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Fuzzy Synthetic Evaluation on Stalk-Like Crops with Biomechanical Properties Indices

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Abstract:
Based on the conclusions drawn from the systematically studying of the stalk biomechanical properties indices of wheat planted in northern China (like wheat, corn, soybean, and millet), the biomechanical evaluation indices system for stalk-like crops was built with the experts' opinions. Seven indices of stalk were determined, including bending strength, bending rigidity, cross sectional moment of inertia, Young's modulus, impact ductility, tensile strength and shear strength. Meanwhile, the judgment matrix was constructed by Delphi Method and Analytic Hierarchy Process, and the results were acceptable by consistency check. All of the indices weights were obtained, which were 0.376, 0.262, 0.153, 0.089, 0.060, 0.037 and 0.023, respectively. At last, the fuzzy synthetic judgment model for stalk-like crops was constructed with the fuzzy synthetic judgment method. Moreover, two varieties of wheat were used as examples to validate the feasibility of the whole biomechanical evaluation indices system and evaluation model.
Keywords: *stalk-like crops; biomechanics; evaluation index; fuzzy evaluation.*

I. INTRODUCTION

Stalk-like crops' lodging is one of the most important factors affecting crops' yield. Nowadays, the lodging resistance of stalk has been regarded as an important index for breeding, but how to evaluate it effectively is still difficult. With the development of engineering technology and its application in agricultural engineering, more and more physical methods have been used to evaluate the lodging resistance of crops. Establishment of mechanical model of crops is one of the popular methods to assess the wheat lodging resistance. For example, (Berry PM, Sterling M, Baker CJ, et al, 2003) described a calibrated model [1]based on the existing models[2] to predict the timing and amount of lodging. However, it is clear that different kinds of wheat show various lodging risk even growing in the same region. Some methods of utilizing mechanical properties indices of crops to help choosing improved variety have been recently attracting more attention of agronomists. On the one hand, Some elementary tested were carried out to obtain the

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biomechanical properties of stalk-like crops [3-9]. On the other hand, assessment methods of lodging resistance with biomechanical properties were applied [10-14].

Although some useful results have been achieved, there was little published information quantifying the indices of mechanical properties of stem to evaluate the lodging resistance of crops. In this paper, an attempt had been made to evaluate stalk-like crops with biomechanical method for helping selecting and breeding crops of high quality. In order to choose proper indices, a series of experimental researches on biomechanical properties about stalks were carried out, and the correlation analysis between biomechanical properties and the morphological characteristics was conducted [15-16]. Based on the results, the biomechanical evaluation system was built with the experts' opinions. Combined with Delphi Method and Analytic Hierarchy Process (AHP), all of the indices weights were finally calculated. Then, the fuzzy synthetic judgment model for stalk-like crops was constructed with fuzzy synthetic judgment method. At last, the whole biomechanical evaluation indices and the evaluation model were tested feasibly by two varieties of wheat on trial.

II. ESTABLISHMENT OF THE BIOMECHANICAL EVALUATION SYSTEM FOR IMPROVED VARIETIES OF STALK-LIKE CROPS

In general, there are two ways to construct evaluation indices system: one is empirical determination and the other is the mathematic method. In this paper, the preliminary indices of crops' biomechanical properties have been chosen on the basis of consulting scientists of related fields and certain selecting principle. They are elastic modulus, the moment of inertia, bending rigidity, bending strength, impact toughness, shear strength, tensile strength, the relaxed modulus and creep compliance. Further, a series of tests about these indices were performed. The results showed that the relaxed modulus and creep compliance could express well the viscoelasticity of stalks, but the testing process was difficult and time-consuming. Therefore, the two indices are not included in the finally indices of biomechanical evaluation system shown in Fig 1, which contains 1 index of the first grade and 7 indices of the second grade.

