HANDY: a device for assessing resistance to mechanical crushing of maize kernel

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Abstract

Background: How to reduce the physical damage during maize kernel harvesting is a major problem for both mechanical designers and plant breeders. A limitation of addressing this problem is the lack of a reliable method for assessing kernel damage susceptibility. Previous methods of testing kernel strength lack in make a comparative discussion from the viewpoint of threshing. The design, construction and testing of a portable tool called "HANDY", which can assess the resistance to mechanical crushing in maize kernel. A device is designed and developed that can impact the kernel with a special accelerator at a given rotating speed and then cause measurable damage of maize kernel. These factors are varied to determine the ideal parameters for operating the HANDY.

Results: Baseline testing of the HANDY is performed to determine the initial range of testing parameters. The result shows that the optimum number of test times is one for one group of maize kernels. Breakage index (BI, target index of HANDY), decreased as the moisture content of kernel increased or the rotating speed decreased within the tested range. Furthermore, the HANDY exhibited a greater sensitivity in testing kernels at higher moisture level influence on susceptibility of damage maize kernel than that in Breakage Susceptibility tests, particularly when the centrifugation speed is about 1800 rpm and the disc is curved type centrifugal disc. Considering that the mechanical properties of kernels vary greatly as the moisture content changes, a subsection linear (average goodness of fit is 0.87) to predict the threshing quality is built by piecewise function analysis, which is divided by kernel moisture. Specifically, threshing quality is regarded as a function of the measured result of the HANDY.

Conclusions: The HANDY provides a quantitative assessment of mechanical crushing resistance of maize kernel. The BI is demonstrated to be a more robust index than breakage susceptibility (BS) when evaluating threshing quality in harvesting in terms of both reliability and accuracy. This study also offers a new perspective for evaluating the

mechanical crushing resistance of grains, and provides technical support for breeding maize varieties which are suitable for mechanical harvesting.

Keywords: Maize kernel, Crushing resistance, Breakage susceptibility test, Handy

Background

The maize has the highest yield compared with other food crops. The planting area of maize was more than 41284 hectares and the total yield was more than 1108.62 million tons in 2019 (National Bureau of Statistics [1]).

Remarkably, the serious physical damage of maize kernels caused by mechanical harvesting has become the primary factor that can affect the quality and grand of maize kernels [2]. Therefore, increasing the mechanical crushing resistance of maize kernels is important to both current food security and to the development of future maize varieties [3]. According to statistics, China farmers lose almost 247.5 kg/ha per year in lost maize yield due to the mechanical damage in harvesting [4]. Hence, study on increasing impact strength of maize kernel has important significance on developing commercial harvesters and enhancing maize quality grade.

Maize kernel crushing resistance is a key determinant of the threshing quality as it can affect the required capability for keeping the integrity of the kernel. Various testing methodologies for predicting the crushing resistance of maize kernels have been presented, the methodologies include compression method [5-6], drop method [7], pendulum method [8] and breakage susceptibility method [9-10]. In addition, several researchers have sought to establish correlations between various morphological [11], chemical [12-13], mechanical properties [14-15], genetic or environmental [16] factors of maize kernels and breakage susceptibility (e.g., measurements of density, hardness, protein content, etc.). Unfortunately, the coefficient of determinations of the regression equations is unsatisfactory, or the results lack in making a comparative discussion from threshing aspect [14].

Furthermore, these methods are typically labor-intensive and often require expensive laboratory equipment. For instance, laboratory-based compression and puncture tests are completed by universal testing machine [17-20]. Besides, some of these methods do not produce the same damage types observed in mechanical threshing maize. Specifically, the predominant damage type of maize kernels in these test methods is distinctive cracks but that in mechanical threshing is fragments [14].

This study describes a portable tool called “HANDY” for assessing mechanical crushing resistance of maize kernel. The design principle of HANDY refers to the form of being loaded of maize kernel in actual threshing. The load in threshing is mainly impact forces, thus, the device uses centrifugal acceleration for imparting impact forces to kernels. The centrifugal acceleration is achieved by a centrifugal disc. Furthermore, the different peripheral speeds and centrifugal disc types are used to generate different levels and directions of impact forces, the combination of peripheral speeds and centrifugal disc types are studied to determine the ideal working parameters. Finally, a model to predict the threshing quality derived from the measured result of the HANDY. From famers’ perspective, it also provides an effective reference for appointing an opportune harvest time to decrease harvesting lose. Biologically, lacking of such a device has been a crucial limitation for breeding efforts focused on suitability for mechanical harvest.

Description of HANDY

Structure of HANDY

The crushing resistance impactor apparatus (HANDY), as shown in Fig.1, is composed of an impact part, a sieve part and a frame part. The impact part includes a hopper, a cover, a shell, a centrifugal disc and a motor and they are arranged concentrically from top to bottom. A material feeding plate is set under the hopper. The hopper is mounted on the feed port which is set on the top surface of the cover. The cover and the shell are tightly fixed by 4 buckles. A centrifugal disc is installed inside the shell, and directly driven by the motor 2. Note that the centrifugal disc is composed of a disc plate and a transmission shaft. Six triangular side plates are welded to the disc plate and the shaft to maintain the stability of the rotation of centrifugal disc. The shaft of motor 2 transfers the torque through the coupling to the centrifugal plate. In order to make the kernels flow down smoothly, the lower part of the shell is conical, and two symmetrical discharge ports are designed and set at the bottom of the shell.

The sieve part is composed of a sieving mechanism and a driving mechanism. The sieving mechanism is composed of a sieve frame and a round hole sieve. The round hole sieve is connected with the frame that are composed of four columns and the connection is achieved by four suspension springs. The driving mechanism is composed of the motor 1 and the crank connecting rod mechanism. Motor 1 is the power source which can drive the crankshaft and connecting rod mechanism, then, it forms the reciprocating motion of the sieve. Two bendable pipes are used to convey samples from the impact part to the sieve part. The upper end of the pipes are fixed with the discharging ports. The lower end of the pipes are set above the sieve. The detailed structural parameters of HANDY are shown in Table 1.

