Elastic Modulus Is an Ideal Indicator to Evaluate Maize Stem Strength

En Lei

Honghe university <https://orcid.org/0000-0003-1009-1754>

Wen Xue Li

Honghe University

Chao Bo Wang

Honghe University

Yue Dong Wang

Agricultural Maechinery Research Institute of Yunnan Honghe Hani and Yi Autonomous Prefecture

Yong Bing Yang

Agricultural Maechinery Research Institute of Yunnan Honghe Hani and Yi Autonomous Prefecture

Qi Yuan Tang (✉ cntqy@aliyun.com)

Hunan Agricultural University

Research

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Elastic modulus is an ideal indicator to evaluate maize stem strength

En. Lei^{1,2}, Wen X. Li², Chao B. Wang², Yue D. Wang³, Yong B. Yang³ and Qi Y. Tang^{1*}

¹College of Agronomy, Hunan Agricultural University, Changsha, SC 410128, China

²College of Life Science and Technology, Honghe University, Mengzi, SC 661199, China

³Agricultural Maechinery Research Institute of Yunnan Honghe Hani and Yi Autonomous Prefecture, Mengzi, SC 661100, China

* Author for correspondence: Qi Y. Tang, E-mail: cntqy@aliyun.com

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27 **Abstract**

28 **Background:** Stem lodging seriously restricts the development of mechanized maize harvesting.
29 However, currently there is no comprehensive stem strength evaluation standard for cultivating
30 new maize varieties with excellent stem performance that are suitable for mechanical harvesting.
31 In this study, we constructed a panel of maize germplasm accessions with various stem strengths
32 by setting up different levels of stalk-rot resistance. We investigated the factors influencing maize
33 stem strength, as well as the relationships among them to clarify the key indices for evaluating
34 stem strength.

35 **Results:** Our results indicated that the stem density, moisture content, bending strength and rind
36 puncture strength were responsive to stalk-rot resistance. However, these indices were in
37 agreement with stem resistance only after the physiological maturity of maize. In particular, the
38 stem rind puncture strength exhibited a closer correlation with the stem resistance in the late stage
39 of physiological maturity. It was also demonstrated that stem density directly affected bending
40 strength and rind puncture strength, whereas indirectly affected the elastic modulus. The elastic
41 modulus includes both load and displacement; therefore, it can prompt the reliability of stem
42 strength evaluation, and is the best description of stalk toughness. The attenuation amplitude of
43 the elastic modulus is always the largest whether it is caused by the aggravation of the disease,

the growth stage delay, or the internode position rise, which significantly improves the sensitivity of stalk strength evaluation. Our results showed that the elastic modulus was correspondent with stem resistance from the silking stage of maize, which not only effectively improved the accuracy of the stalk strength evaluation, but also was extremely beneficial to improve the efficiency of maize variety selection.

Conclusions: The elastic modulus can be used to evaluate the maize stem strength truly and accurately, and especially in the high stalk rot incidence region, it is very beneficial to improve the breeding efficiency of the maize varieties suitable for mechanical harvesting.

Keywords: Maize stem, Lodging resistance, Stalk rot, Stem bending strength, Stem rind puncture strength, Elastic modulus

Background

Lodging is a common phenomenon in maize production and occurs throughout the growth stage. Lodging before physiological maturity affects the maize grain yield and lodging after physiological maturity increases the mechanical harvesting difficulty. Now, mechanical grain harvesting is an important development direction in maize production, different from traditional manual harvesting and mechanical grain harvesting, requiring that the grain has a lower moisture content during grain direct harvesting, so it is necessary to leave the maize stem standing and dehydrating in the field at least 2 weeks after physiological maturity to reach the harvest standard [1], and this requires the higher lodging resistance ability of the maize stem.

Maize lodging is divided into stem bending type and root inclination type and there is no necessary relation and correlation between them [2]. In terms of the factors affecting lodging, strong wind and stem rot are common factors leading to stem bending type lodging [3], and heavy rainfall, high soil moisture and weak root growth are the main factors leading to root inclination

type lodging [4]. Especially in Southwest China, due to the unique ecological climate conditions, maize has poor disease resistance and severe stem rot and this is an important reason for stem bending type lodging [5]. The fundamental solution to disease type lodging of maize is to breed high-resistance varieties [6, 7], but we cannot guarantee the breeding of the maize varieties with high resistance to rot and high strength, suitable for mechanical harvesting, by only using traditional disease evaluation method [8].