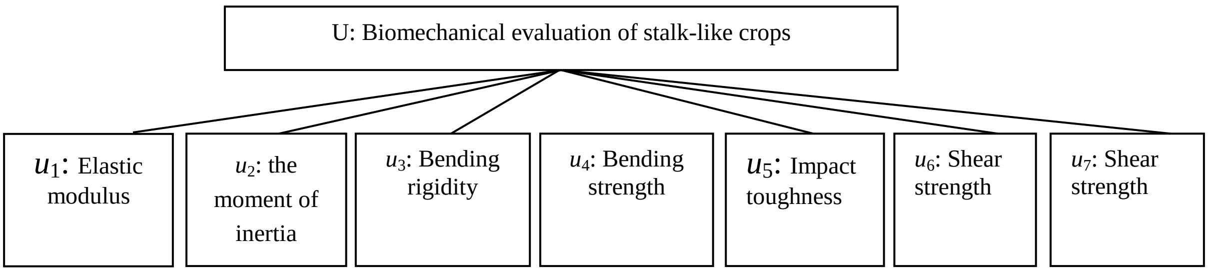

Fig.1 Structure of biomechanical properties evaluation system for stalk-like crops

III. CONSTRUCTION OF FUZZY SYNTHETIC EVALUATION MODEL

The fuzzy evaluation method can sufficiently combine quality and quantity. And it can

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give a synthetic quantitative model by the principle of fuzzy relation synthesis based on fuzzy mathematics, combining some factors which are uneasy to describe quantitatively or whose boundaries are not clear. The feature of this method lies on the only evaluation value of the evaluated object no matter which the object set belongs to. The fuzzy synthesis evaluation model has been used widely in many fields and gains great economic benefits and social benefits [17-21]. The content presented in this section details the fuzzy synthesis evaluation method applied in the biomechanical properties of stalks.

3.1 Factor set

Factor set is consisted of various factors of the evaluated object. It can be expressed as formula (1)

$$\mathbf{U} = (u_1, u_2, u_3 \cdots, u_m) \tag{1}$$

where U is the factor set and $u_i (i = 1,2,3,\cdots,m)$ is the influencing factor respectively.

In the study of biomechanical properties evaluation of stalk, U is the factor sets influencing the biomechanical properties of stalk and contains seven sub-factors.

Therefore, $m = 7$.

3.2 Evaluation set

The evaluation set is consisted of various possible components about the objects. The evaluation set V can be expressed as equation (2) and $v_i (i = 1,2,\cdots,n)$ represent possible evaluation results. The purpose of the fuzzy comprehensive evaluation is to obtain the optimum result from the judge set evaluation, by considering all possible factors.

$$V = (v_1, v_2, v_{3,} \cdots v_n) \tag{2}$$

In the study of biomechanical properties evaluation of stalk, we adopt the evaluation set of four grades. The element in $V = (v_1, v_2, v_3, v_4)$ stands for excellent, good, fair and poor, respectively.

3.3 Weight set

In the factor set, the importance of each factor is different. In order to take the importance of each factor into account, we should give appropriate weights $a_i (i = 1,2,3,\cdots,m)$ for each factor $u_i (i = 1,2,3,\cdots,m)$. The set consisted by each weight is called the weight set. It can be expressed as formula (3).

$$\boldsymbol{A} = (a_1, a_2, a_3 \cdots, a_m) \tag{3}$$

Generally, the elements of the set should meet the condition of normalization and non-negative as shown in formula (4).

$$\sum_{i=1}^{n} a_i = 1 \quad a_i \geq 0 \quad (i = 1,2,3,\cdots,m) \tag{4}$$

Each item of a_i can be seen as the membership grade of each factor $u_i (i = 1,2,3,\text{L},m)$ to "importance". Thus, weight set can be considered as the fuzzy subset of factor set.

In order to obtain the weight coefficient of each indicator variable about stalk crops in the biomechanical evaluation index system, a comprehensive analysis of the Delphi method and

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AHP was carried out, and an expert questionnaire of judgment matrix was designed. Ten experts from Shanxi Agricultural University and Taiyuan University of technology participated in the questionnaire. They are engaged in the study of material mechanical properties for a long time.

After repeatedly summary and feedback each expert's opinions, the final level of importance were determined when the experts are reaching unanimity. Then, the importance of each index was quantified by 1-9 scale method (meanings are shown in Table 1) of AHP. Finally, the results were filled in Table 2.