<Fig.1>

<Table 1>

Working mechanisms of HANDY

First, placing a sample of maize kernels in the hopper. Then energizing the motors. Driven by the motor 2, the centrifugal disc will rotate at a certain speed. The speed of the motor 2 is set by using a variable speed drive. Then drawing out the feeding plate. Under the action of gravity force, the kernels will fall into the feeding port. Under the action of centrifugal force, the kernels will be accelerated rapidly by the centrifugal disc, and be thrown out of the centrifugal disc at a certain speed. Then, kernels will collide with the inner wall of the shell. After that, all the kernels will fall into the bottom of the shell, and then slide into the sieve through the pipes. Finally, the fragment kernels will be sieved by the sieve under a certain vibration frequency.

Testing of HANDY

Purpose of the tests

The first purpose of the tests is to determine the optimum parameters for the HANDY. The parameters are centrifugal speed and type of centrifugal disc. The parameters are chosen because they can affect the levels and directions of impact forces that applied to kernels. Furthermore, the levels and directions of impact forces can influence the repeatability and uniformity of the results. Moreover, if the system is operated at an unsuitable speed, it will erratically produce vibration which is unstable for experimental purposes.

The second purpose of the tests is to access the performance of HANDY. The performance is access by comparing the test result of HANDY to Breakage Susceptibility test. Note that Breakage Susceptibility test is commercially used to evaluate the mechanical strength of kernel, which is operated by an acceleration device [21].

The third purpose of the test is to indicate that the HANDY can be used to predict the threshing quality. The method is to build a model to show the relationship between the BI (the crushing resistance of maize kernels assessed by the HANDY) and its broken rate (BR, the index of threshing quality) in actual mechanical threshing.

Procedure of the testing

For the Breakage Susceptibility test, the HANDY test and the mechanical threshing test, 21 commercial common maize hybrids from northern China are utilized as test material. The moisture content of the kernels is determined (15.80% – 30.92%) by using a grain moisture measurement instrument (Japan, KETT, PM–8188–A). Table 2 presents some physical properties of the maize varieties.

<Table 2>

For the Breakage Susceptibility test and the HANDY test, the sample maize kernels are threshed manually, and are cleaned to remove all foreign materials, such as dust, female flower and damaged kernels. After that, the kernels of the same variety are mixed evenly, 200 g sample is set as a sample group and weighed by an electro mechanical counter (with an accuracy of 0.01 g) and then poured into the hopper for the tests. The replicants of tests is set as five.

For the HANDY test, the breakage index (BI), is the ratio of the weight of all completely crushed kernels (without seed coat connection) to the total sample (as shown in Eq.1). Note that the crushed kernels are composed of two parts: sieved and un-sieved broken kernels. The un-sieved broken kernels are picked manually and their characteristics are shown in Fig.2.

<Fig.2>

$$BI = \frac{W_S + W_{US}}{W_1} \times 100\% \qquad (1)$$

Where W_s refers to the weight of the sieved broken kernels, g; W_{us} refers to the weight of broken kernels that un-sieved g; W_1 is the total weight of a set of samples, g.

For the Breakage Susceptibility test, the Breakage susceptibility (BS) of the samples are determined using the HANDY with the traditional straight centrifugal discs. A feed rate of 100 g/min and a centrifugal speed of 26.69 m/s are used in the test. BS is characterized by the ratio of the weight of the sieved broken kernels to the total samples (as shown in Eq.2). Note that the tested samples are sieved through12/64 inch openings.

$$BS = \frac{W_S}{W_1} \times 100\% \qquad (2)$$

For mechanical threshing test, the whole maize ear is utilized. An axial flow corn threshing cylinder (rotating speed is 300 rpm, concave clearance is 55 mm) is used to thresh maize ears (Fig.3). The type of threshing element is cylinder chose rasp bars. The threshing cylinder is designed with a diameter of 520 mm and a length of 2700 mm. In each experiment, the feeding rate of threshing cylinder is 8 kg/s. The experiment of each group is repeated for 3 times. Note that broken rate (BR) of kernel is an important index to evaluate the working quality of threshing and separator device [22]. The BR is calculated as follows:

$$BR = \frac{W_m}{W_2} \times 100\% \tag{3}$$

Where W_m refers to the mass of the weight of the broken kernels that have obvious broken characteristic, g; W_2 refers to the total mass of a set of samples for mechanical threshing test, g.

<Fig.3>

Baseline testing of HANDY

Baseline experiments are conducted to determine the experimental variables that could be tested and then determine the optimum parameters for operating the HANDY. The baseline experiments are accompanied by using the two varieties (SR 999, ZD 958) of maize samples, the moisture contents of which is around 25%. The type of centrifugal disc is straight type. The rotating speeds of the disc are 1300, 1500, 1800 and 2100 and 2300 rpm (corresponding to 20.41, 23.55 and 26.69, 28.26, 32.97 and 36.11 m/s peripheral speed). Three equal groups of kernels are chosen from each variety and each group is subjected to impacts for once, twice and three times, respectively. The BI obtained for each centrifugal speed and the number of impact for the two maize varieties, are shown in Table 3.

<Table 3>

As shown in Table 3, the increase of the BI is negligible when the kernels are repeatedly impacted for twice and three times. Furthermore, impacting samples for several times will produce a lot of broken kernels, thus increasing workloads of postprocessing. As a result, the test number is once as the optimum time for testing. The HANDY operated at lower speed cannot cause detectable damage to kernels. On the contrary, higher speed will cause significant damage to kernels and increase the number of broken kernels. However, the speed less than 1500 rpm and more than 2100 rpm can produce little and massive broken kernels, respectively. Both too little or too much broken kernels be caused are unacceptable for the experiments, and the detail be discussed in the chapter of “Test for establishing optimum operating parameters of HANDY”. As a result, further experiments focus on the speed range of 1500-2100 rpm. Three centrifuge discs types of straight, curved and oblique are chosen for further testing because they can affect the moving direction of the kernels [23-24]. Therefore, the experimental factors and variables in this research are: Centrifugal speed = 1500 rpm, 1800 rpm, 2100 rpm (23.55 m/s, 28.26 m/s, 32.97 m/s); Centrifuge discs types = straight, curved and oblique; Testing times = once.