Some studies have pointed out that the stem bending type lodging rate is closely related to bending strength, rind puncture strength, internode dry weight per unit length, moisture content and other indicators after physiological maturity in maize [1], but there are significant differences in the varieties, growth stage and test method among the above indicators [9–12], that is, the test has a large error, poor stability and low reliability. The study found that maize stem structure and the shape, number and cell wall components of vascular bundles could affect the stem lodging resistance ability, and particularly, the stem with certain toughness showed high tensile strength, improving the stem fracture mechanical strength, beneficial to crop improvement and production [13, 14]. However, our current understanding of maize stem toughness is very limited.

The elastic modulus has previously been used in the maize stem test to verify the feasibility of the elastic modulus to describe stem strength, but this is only limited to the effect comparison under different loading modes. The study concluded that the elastic modulus values of the dry and mature maize stem rind tissue were between 6 and 16 GPa respectively under the bending, compression and tension loading mode and the stem internodes elastic modulus was significantly higher than that of stem nodes [15]. It was also concluded that the elastic modulus under the compression loading mode was rarely used for testing the plants with parenchyma cells such as maize and sorghum, because the these plants tissue samples are easy to bend, thus leading to the increase of test system error [16]. Due to the large difference in the ratio of area of vascular bundle sheath to the fiber cell wall thickness, the elastic modulus value of the same sample under radial

tensile loading mode changes greatly, the test random error is larger [17], and the elastic modulus under the bending loading mode is the test method with the least effort and best repeatability [15]. Then, is the elastic modulus significantly related to the stem strength? Can the elastic modulus be used as an evaluation indicator of stem strength? These still need further analysis and research.

This study focuses on analyzing the stem strength correlations and defining key indicators for the stem strength evaluation in the high stem rot incidence region by studying the stem senescence mechanism caused by diseases to provide a theoretical basis for the breeding of high-resistance maize varieties suitable for mechanical harvesting.

Results

Stem density and moisture content

It can be seen from Fig. 3 that the maize stem density is responsive to varieties stem resistance, but there are significant differences in different growth stages. Before the R6 stage (excluding R6, the same below), the six varieties order according to the average density (the average density of the third, fifth and seventh internodes, the same below) is as follows: LS1, XZY801, HXD88, ZH431, ZD619 and XY696. The corresponding quantitative order is: 2, 4, 5, 1, 6, 3 (the same below). The results of correlation analysis showed that the consistency between stem density and stem resistance was not significant ($r=0.200^{ns}$, $P=0.704$). After the R6 stage (including R6, the same below), except ZD619, the average density increased with the increase of stem resistance, and the order is as follows: HXD88, XZY801, XY696, ZD619, LS1 and ZH431 ($r=0.657^*$, $P=0.156$).

In terms of stem moisture content, before the R6 stage, the order according to the average moisture content is as follows: XZY801, ZH431, LS1, HXD88, ZD619 and XY696 ($r=0.371^{ns}$,

$P=0.468$). After the R6 stage, the order is as follows: XZY801, HXD88, ZD619, LS1, ZH431 and XY696 ($r=0.600^{ns}$, $P=0.208$). Therefore, the stem water content was not consistent with the resistance of stem.

The density and moisture content decreased with the growth stage extension. The six varieties average density decreased from 735.0 mg cm^{-3} 10 days after silking to 400.3 mg cm^{-3} 20 days after physiological maturity, reducing by 83.6% and the moisture content decreased from 87.1% to 75.7%, down 11.4 percentage point. The stem density and moisture content also decreased with the internode position upward moving, and the density downtrend was obviously greater than that of moisture content. The third internode density was 17.0% and 33.3% higher than that of the fifth and seventh internodes respectively, and its moisture content was 2.7 and 4.6 percentage point higher than that of the fifth and seventh internodes, respectively.