Table 1 One to nine scale of judgment matrix

assignment of a_{ij}	grade of importance
1	i and j are of equal importance
3	i is slightly important than j
5	i is more important than j
7	i is much more important than j
9	i is extremely more important than j
2，4，6，8	the median of the two adjacent judgments
1/3，1/5，1/7，1/9	the importance of the two elements is the reciprocal of above scaling

Table 2 Expert consultance form about relative importance of stalk biomechanical properties indices

U	Elastic modulus u_1	the moment of inertia u_2	Bending rigidity u_3	Bending strength u_4	Impact toughness u_5	Shear strength u_6	Shear strength u_7
Elastic modulus u_1	1						
the moment of inertia u_2	—	1					
Bending rigidity	—	—	1				

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u_3							
Bending strength u_4	—	—	—	1			
Impact toughness u_5	—	—	—	—	1		
Shear strength u_6	—	—	—	—	—	1	
Shear strength u_7	—	—	—	—	—	—	1

In our study, according to the survey results from the experts, the judgment matrix was determined for the second layer factor $u_1, u_2, \cdots, u_7$ of stalk in biomechanical evaluation system relative to the total target layer U shown as follows:

$$\mathbf{U} = \begin{bmatrix} 1 & 1/3 & 1/5 & 1/7 & 3 & 5 & 4 \\ 3 & 1 & 1/3 & 1/5 & 4 & 6 & 5 \\ 5 & 3 & 1 & 1/3 & 5 & 7 & 6 \\ 7 & 5 & 3 & 1 & 6 & 9 & 7 \\ 1/3 & 1/4 & 1/5 & 1/6 & 1 & 4 & 3 \\ 1/5 & 1/6 & 1/7 & 1/9 & 1/4 & 1 & 1/3 \\ 1/4 & 1/5 & 1/6 & 1/7 & 1/3 & 3 & 1 \end{bmatrix}$$

By establishing judgment matrix, the analysis of the problems is simplified mathematically, hence we can deal with the complex issues using quantitative and qualitative analysis. So in order to ensure that the conclusion is reasonable, we need to check the consistency of judgment matrix. The consistency index is showed as formula (5).

$$CR = \frac{CI}{RI} \tag{5}$$

In formula (5), $CI = \frac{\lambda_{\max} - n}{n-1}$ stands for the consistency index of judgment matrix, $\lambda_{\max}$ stands for the largest characteristic root of judgment matrix, n stands for the order of judgment matrix, RI stands for the mean random consistency index. The RI values of 1 to 9 order judgment matrix are shown in Table 3. If the random conformance rate $CR < 0.1$, it means that the judgment matrix satisfies the consistency. Otherwise, the judgment matrix elements need to be adjusted.

Table 3 Criterion for Average random consistency index RI

Order	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

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In this paper, the biomechanical evaluation index system of stalk has only two layers, so the judgment matrix needs to be ordered in single level and the consistency check is required. The results are shown as following:

(1) the product of each element in every row of the judgment matrix M_i

$$M_i = \prod_{j=1}^{n} C_{ij}, i = 1,2\cdots n$$

With the above data of U, then

$M_1 = 4/7, M_2 = 24, M_3 = 1050, M_4 = 13230, M_5 = 1/30, M_6 = 1/22680, M_7 = 1/840$

(2) $\overline{W_i} = \sqrt[n]{M_i}$

$$\overline{W} = [0.923,\quad 1.575,\quad 2.701,\quad 3.880,\quad 0.615,\quad 0.239,\quad 0.382]^T$$

(3) $W_i = \dfrac{\overline{W_i}}{\sum_{j=1}^{n}\overline{W_j}}$

$$\mathbf{W = [0.089 \quad 0.153 \quad 0.262 \quad 0.376 \quad 0.060 \quad 0.023 \quad 0.037]^T}$$

(4) The maximum eigenvalue of the judgment matrix is $\lambda_{\max}$.

$$\lambda_{\max} = \frac{1}{7}\left(\frac{0.6887}{0.089} + \frac{1.1447}{0.153} + \frac{1.9713}{0.262} + \frac{0.6887}{0.089}\frac{3.3760}{0.376} + \frac{0.4458}{0.06} + \frac{0.1724}{0.023} + \frac{0.2762}{0.037}\right) = 7.7314$$