The repeatability of the HANDY test is also explored. The maize kernels at different moisture contents are tested.

Results and discuss

The test results obtained in this study are reported in three main parts. The first part includes the result of optimum parameters of the HANDY. The second part describes the results of the experiments which are designed to compare the effectiveness and applicability of BI and BS. BI and BS are utilized in evaluating the mechanical crushing resistance of kernels. The third part analyzes the applicability of the HANDY to evaluate the threshing quality of maize kernels.

Working condition of HANDY

During the testing, a slight irregular vibration of the frame is observed. The impact part can generate small noise though it is fixed to ground by the rubber casters. The operation of the HANDY is not as laborious as traditional testers for measuring maize crushing resistance. A great flexibility in adjusting operation parameters is achieved with the HANDY. However, the device needs improve intelligence in picking un-sieve broken kernels.

Test for establishing optimum operating parameters of HANDY

Peripheral speed of the centrifuge disc

In order to ensure the device to have a stable performance and repeatable results, the tests using straight type centrifuge disc are conducted at three peripheral speeds (23.55 and 28.26 and 32.97 m/s corresponding to 1500 rpm, 1800 rpm, 2100 rpm rotating speed). The speed range has been determined by the baseline test result. The BI at three rotating speeds are depicted in Fig.4a. The BI measured with three rotating speeds (1500 rpm, 1800 rpm, 2100 rpm) are 0.03% – 13.73%, 0.98% – 34.67%, 7.60% – 51.65%, respectively. The average BI are 2.82%, 8.53% and 22.65%, respectively. Statistical analysis of the BI shows a remarkable consistency in the results when the speed is different: the three curves of BI present similar trend. Specifically, the BI decreased with the moisture content increased under the overall, which is almost in long-tailed distribution. In order to obtain the BI with smaller variability, both the variation of coefficient and distribution dispersion under different rotating speeds are discussed.

Fig.4b shows the coefficient of variation of the BI at different rotating speeds. The average coefficients of variation of the results are 56.57, 16.31, 19.12 when rotating speeds are 1500 and 1800 and 2100 rpm, respectively. Note that the BI is close to 0 when the rotating speed is 1500 rpm and the kernel moisture is more than 21%. In this case, small numerical changes of the BI can also have a significant effect on the coefficient of variation, resulting in low repeatability. This is the reason why the coefficient of variation of BI is larger when the rotating speed is 1500 rpm than others. As a result, the speed at 1500 rpm is too low for the HANDY operation. The coefficient of variation of the BI obtained at the speed of 2100 rpm is worse than those at the speed of 1800 rpm. This also shows that when the HANDY works at the rotating speed of 1800 rpm exhibited a better repeatability and higher precision in discovering the kernels with different level of mechanical crushing resistance.

Fig.4c shows the distribution of the BI at different rotating speeds. When the rotating speed is 1500 rpm, 50% of the BI are less than 1.5%, which indicates that the BI has significant uneven distribution. This further shows that the HANDY operated at this speed causes less measurable damage to kernels. When the rotating speed is 1800 rpm, 57.14% of the BI are within 3% - 7%, 50% of which are within 2% - 3%. The BI obviously varied among different-moisture intervals, which ensure the continuity of BI. The HANDY works at the rotating of 2100 rpm can produce substantial amount of damage to kernels which have various crushing resistance.

In addition to the above discussions, the time to pick broken kernels also needs to be considered. When the rotating speed is lower than 1500 rpm, the impact energy cannot be transmitted from the centrifugal disc to the kernels sufficiently. As a result, few kernels are broken completely and it is hard to pick them out. On the contrary, when the rotating speed is higher than 2100 rpm, it will take about additional 2 minutes to pick the broken kernels out. It even produces massive maize flour or juice. However, when the rotating speed is about 1800 rpm, a number of the kernels are broken with obvious broken characteristic and then easy to be picked. Moreover, the time to pick broken kernels is acceptable. Thus, when the speed is around 1800 rpm, the test results are conducive to evaluate the crushing resistance of kernels.

<Fig.4>

Type of the centrifuge disc

From a machine design perspective, the design objective of the centrifugal disc should make all the kernels be subjected to identical impact, and produce little random splatter of kernels. From the angle of kinematics, the type of the discs can affect the magnitude and direction when kernels departing from the discs [25]. Thus, the objective of the analysis is to find an optimal centrifuge disc type. Three type of centrifuge disc (straight, curved and oblique) are selected and designed for this study (Fig.5). Tests are conducted at rotating speeds of 1800 rpm by using the HANDY.

<Fig.5>

Fig.6a shows the BI when using different types of centrifugal discs. For all the tested maize varieties, the BI for different types of the centrifuge discs (straight, curved and oblique) are within 0.98% – 34.67%, 1.20% – 36.55%, 1.07% – 34.21%, respectively. The BI decreases with the increase of moisture content. Note that, when the moisture content increases to about 23%, the BI decreases to minimum. When the moisture content continue increasing from 23%, the BI changes within a small range.

The coefficient of variation and the distribution dispersion of the BI measured with different centrifuge disc types are discussed. As Fig.6b shows, the curved disc produces the BI with lower coefficient of variation compared to the straight and oblique disc. The average coefficient of variation for the straight and oblique disc is 1.03 and 1.71 times greater than that shown by the curved disc, respectively.

Fig.6c shows the distribution of the BI for different type of centrifugal discs. The SPSS 23.0 is used, the influence of centrifugal disc type on BI is analyzed through two methods: descriptive statistics analysis and difference testing. There is no significant difference in data distribution among the three centrifugal discs. This means that for the kernels with the same crushing resistance, all centrifugal discs can cause considerable amount of damage to them. However, the result of the difference test shows that more sensibility for the same test kernel samples by using the curved centrifugal disc (Fig.7). This further shows that in comparison with the straight and oblique centrifugal discs, the curved disc has superior sensitivity and is suitable for assessing to mechanical crushing resistance of maize kernel. It is more effective to distinguish the maize varieties with small difference in crushing resistance. Therefore, it is appropriate to choose the curve type as the optimum centrifugal disc.