Bending strength and rind puncture strength

It can be seen from Fig. 4 that the bending strength and rind puncture strength are also responsive to the stem resistance, but there are significant differences in different growth stages. Before R6, the six varieties order according to the average bending strength and puncture strength is as follows: ZD619, XZY801, LS1, HXD88, ZH431 and XY696 ($r=0.600^{ns}$, $P=0.208$). The bending strength and puncture strength of stem are not consistent with stem resistance. After R6, the bending strength and puncture strength increase with the stem resistance increase in general, the order according to the bending strength is as follows: HXD88, XZY801, ZD619, XY696, ZH431 and LS1 ($r=0.771^{**}$, $P=0.072$), and the order according to the puncture strength is as follows: ZD619, HXD88, XZY801, XY696, ZH431 and LS1 ($r=0.943^{**}$, $P=0.005$). Only after the physiological mature stage, the bending strength and rind puncture strength are consistent with the stem resistance.

The bending strength and puncture strength decreased with the growth stage extension and the

internode position upward moving. The average bending strength decreased from 281.3 N 10 days after silking to 120.7 N 20 days after physiological maturity, and the puncture strength decreased from 49.3 N to 28.1 N. The bending strength and puncture strength of the third internode were respectively 1.7 and 1.3 times those of the fifth internode, and respectively 2.4 and 1.6 times those of the seventh internode.

Elastic modulus

Elastic modulus is originally an index to measure the elastic materials deformation difficulty. The larger the value is, the greater the stress required for the test materials deformation. Different from Fig. 3 and Fig. 4, it can be seen from Fig. 5 that before R6, the order according to the average elastic modulus is as follows: ZD619, HXD88, XZY801, LS1, XY696 and ZH431 ($r=0.943^{**}$, $P=0.005$), and after R6, the order is as follows: HXD88, ZD619, XZY801, ZH431, XY696 and LS1 ($r=0.771^{**}$, $P=0.072$), indicating that whether before or after the physiological mature stage, the stem elastic modulus is consistent with the stem resistance.

The elastic modulus decreased with the growing stage extension and the internode position upward moving. The average elastic modulus decreased from 21.8 GPa on the 10th day after silking to 7.6 GPa on the 20th day after physiological maturity, reducing by 65.1%. The elastic modulus of the third internode was respectively 3.0 and 6.7 times that of the fifth and seventh internodes.

Regression relationship between stem resistance and density, strength and elastic modulus

It can be seen from Fig. 6 that maize stem resistance is significantly correlated with the density, bending strength, puncture strength and elastic modulus. The stem rot incidence rate and disease index can be highly fitted into an exponential regression equation with stem density (Fig. 6-a and 6-b), and they can be highly fitted to a power function regression equation (Fig. 6-c, 6-d, 6-e, 6-f, 6-g, and 6-h) with the bending strength, puncture strength and elastic modulus.

However, the change of resistance to stem rot has a different effect on the above indicators. For example, each time the stem rot incidence rate increases by 10 percentage point, the average density, bending strength and puncture strength decrease by 4.5%, 3.6% and 2.6% respectively, while the elastic modulus decreases by 5.3%, reducing more than other indicators. Each time the disease index increases by 10%, the average density, bending strength and puncture strength decrease by 4.0%, 2.8%, and 2.0% respectively, while the elastic modulus decreases by 4.3%, similarly reducing more than other indicators. Therefore, the elastic modulus is more sensitive to the stem resistance.

Influence factors related to elastic modulus

It can be seen from Fig. 7 that maize stem density is significantly positively correlated with the bending strength and puncture strength respectively, which can be highly fitted into an exponential regression equation (Fig. 7-a and 7-b) and the determination coefficient R^2 is 0.7244 and 0.7002, respectively. The bending strength and puncture strength were also significantly positively correlated with the elastic modulus, which can be highly fitted to the power function and exponential regression equation (Fig. 7-c and 7-d), and the determination coefficient R^2 is 0.8614 and 0.7505, respectively. Correlation analysis found that although the stem density and elastic modulus also showed a significant positive correlation, the maximum R^2 between them was only 0.5028. In other words, the change density directly affects the bending strength and the puncture strength, and then indirectly affects the elastic modulus.

