing speed X_3 [mm/min]	Internode critical shearing strength Y_1 [MPa]	Node critical shearing strength Y_2 [MPa]	DV Y_3 [MPa]	Maximum values of the desirability function D_{Max}
1	15	25	18.85	36.93	18.06	0.86397
2	15	25	15.61	39.40	23.79	0.86395
3	15	25	14.18	40.80	26.62	0.86396
4	15	25	14.56	41.14	26.57	0.86396
5	15	25	16.76	40.41	23.65	0.86397
6	15	25	20.77	38.63	17.86	0.86401
7	15	25	26.59	35.78	9.19	0.86406
	75	25	37.95	29.39	8.56	0.86409

CONCLUSIONS

(1) In this study, single factor test and analysis of variance were used to analyse the influencing factors of the critical shearing strength of nodes and internodes. The test results showed that the moisture content, sampling location and shearing speed had significant effects on the critical shearing strength of internodes and nodes.

(2) Regression models of internode and node critical shearing strength of corn stalks were established and analysed based on variance method and response surface method. The results showed that the order of the influencing factors on the internode critical shearing strength was moisture content >sampling location >shearing speed and that on the node critical shearing strength was sampling location >moisture content >shearing speed; the interaction factor of moisture content and sampling location had significant effects on the critical shear strength of nodes and internodes.

(3) Through the application of the Desirability Function Approach, the optimization problem of three response values, including DV, the node and internode critical shearing strength, was transformed into a single response value optimization, and then the relatively stable parameters of the whole corn stalks shearing were obtained. When using the shearing speed of 25 mm/min to cut corn stalks with a moisture content of 15%, the corn stalks had lower shearing strength and higher shearing stability.

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