<Fig.6>

<Fig.7>

Repeatability of results

The plots of BI versus moisture content for the maize kernel (Fig.8) shows that the graphs for the five replicate tests are similar. The maximum difference of BI within any set is 1.19% which shows that the HANDY can produce repeatable results (speed: 1800 rpm, disc type: curved type).

<Fig.8>

Breakage Susceptibility test results

Fig.9a shows the results of Breakage Susceptibility tests. As expected, the results follow the normal breakage behavior of kernels. That is the BS of kernels decreases as the moisture content increases. When the BS is at maximum value, the maize kernels shows higher mechanical crushing resistance. The change rules of BS of maize kernels obtained by HANDY are similar with those obtained by using the Stein Crush resistance tester, Wisconsin Tester, and Centrifugal Corn Crush resistance tester in previous studies [26-29].

HANDY test results

The rotating speed of HANDY is 1800 rpm with the curved centrifugal disc. The BI obtained for the same maize kernels, As shown in Fig.9b, the change rules of BI obtained by HANDY tests and BS obtained by the Breakage Susceptibility tests are similar. For both Breakage Susceptibility tests and HANDY tests, the moisture content of kernel is used as a variable. With the increasing of moisture content, the overall changing rules of BI and BS can be divided into three stages: stage I, stage II and stage III. The moisture content ranges of the three stages are: 14% – 18%, 18% – 25% and 25% – 31%.

For stage I (14% – 18%), stage II (18%– 25%), and stage III, both BS and BI drop sharply, drop slowly and keep stable with the increase of moisture content, respectively. For maize kernel materials, the lower the moisture content, the higher the hardness and brittleness [14]. Therefore, the mechanical characteristics of kernels are brittle and hard in stage I, which makes it more likely to break into small pieces. In stage III, the kernels show plasticity, high elasticity and flexibility. In stage II, the mechanical characteristics of kernels are between that in stage I and stage III.

An obvious difference between BS and BI in stage III is observed. Specifically, the results of BI increases to the maximum value and then decreases with the further increases in moisture content [30-31]. In contrast, the BS in stage III is reduced close to zero. Consider the energy absorption capability, the wet kernels is higher than dry ones, the kernels achieve a greater flexibility at high moisture, thus making the kernels absorb more deformation energy before crack [32-33]. It cannot be neglected that numerous kernels are split into parts but still connected by seed coat. As a result, those broken kernels connected by seed coat cannot pass the circular sieve (12/64 inch in diameter), resulting in the BS reduced close to zero in stage III (as shown in Fig.9a). However, in the HANDY tests, BI shows as a bell-shaped curve in stage III (as shown in Fig.9b). As a result, compared with the BS, the BI can effectively reflect and evaluate the mechanical crushing resistance of the kernels at this stage.

<Fig.9>

Results of mechanical threshing tests

Generally, mechanical damage is induced by impact during harvesting which can debases the quality and shortens the storage period of maize kernels [34-35]. In order to prove that HANDY can be used to predict the impact damage severity of maize during harvesting, the mechanical threshing test of maize ear is carried out. The HANDY test, meanwhile, is conducted at the optimum parameters.

The results of BR and BI are shown in Fig.10a. For all the tested hybrids, the ranges of the BR and BI are 1.28% – 13.53%, 1.07% – 34.21%, respectively. Fig.10a indicates that the relationship between the BR and the BI is obviously diverse in three moisture content ranges. When the moisture content is less than 18%, both BR and BI decreased with the increase of moisture content, but the decreasing rate of BI is higher than BR. When the moisture content is 18%-25%, the BI continuous decreasing but the BR is increasing. When the moisture content is more than 25%, the change regularity of BR and BI is similar and increasing overall. In aggregate, with the increase of kernel moisture content, the broken rate first decreased and then increased, which are close to the result obtained before [36].

<Fig.10>

Fig.10b shows the relationship between the BR and the BI which eliminate the information of kernel moisture compared with Fig.10a. The plot procedure is as follows: First, select a single moisture content of kernel on both curve of BI and BS (denoted by the straight line in Fig.10a). The intersection of this straight line with the BI curve becomes the x-coordinate and the intersection of the straight line with the BS curve becomes the y-coordinate of the Fig.10b. Plot this point in a separate graph (point X in Fig.10b), which represents the relationship between the BR and the BI and no longer possesses a kernel moisture element. Repeat this process for each kernel moisture to construct the remainder of Fig.10b. As a result, the BI (independent variable) are used to generate a subsection linear regression functions that could be used to predict BR (dependent variable) achieved using the HANDY. The equation is:

$$y=\begin{cases}0.149x-0.378 & MC<18\% & (R^2=0.86)\\ -0.223x+3.348 & 18\%\le MC<25\% & (R^2=0.87)\\ 0.844x+1.913 & 25\%\le MC & (R^2=0.87)\end{cases} \tag{4}$$

The R^2 of the regression model at three moisture content are 0.86, 0.87 and 0.87, respectively, which further illustrates the BI prove capable of explaining on average about 86.67% of the BR of maize kernel in threshing. These values indicate that the subsection linear regression model may be considered satisfactory, however, it is necessary to check the linear regression model in Eq.(4) to evaluate whether it can provide an acceptable approximation or not. The approximation precision level of the linear regression model is evaluated through calculation of relative errors between the results obtained from the HANDY and threshing tests. The evaluation results are given in Fig.11. As expected, the results show that the BR predicted values and the measured ones are in good conformity at three kernel moisture ranges (Fig.11a). As shown in Fig.11b, it's seen that the range of relative error are calculated between 1.99 and 32.81%. The average relative error for three moisture range is 11.08%, 23.69% and 17.86%, respectively. A relative error of less than 20% is observed for 15 out of 24 experiments (i.e. for 62.5% of experiments). As a result, considering the variability of physiological characters in maize kernel the linear regression model the coefficient of determinations of these regression equations are satisfactory.