Discussion

The bending strength, rind puncture strength, dry weight per unit length, rind thickness and vascular bundles number were all the factors influencing the stem strength [2], [20–23]. Moreover, the main performance of high stem strength was high bending strength and rind puncture strength, and many vascular bundles [23, 24]. Some studies have shown that the lodging reduction mainly

depends on stem bending strength improvement under the close planting condition [25], secondly the rind puncture strength [26]. Although the stem shearing method is often used to evaluate the mechanical strength, the shear force increases with the stem maturity increase, which is contrary to the variation law of the stalk standing performance in the late growth stage [27]. The stem bending strength was positively correlated with the content of cellulose, lignin and other chemical components in the cell wall [25, 28, 29], and especially under the high-density planting condition, the stem bending strength can be significantly improved by increasing the cellulose and lignin content, thus effectively reducing the lodging rate [30, 31].

In terms of stem tissue structure, the total area of exodermis vascular bundles and the cell walls thickness were significantly correlated with bending strength [30, 32]. That is, the stem is structurally responsive to natural loads, and varieties with higher bending strength can more effectively distribute the rind tissue. The maize plant's own weight load had little effect on the bending strength, but the change of stem dry matter content significantly affected its mechanical strength. When the dry matter transfer rate increases by 4.1-191%, the average bending strength of the third, fourth and fifth internodes decreases by 14.0-36.0%, thus resulting in the a 17-275% increase in stem lodging rate [33]. However, for varieties that ripens with a living stem, due to the low utilization rate of stem dry matter, the mechanical strength is enhanced, and the stem lodging is less [34]. The results also show that it is reliable to measure the stem strength by bending strength from the silking stage to the physiological mature stage, and the gravitational center height coefficient becomes the key after the physiological mature stage [10]. That is to say, the stem strength evaluation method will change with the growth stage change and it is obviously not enough to evaluate the stem strength only by bending strength. In other words, the mechanical mechanism of stem strength needs to be further explored.

There are many defects in the rind puncture method. For example, changing the shape and size of the puncture probe significantly affects the puncture strength measured value, so the test

system error is large and the test result has poor accuracy and low reliability [11]. Moreover, we know from many years of breeding experience that the rind puncture strength used as an evaluation index cannot guarantee the excellent varieties breeding with significantly enhanced stem strength [35], and the rind puncture strength only accounts for 18% in the stem strength change [12].

This study also found that the variation law of bending strength and puncture strength is consistent, but there is a big difference between them in reflecting the mechanical strength. The stem internode is composed of exodermis (rind) and pith from outside to inside from the perspective of anatomical structure and the boundary between the epidermis and the pith becomes more obvious with the gradual maturity and the plant senescence. The exodermis is composed of smaller and closely arranged cells with thicker cell walls, while the pith is composed of larger and loosely arranged cells with thinner cell walls and high water content. Although both affect stem strength, the exodermis compactness mainly reflects the puncture strength and the whole stem hardness reflects bending strength. In other words, the puncture strength is only related to the characteristics of the exodermis tissue structure, while the bending strength is affected by both the compactness of the exodermis and the fullness of the pith. Even so, compared with the bending strength, the stem rind puncture strength has a closer relationship with resistance to rot.

From the perspective of stem senescence caused by disease, the pathogen may reduce the mechanical strength mainly by destroying the tissue structure of the rind. At this time, the rind puncture method can more truly predict the stem strength change. Unfortunately, the rind puncture strength is consistent with the stem strength only after the physiological mature stage so it is impossible to accurately evaluate the stem strength by the rind puncture method before the physiological mature stage, which will greatly limit the breeding efficiency of varieties by the stem strength identification.

The results of the study on the maize stem toughness shows that the weak stem is not caused

by the tensile strength decrease, but by the its toughness loss, which is largely related to the decrease of exodermis vascular bundles and the thin secondary wall tissue of epidermis, but not related to the relative cellulose content and other factors [9]. The study results show that the elastic modulus under bending loading mode can be used to evaluate the stem strength for three reasons. The first is that the elastic modulus includes the load and stem deformation displacement, showing the stem bending strength and the stem toughness to resist deformation, and effectively improving the authenticity of evaluating the stem strength. The second is that the elastic modulus has the greatest decline whether due to disease aggravation, the growth stage delay or the internode position rise, significantly improving the sensitivity of evaluating stem strength. The third is that the elastic modulus is consistent with the variation law of stem strength from the beginning of the silking stage, which not only improves the accuracy of stem strength test, but also greatly improves the breeding efficiency of high-resistance varieties. It should be noted that for the high-resistance variety ZD619 selected in this study, the elastic modulus decreased significantly at the late physiological mature stage, and this may be related to the flexibility loss caused by recessive gene [9], which needs further study.