Therefore,

$$CI = 0.1291,\quad RI = 1.32,\quad CR = 0.0923 < 0.1$$

According to the results, it can be found that the judgment matrix U has satisfactory consistency. So the indices of biomechanical properties arranged in descending sequence of importance in the present case are: bending strength, bending rigidity, the moment of inertia, elastic modulus, impact toughness, tensile strength, shear strength. The corresponding weight coefficients are respectively: 0.376, 0.262, 0.153, 0.089, 0.060, 0.037, 0.023. The weight set of biomechanical evaluation system of Stalk is

$$A = (0.089,\quad 0.153,\quad 0.262,\quad 0.376,\quad 0.060,\quad 0.023,\quad 0.037)$$

3.4 Single factor fuzzy evaluation

To determine the membership degree of evaluation object to evaluation element set from a single element is so called the single factor fuzzy evaluation.

It is supposed that the evaluation object is carried out by the i-th factor in the factor set, here r_{ij} represents the membership degree of u_i to v_j, which is the j-th element in evaluation set. Then, the evaluation results can be expresses as following fuzzy set.

$$R_i = (r_{i1}, r_{i2}, r_{i3}, \cdots, r_{in}),\quad (i = 1,2,3,\cdots,m)$$

Single factor fuzzy evaluation is the key of comprehensive evaluation. It is carried out by investigation and statistics method or fuzzy statistics.

After evaluating all factors, the matrix is obtained as follows:

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$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{6}$$

In the matrix (6), R stands for single factor evaluation matrix, it can be seen as a fuzzy relation between factor sets U and V . i.e. the reasonable relationship between influence factors and the evaluation objects.

3.5 Fuzzy synthesis evaluation

Single factor fuzzy assessment method can only take account one single element's influence to the evaluation objects. However, to consider all factors and get scientifically reasonable evaluation results, it is necessary to carry out the fuzzy comprehensive evaluation.

We can learn from the single factor evaluation matrix that: the i-th row values of R stand for the impact degree of the i-th factor to evaluation object taking values of each evaluation element. The j-th column values of R stand for the degree of all the factors impacting the evaluation object taking the j-th evaluation element. Therefore, the contribution of all elements can be accounted by the sum of each column elements. That is

$$R_j = \sum_{i=1}^{m} r_{ij} \qquad j = 1,2,3,\cdots n$$

Besides the importance of the each item should be consider as well. If each element in the R_j is multiplied by the corresponding weighting factor $a_i (i = 1,2,3,\cdots,m)$, the integrated influence of all factors is more reasonably. So the fuzzy comprehensive evaluation can be written as:

$$B = A \cdot R$$

The weight set A is a fuzzy vector. The formula represented by the fuzzy matrix multiplication is therefore:

$$B = (a_1, a_2, a_3 \cdots, a_m) \cdot \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}$$

$$= (b_1, b_2, \cdots, b_n)$$

In above formula, B is called the fuzzy comprehensive evaluation set.

$$\sum_{i=1}^{m} a_i = 1$$

In the fuzzy mathematics, when we adopt different calculation methods to calculate fuzzy comprehensive evaluation index $b_j (j = 1,2,3,\cdots,n)$, the results usually vary in practical application, we can choose more reasonable calculation method for specific problems. In this paper, we adopt weighted average algorithm and use ordinary matrix multiplication to

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calculate the product of the weight vector and evaluation matrix. This algorithm contains a joint action of all factors in the evaluation. The formula is shown as follows:

$$b_j = \sum_{i=1}^{m} a_i r_{ij} \qquad j = 1,2,3,\cdots n$$

IV. CASES STUDY

Four kinds of improved variety winter wheat in northern China were chosen to perform the experiments in order to study the biomechanical properties of winter wheat. The biomechanical properties (such as cross sectional moment of inertia, tensile strength, bending strength, shear strength, Young's modulus and bending rigidity) of basal second internodes were measured at three growth stages of wheat, which were flowering stage, milk stage and dough stage [15]. Here, the data of wheat stalks at flowering stage were chosen as the source of determining the evaluation grade because the breeding process could be regulated by breeding scientists. According to the mean values of each biomechanical index about each variety, the evaluation grade were obtained as follows: its maximum values were regarded as lower limit of "excellent" and the higher limit of "good", its mean values of all varieties were considered as lower limit of "good' and higher limit of "fair", and its minimum values were regarded as lower limit of "fair" and the higher limit of "poor".