<Fig.11>

Conclusion

This work is undertaken to develop a device called HANDY for assessing resistance to mechanical crushing of maize kernels. Imitating the loading model (impact) of the mechanical threshing of kernels, HANDY is designed based on centrifugal acceleration, which is used to provide acceleration power for kernels. For obtaining results with small variability and high repeatability, the curve type centrifugal disc and the speed about 1800 rpm can be chosen. Compared with traditional Breakage Susceptibility Test, HANDY has a greater sensitivity in determining the influence at higher moisture content on the measurement of mechanical crushing resistance. A linear regression model is developed to relate HANDY test results to the mechanical threshing quality, with an average R^2 of 0.84. The HANDY, moreover, this prototype is flexible and can be modified for testing many other grains.

Abbreviations

BI: breakage index (%); BS: breakage susceptibility (%); BR: breakage rate (%).

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Authors' contributions

XY carried out the experiments, data analysis, paper writing. SY and XY participated in the design of the study, all authors prepared and checked the materials. GXJ, LYO and XGY revised the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable

References

1. National Bureau of Statistics. Announcement of National Bureau of statistics on grain output data in 2019.

http://http://www.stats.gov.cn/tjsj/zxfb/201912/t20191206_1715827.html.

2. Wan K-R, Li S-K. Progresses in research on grain broken rate by mechanical grain harvesting. Scientia Agricultura Sinica. 2017;50(11), 2018–26.
3. Li L-L, XUE J-Xie R-Z, Wang K-R, Ming B, Hou P, et al. Effects of grain moisture content on mechanical grain harvesting quality of summer maize. Acta Agronomica Sinica. 2018; 44(12): 1747-54.
4. Fang H-M, Niu M-M, Shi S, Liu H, Zhou J. Effect of harvesting methods and grain moisture content on maize harvesting quality. Transactions of the Chinese Society of Agricultural Engineering. 2019;35(18):11-18.
5. Su Y, Cui T, Zhang D-X, Xia G-Y, Gao X-J, He X-W, et al. Damage resistance and compressive properties of bulk corn kernels at varying pressing factors : experiments and modeling. Journal of Food Process Engineering. 2019;42(7).
6. Su Y, Cui Tao, Zhang D-X, Xia G-Y, Gao X-J, He X-W, et al. Effects of shape feature and loading condition on mechanical properties of maize kernels. Journal of Food Processing and Preservation. 2019; 44(1).
7. Li X-P, Ma F-L, Gao L-X. Dropping impact experiment on corn seeds. Transactions of the Chinese Society of Agricultural Engineering. 2009;25(1), 113–16.
8. Srivastava AK, Herum FL, Stevens KK. Impact parameters related to physical damage to corn kernel. Transactions of the ASAE.1976;19(6),1147–51.
9. Bilanski WK. Damage resistance of seed grains. Transactions of the ASAE.1966; 9(3):560-63.
10. Bartsh JA, Haugh SG, Athow KL, Peart RM. Impact damage to soybean seed. ASAE Paper; 1976; No.79-3037, ASAE, St. Joseph, MI 49085.
11. Lee KM, Herrman TJ, Lingenfelser J, Jackson DS. Classification and prediction of maize hardness-associated properties using multivariate statistical analyses. Journal of Cereal Science. 2005; 41, 85-93.
12. Peplinski AJ, Paulsen MR, Bouzaher A. Physical, chemical, and dry-milling properties of corn of varying density and breakage susceptibility. Cereal Chemistry.

1992; 69(4): 397-00.

13. Blandino M, Sacco D, Reyneri A. Prediction of the dry-milling performance of maize hybrids through hardness-associated properties. Journal of the Science of Food & Agriculture. 2013; 93(6):1356-64.
14. Su Y, Cui Tao, Zhang D-X, Xia G-Y, Gao X-J, He X-W, et al. MLR and experimental testing for characterization and classification of damage resistance of maize hybrids based on mechanical properties. Journal of Food Process Engineering. 2019; 42(13).
15. Baslar M, Kalkan F, Kara M, Ertugay MF. Correlation between the protein content and mechanical properties of wheat. Turkish Journal of Agriculture & Forestry. 2012; 36: 601-07.
16. François XO, Lasme P, Michelet C, Dubat A, Gardet O, Heumez E, et al. Bread wheat milling behavior: effects of genetic and environmental factors, and modeling using grain mechanical resistance traits. Theoretical and Applied Genetics. 2017; 130: 929-50.
17. Naik DL, Kiran R. Nave Bayes classifier, multivariate linear regression and experimental testing for classification and characterization of wheat straw based on mechanical properties. Industrial Crops and Products. 2017; 112:434-48.
18. Koch M, Naumann M, Pawelzik E. Cracking and fracture properties of potato (solanum tuberosum l.) tubers and their relation to dry matter, starch, and mineral distribution. Journal of the Science of Food & Agriculture. 2019; 99: 3149-56.
19. François XO, Lasme P, Michelet C, Dubat A, Gardet·O, Heumez E. Bread wheat milling behavior: effects of genetic and environmental factors, and modeling using grain mechanical resistance traits. Theoretical and Applied Genetics. 2017; 130:929-50.
20. Jie K, Sun Y-Y, Liu T-T, Zhang P-P, Zhou M, Wu J-S, et al. Physiological mechanisms behind differences in pod shattering resistance in rapeseed (Brassica napus L.) varieties[J]. Plos One, 2016; 11(6): e0157341.