In the past long time, the stem rot evaluation method based on manual harvest has played a positive role in breeding high-resistance varieties, but stem rot was mainly investigated from the milk ripeness stage to the wax ripeness stage [19, 36, 37], which is obviously not consistent with the delayed harvest under the mechanical harvesting condition. It was found in this study that the stem rot had no significant effect on the density, moisture content, bending strength and puncture strength of stem of main varieties applied in production before the physiological mature stage. Moreover, the varieties characters were the main factors affecting the stem strength at this stage, and the stem rot had a significant effect on the above indicators only at the physiological mature stage and after, that is, the maize stem rot symptoms showed strong concealment and delay. Therefore, if the stem rot investigation method is used to evaluate the stem strength, it is suggested

that the stem rot test period should be postponed to the physiological mature stage at least, and the disease grade should be reestablished and the evaluation standard improved.

Limitations

Elastic modulus, also known as Young's modulus, is originally only an important parameter to evaluate the elastic materials deformation resistance. Maize stem is not commonly used as elastic materials but produces elastic deformation under external forces. The existing study found that the elastic modulus under bending loading mode can be used to measure the difficulty of stem bending deformation, which is related to the stem toughness to some extent [15]. There are many methods to calculate the elastic modulus. According to the engineering materials bending principle, the following equation can be used to approximately calculate the maize stem bending elastic modulus [15].

$$E = \frac{a^2 b^2}{3IL} \phi$$

Where, (E) is the elastic modulus, (L) is the distance between the left and right support points on both ends, (a) and (b) are the distance from the left and right support points to the load point respectively, (I) is the bending moment of the stem rind tissue area, and (ϕ) is the deflection. According to the theory of material distribution and transport in the stem, it is considered that the stem toughness is not only related to the stem rind tissue but also closely related to the substance content in the inner pith tissue especially before the physiological mature stage [33].

Therefore, the biggest difference between the elastic modulus calculation in this study and that of the existing study lies in two aspects. One is the improvement of the bending moment calculation method. The bending moment only including the rind area is changed into the bending moment of the stem cross section, that is, the stem sample bending moment $I = \pi D_1^2 D_2^2 / 64$, where D_1 and D_2 are the length of the longer axis and the shorter axis on the cross section respectively. The second is to include the bending strength in the original equation. This not only

improves the elastic modulus accuracy in expressing the stem toughness but also improves the maneuverability of measuring the stem bending moment area. The shortcomings of this study lie in considering the stem cross section as an ellipse. In fact, the mature stem cross section is an irregular ellipse-like shape, which may cause systematic error in data testing, but will not affect the paper overall conclusion.

Conclusions

This study analyzes the factors affecting maize stem strength, compares the relationship between different evaluation indicators (the stem density, moisture content, bending strength, rind puncture strength and elastic modulus) and stem strength through studying the mechanism of maize stem senescence caused by diseases. The result shows that the maize stem density, moisture content, bending strength and rind puncture strength can be accurately responsive to stem strength only after physiological maturity. By comparison with them, the elastic modulus can evaluate the stem strength more truly and accurately and it is an ideal index to evaluate the stem strength, which can be used to improve the structural model of stem lodging resistance ability and is very beneficial to the improvement of varieties breeding efficiency suitable for mechanical harvesting especially in the high stem rot incidence region.

Methods

Design of experiments

In 2018, a field experiment for this study was conducted in the farmland at Jiale Village, Jinma Town, Luxi County, Honghe Prefecture, Yunnan Province (24°46' N, 103°30' E). In this study, maize varieties with different resistance to stem rot were selected to construct a population structure with different stem strength. The tested varieties were successively selected according to the variety comparison test in 2016 and 2017. The varieties order according to resistance to stem rot is as follows: from high to low, ZD619, HXD88, XZY801, XY696, LS1, and ZH431

(Fig.1). The results of variance analysis and correlation analysis showed that the difference in the incidence rate and disease index of maize stem rot was very significant among the tested varieties ($P<0.001$), and the incidence rate and disease index were significantly negatively correlated with the average mechanical strength (bending strength and puncture strength) of the stem third, fifth and seventh internodes respectively ($P<0.01$). In addition, in order to analyze the correlation between stem strength index and stem resistance, grading and scoring method was used to quantify the varieties according to the sequence of resistance.