Table 4 The range of each evaluation grade for each biomechanical indices of wheat stalk

Evaluation biomechanical indices	Excellent	Good	Fair	Poor
Tensile Modulus/MPa	≥1499.02	859.98～1499.02	408.47～859.98	≤408.47
the moment of inertia /mm^4	≥14.903	11.244～14.903	8.379～11.244	≤8.379
Bending rigidity /$N·mm^2$	≥13175.27	8885.81～13175.27	5033.01～8885.81	≤5033.01
Bending strength /MPa	≥15.953	10.539～15.953	5.406～10.539	≤5.406
Impact toughness /(kJ/m^2)	≥25.316	23.604～25.316	22.164～23.604	≤22.164
Shear strength/MPa	≥8.972	7.737～8.972	6.987～7.737	≤6.987

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Evaluation biomechanical indices	Excellent	Good	Fair	Poor
Tensile Strength/MPa	≥31.480	25.298～31.480	20.277～25.298	≤20.277

In this section, two varieties of wheat stalk were taken as examples to study the evaluation system and fuzzy synthetic evaluation model of biomechanical properties of wheat stalk.

4.1 Construction of fuzzy synthetic evaluation model

The frequencies to which grade the tested values belongs were counted and each tested value of mechanical index is compared with the evaluation grade listed in table 4. After normalization, the fuzzy evaluation matrixes of each variety of wheat stalks were obtained respectively as follows.

$$\mathbf{R}_{\text{shannong}\mathbf{91003}}=\begin{bmatrix}0&0&0.5&0.5\\0.167&0.333&0.5&0\\0&0&0.5&0.5\\0&0&0.5&0.5\\0.3&0&0.333&0.667\\0.333&0&0.167&0.5\\0.167&0.167&0.167&0.5\end{bmatrix}\quad \mathbf{R}_{\text{shannong129}}=\begin{bmatrix}0.333&0.5&0.167&0\\0&0.167&0.5&0.333\\0.333&0.667&0&0\\0.5&0.333&0.167&0\\0.1&0&0.3&0.6\\0.5&0&0.167&0.333\\0.667&0.333&0&0\end{bmatrix}$$

4.2 Results of Fuzzy Evaluation

In the previous section, the weight set has been determined as

$$A=(0.089,0.153,0.262,0.376,0.060,0.023,0.037)$$

Each fuzzy synthetic evaluation matrix will be obtained by Fuzzy transformation between the above fuzzy evaluation matrix and the evaluation weight set A. Thus,

$$\mathbf{B}_{\text{shannong}\mathbf{91003}}=\mathbf{A}\circ\mathbf{R}_{\text{shannong}\mathbf{91003}}=\left(0.0573\ 0.0572\ 0.3993\ 0.4862\right)$$

$$\mathbf{B}_{\text{shannong129}}=\mathbf{A}\circ\mathbf{R}_{\text{shannong129}}=\left(0.3472\ 0.3823\ 0.1758\ 0.0947\right)$$

It was concluded from the above results that the biomechanical properties of wheat variety named “Shannong 91003”was evaluated as poor with possibility 48.62% and as fair with 39.93%. While “Shannong 129”was evaluated as excellent with possibility 34.72% and as good with possibility 38.23%.Therefore, the “Shannong 91003” is determined as fair and poor, while the “Shannong129”is excellent based on the maximum membership degree law.

V. CONCLUSIONS

(1) The biomechanical evaluation system for stalk of stalk-like crops was established including seven evaluation indices, such as bending strength, bending rigidity, the moment of inertia, tensile modulus, impact toughness, tensile strength, and shear strength. Each index

weight was determined respectively as 0.376，0.262，0.153，0.089，0.060，0.037，0.023 by applying the Delphi Method and Analytic Hierarchy Process.

(2) The fuzzy synthetic evaluation model was constructed and two varieties of winter wheat stalk were chosen as examples for evaluation synthetically. The results showed that it was feasible to evaluate the wheat by the biomechanical properties system of wheat stalk and the fuzzy synthetic evaluation model. From the membership degree of each grade (excellent, good, fair, and poor), in our experiment, the biomechanical properties of "shannong 129" is better than those of "shannong91003". Our results could provide useful advices for scientists to breed improved varieties by selecting effective agronomic measures.

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