21. Singh SS, Finner MF. A centrifugal impacter for damage susceptibility evaluation of shelled corn. Transactions of the ASAE American Society of Agricultural Engineers. 1983; 26(6):1858-63.
22. Chai Z-W, Wang K-R, Guo Y-Q, Xie R-Z, Li L-L, Ming B, et al. Current status of maize mechanical grain harvesting and its relationship with grain moisture content. Scientia Agricultura Sinica. 2017; 50(11): 2036-43 .
23. Villette S, Piron E, Miclet D. Hybrid centrifugal spreading model to study the fertiliser spatial distribution and its assessment using the transverse coefficient of variation. Computers & Electronics in Agriculture. 2017; 137:115-29.
24. Bilal H, Simon C, Jürgen V, Koen CM, Frédéric C, Michel P, et al. High speed stereovision setup for position and motion estimation of fertilizer particles leaving a centrifugal spreader. Sensors. 2014; 14, 21466-82.
25. Floyd MC, Edmund YSC. Design relationships for centrifugal fertilizer distributors. Transactions of the ASAE. 1967; 91-95, Paper No. 65-605.
26. Singh SS. Development of a centrifugal corn breakage tester. M.S. Department of Agricultural Engineering, University of Wisconsin, Madison, WI. 1980.
27. Tang, J, Sokhansanj S, Sosulski F. Determination of the breakage susceptibility of lentil seeds. Cereal Chemistry, 1991; 68, 647-50.
28. Siska J, Hurburgh CR. Prediction of Wisconsin tester breakage susceptibility of corn from bulk density and NIRS measurements of composition. Transactions of the ASAE. 1994; 37(5), 1577-82.
29. Lian Z, Cao C, Zhu WX. Design and characteristic test of a centrifugal corn crush resistance tester. Transactions of the Chinese Society for Agricultural Machinery. 1997; 29(2), 76-79.
30. Saiedirad MH, Tabatabaeefar A, Borghei A, Mirsalehi M, Badii F, Varnamkhasti MG.. Effects of moisture content, seed size, loading rate and seed orientation on force and energy required for fracturing cumin seed (cuminum cyminum linn.) under quasi – static loading. Journal of Food Engineering. 2008; 86(4), 565-72.

31. Tavakoli H, Mohtasebi SS, Rajabipour A, Tavakoli M. Effects of moisture content, loading rate, and grain orientation on fracture resistance of barley grain. Research in Agricultural Engineering. 2009; 55(3), 680-09.
32. Li Y, Chandio FA, Ma Z, Lakhiar IA, Suleman M. Mechanical strength of wheat grain varieties influenced by moisture content and loading rate. International Journal of Agricultural and Biological Engineering. 2018; 11(4), 52-57.
33. Gorji A, Rajabipour A, Tavakoli H. Fracture resistance of wheat grain as a function of moisture content, loading rate and grain orientation. Australian Journal of Crop Science. 2010; 4(6), 448-52.
34. Cui T, Fan CL, Zhang DX, Yang L, Li YB, Zhao HH. Research progress of maize mechanized harvesting technology. Transactions of the Chinese Society for Agricultural Machinery. 2019; 50(12):1-13.
35. Li SK. Factors affecting the quality of maize grain mechanical harvest and the development trend of grain harvest technology. Journal of Shihezi University (Natural Science). 2017; 35(3): 265-72.
36. Li L-L, Xue J, Xie R-Z, Wang K-R, Ming B, Hou P, et al. Effects of grain moisture content on mechanical grain harvesting quality of summer maize. Acta Agronomica Sinica. 2018; 44(12): 1747-1754.

Figure Caption

Fig.1 Modified crush resistance tester

Fig.2 Type of breakage kernels caused by crush resistance tester

Fig.3 Threshing device of device

Fig.4 Results comparison of different speed to evaluate maize kernel

Fig.5 Type of disc

Fig.6 Results comparison of the different type of centrifuge disc to evaluate maize kernel

Fig.7 Difference examination of BI between moistures by use different disc type

Fig.8 BI versus moisture content of the maize kernel during the repeatability test for the

HANDY (Speed is 1800 rpm; Type of centrifugal disc is curved)

Fig.9 Results of breakage susceptibility and breakage index

Fig.10 The results of broken rate and the breakage index of kernels

Fig.11 Evaluation of approximation accuracy level of the subsection linear regression model

Table Caption

Table 1 Structural parameters of the tester

Table 2 Maize varieties and characteristics

Table 3 BI (%) obtained in the baseline study at the kernel moisture content of 25%

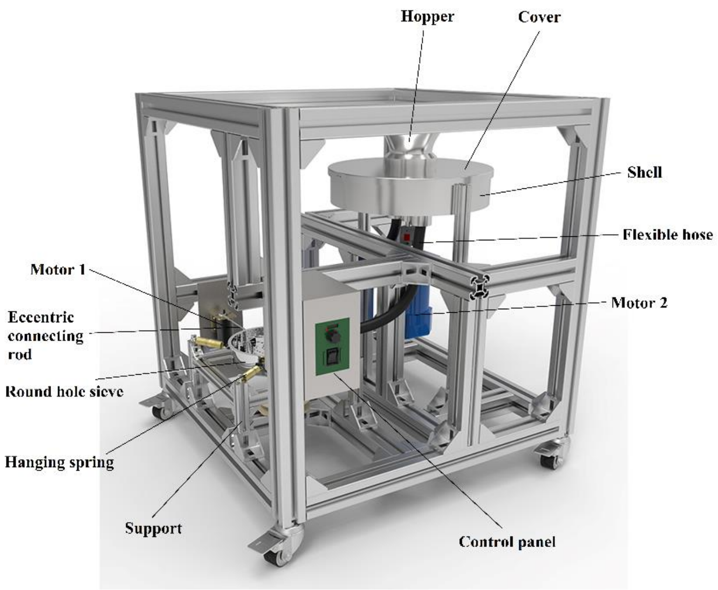


Fig.1 Modified crush resistance tester

Fig.2 Type of breakage kernels caused by crush resistance tester.