A randomized block design in the field experiment was adopted. The experimental treatment was repeated for each variety 3 times. There were 18 blocks in total and each of them was 9.6 m long and 4.8 m wide, planted with 8 rows, of which 4 were used for destructive sampling and the other 4 were used for investigating stem rot. On May 7, 2018, the land was plowed and planted with maize with a seed spacing of 27.8 cm and 3 seeds sown in each hole, and the final singling of seedlings was conducted at the three-leaf stage. N, P_2O_5 and K_2O fertilizers applied were respectively 180 kg hm^{-2} , 112.5 kg hm^{-2} , and 165 kg hm^{-2} . Among them, N and K_2O fertilizer was applied twice according to the ratio of base fertilizer to panicle fertilizer equal to 5:5, and P_2O_5 fertilizer was applied once as base fertilizer during sowing. Pest and weed control was conducted according to high-yield cultivation requirements and no fungicide related to disease control was sprayed during the whole growth stage.

Sampling and measurement

We collected 11 representative samples from each block 10 days after maize silking (R1+10), 30 days after silking (R1+30), 50 days after silking (R1+50), at the physiological mature stage (R6), 10 days after physiological mature stage (R6+10), and 20 days after physiological mature stage (R6+20) respectively. We dug out the whole plant from the root with a steel knife, removed the roots, leaf sheaths, leaves and other tissues and only kept a clean stem, and then measured each internode length from the second internode to the seventh internode in turn from bottom to top,

as well as the length of the longer axis and shorter axis on cross section (see Fig.2).

Bending strength and rind puncture strength

The three-point bending strength and rind puncture strength were respectively tested by ZQ-PT880 high-precision electric tensile and compression testing machine. The specific test steps are as follows. Place the stem flat on the instrument's test bench support, The distance between the support points on both ends is 12 cm, In the downward fracture mode, bend the middle part of the third, fifth and seventh internodes in turn along the shorter axis on cross section, record the load when the stem breaks as the bending strength and meantime record the deformation displacement. The instrument parameters are set as follows: preload of 9.99 N, test speed of 30 mm min⁻¹, and elongation at break of 30%.

Continue to test the stem rind puncture strength by the above mechanical testing machine. Replace the test fixture and install the puncture probe. The probe was a needle-like cylinder with a uniform thickness and a diameter of 1.12 mm. Place the maize stem flat on the instrument's test bench, puncture the middle part of the second, fourth and sixth internodes in turn along the shorter axis on cross section in the fixed downward displacement mode, and record the maximum load displayed on the instrument as the rind puncture strength. The instrument parameters are set as follows: fixed displacement of 0.5 cm, preload of 0.09 N, and a test speed of 10 mm min⁻¹.

Density and moisture content

Cut the maize stem after the above test at the node, weigh each internode from the second internode to the seventh internode respectively, calculate each internode density according to the following equation, and then calculate the arithmetic average. $D = \pi r_1 r_2 L$, where D is the stem density, r_1 and r_2 are 1/2 length of the longer axis and shorter axis on cross section respectively, and L is the internode length. Put all the above tested internodes into a heat-resistant nylon mesh bag, then place it in the electric blast drying oven at the constant temperature of 75°C and dry it

to a constant weight, and calculate the stem moisture content by weight difference.

Elastic modulus

According to the elastic modulus calculation method of hard material three-point bending test [18], combined with the inherent morphological characteristics of maize stem, the equation of calculating the elastic modulus after the improvement of this study is as follows.

$$E = \frac{L^3}{48I} \left(\frac{\Delta F}{\Delta \delta} \right)$$

Where E is the elastic modulus of the stem, L is the span of two support points on both ends at the time of testing the bending strength, fixed at 120 mm, F is the stem bending load, δ is the sample deflection, namely, bending displacement, I is the sample bending moment, $I = \pi D_1^2 D_2^2 / 64$, D_1 is the length of the longer axis on cross section of the stem, and D_2 is the length of the shorter axis on cross section.

Stem rot

The existing traditional research method has been modified in this study according to the actual needs of mechanical grain harvesting under the condition of not affecting stem rot evaluation results. The investigation period is originally from the milk ripeness stage to the wax ripeness stage [19] and is now extended to the physiological mature stage.