Fig.3 Threshing device of device

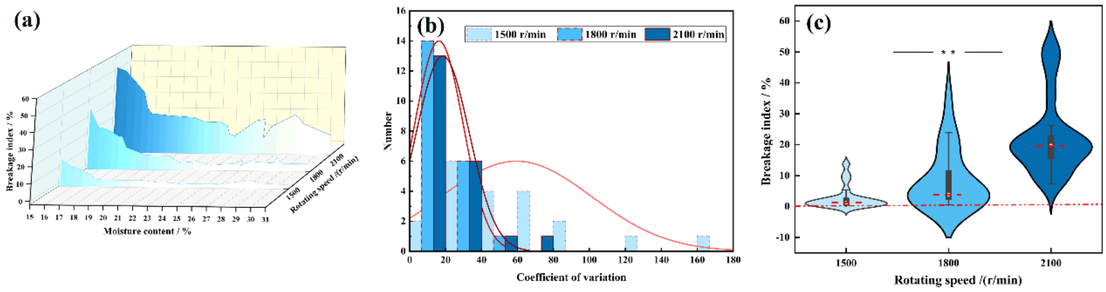


Fig.4 Results comparison of different speed to evaluate maize kernel.

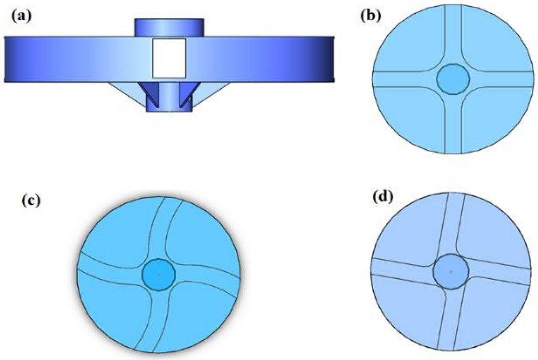


Fig.5 Type of centrifuge disc.

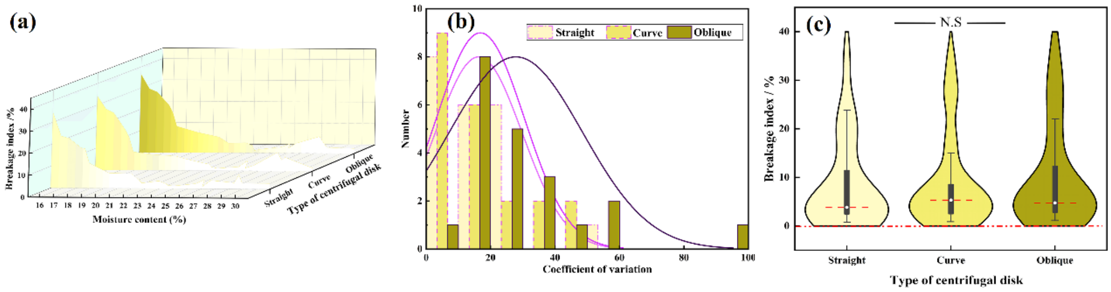


Fig.6 Results comparison of the different type of centrifuge disc to evaluate maize kernel

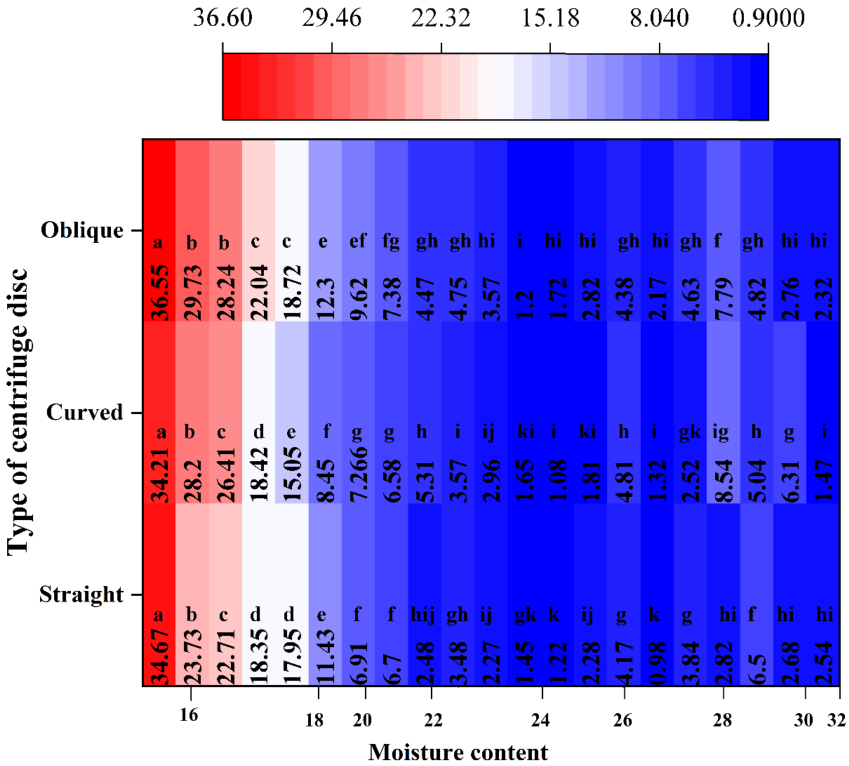


Fig.7 Difference examination of BI between moistures by use different disc type

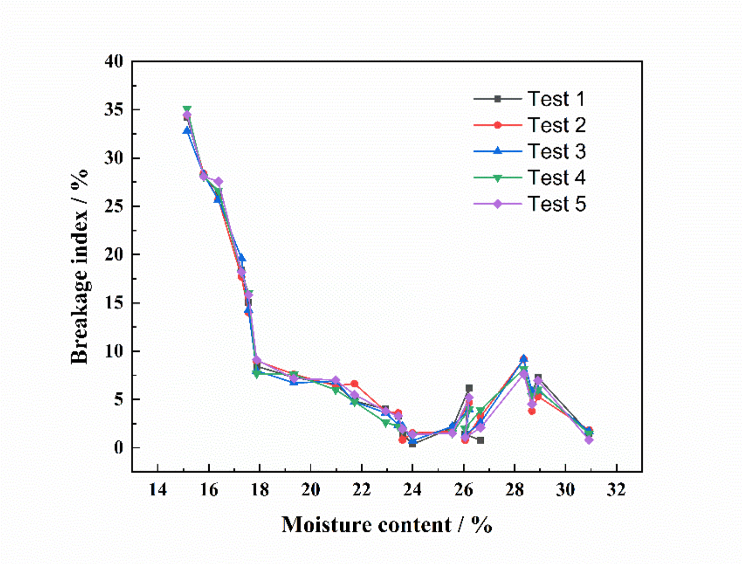


Fig.8 BI versus moisture content of the maize kernel during the repeatability test for the HANDY (Speed is 1800 rpm; Type of centrifugal disc is curved)

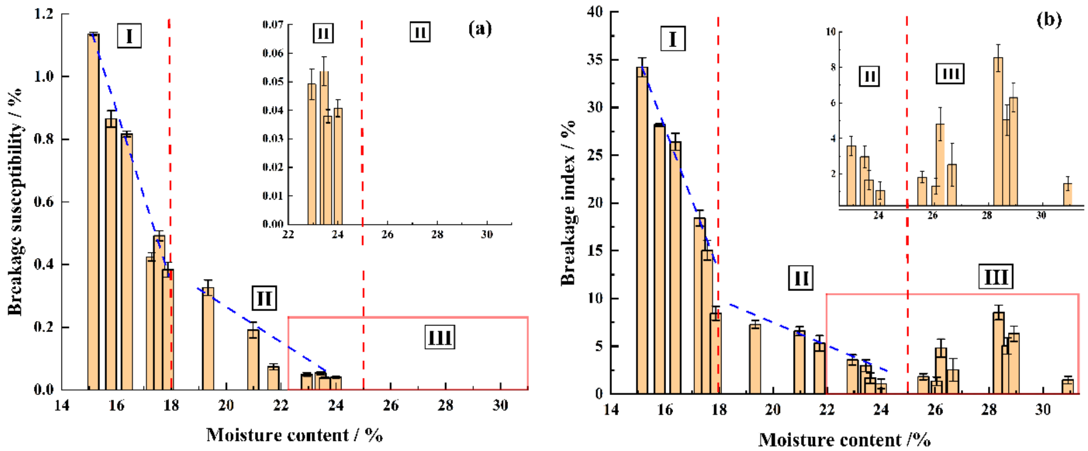
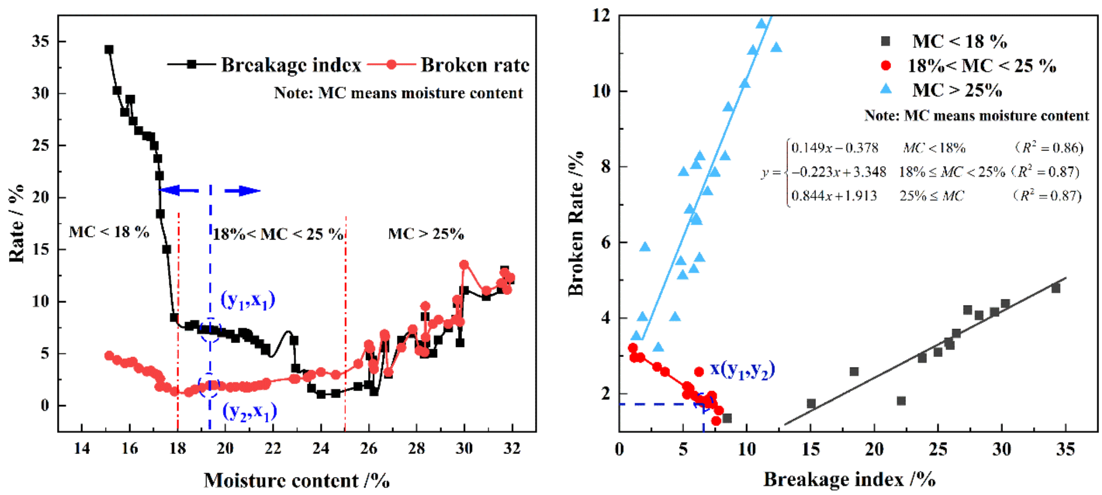


Fig.9 Results of breakage susceptibility and breakage index



$$y=\begin{cases}0.149x-0.378 & MC<18\% \quad (R^2=0.86)\\ -0.223x+3.348 & 18\%\le MC<25\% \quad (R^2=0.87)\\ 0.844x+1.913 & 25\%\le MC \quad (R^2=0.87)\end{cases}$$

Fig.10 The results of broken rate and the breakage index of kernels

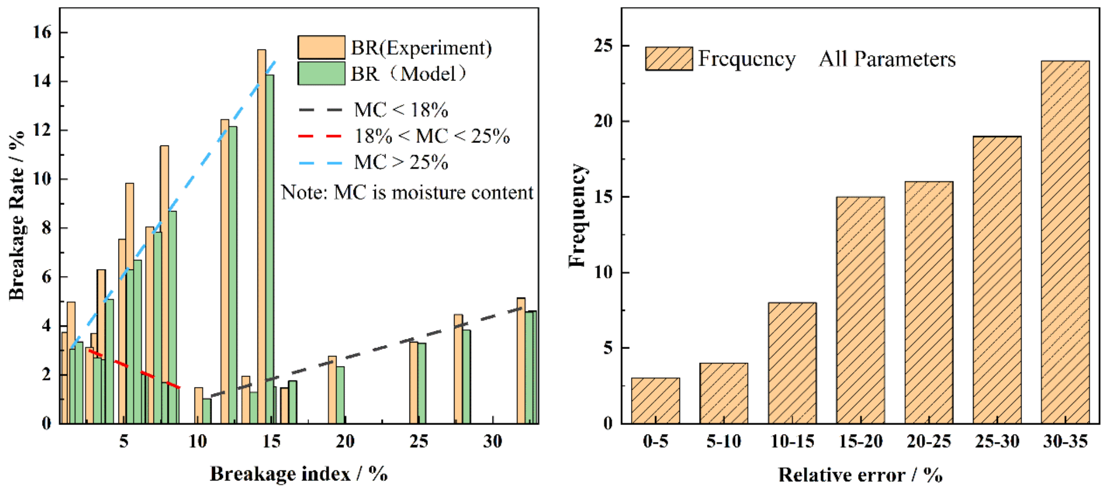


Fig.11 Evaluation of approximation accuracy level of the subsection linear regression model