The incidence level is set as Level 0, 1, 3, 5 and 7. Level 0 means that the plant is healthy without stem rot. Level 1 means that water-soaked spots appeared at the stem basal internode, the stem is hard, and the plant is normal in general. Level 3 means that the basal internode becomes soft but the ears grow normally. Level 5 means that the basal internode of becomes soft, the ears droop and the cob is wet and soft, without plant lodging. Level 7 means that the basal internode of the stem is rot with plant lodging. In 4 four maize rows for stem rot research within each block, 100 plants were selected continuously (excluding the rows on both ends). The incidence rate and

disease index were calculated by counting the number of diseased plants and identifying the incidence level.

$$\text{The incidence rate}(\%) = \frac{\text{Diseased plants}}{\text{Total plants}} \times 100;$$

$$\text{The disease index} = \frac{\sum (\text{Diseased plants of all levels} \times \text{Representative values of all levels})}{\text{Total plants} \times \text{The representative value of the highest level}} \times 100$$

Repeatability and statistical analysis

Maize stem shape variation and structure is the main reason for the test error, and the test error can be effectively reduced by increasing the repetition times and sample size. This study adopted the block design in the field experiment, set up three repetitions according to the soil fertility distribution under local control. When testing quantitative characteristics (such as stem density, moisture content, bending strength, puncture strength and elastic modulus), 11 plants were sampled again in each block and this is equivalent to 33 independent sampling with the sample size n larger than 30. When testing maize stem rot in qualitative characteristics, 100 plants were researched in each block with a sample size much larger than 30. Therefore, the sample size of the above sampling is a large simple size, and the sampling distribution of the sample average obeys normal distribution.

The data processing system of IBM SPSS statistics 21.0 was used for analysis of variance and correlation. The least significant difference was adopted for the multiple comparisons in the analysis of variance of experimental treatment, and the significance level was 0.05. The *LSD*

algorithm between different levels of different varieties and growth stages is $LSD_{0.05} = t_{0.05(df)} \sqrt{\frac{MS_e}{ar}}$,

where $t_{0.05(df)}$ is the critical t -value of factors degree freedom under F test, MS_e is the error mean square, a is the factors levels number, and r is the experimental treatment repetition times. The

LSD algorithm of variety $\times$ growth stage interaction is $LSD_{0.05} = t_{0.05(df_e)} \sqrt{\frac{2MS_e}{r}}$, where df_e is the test

error degree freedom. The hypothesis test of regression relationship between variables was conducted by F test, and the significance level was 0.05. Linear model was used to analyze the correlation between stem strength index and variety resistance, and the significance level was set as 0.1.

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Authors' contributions

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Author details

¹College of Agronomy, Hunan Agricultural University, Changsha, SC 410128, China. ²College of Life Science and Technology, Honghe University, Mengzi, SC 661199, China. ³Agricultural Machinery Research Institute of Yunnan Honghe Hani and Yi Autonomous Prefecture, Mengzi, SC 661100, China.

Figures

Fig. 1 Maize stalk-rot resistance of tested varieties

Fig. 2 Structure diagram of maize stem test

Fig. 3 Consistency between stem density, moisture content and stem resistance in maize

Note: the 3rd, 5th and 7th in the figure represent the 3rd, 5th and 7th internodes of maize respectively. * indicates that the significance level of the difference between treatments is 0.05

(0.01 < p < 0.05). * * indicates that the significance level of the difference between treatments is 0.01 (p < 0.01). The same below.

Fig. 4 Consistency between stem bending strength, rind puncture strength and stem resistance in maize

571 **Fig. 5** Consistency between stem elastic modulus and stem resistance in maize

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Fig. 6 Regression relationship between stem density, bending strength, rind puncture strength and elastic modulus with stem resistance

Fig. 7 Regression relationship among stem density, bending strength, rind puncture strength and elastic modulus

Figures

Figure 1

Maize stalk-rot resistance of tested varieties

Figure 2

Structure diagram of maize stem test

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Figure 4

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Figure 5

Consistency between stem elastic modulus and stem resistance in maize

Figure 6

Regression relationship between stem density, bending strength, rind puncture strength and elastic modulus with stem resistance

Figure 7

Regression relationship among stem density, bending strength, rind puncture strength and elastic modulus