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The Effects of Moisture Content and Loading Orientation on Some Physical and Mechanical Properties of Tiger Nut

[1,2]Long Wang, [1,2]Can Hu, [1,2]Wensong Guo, [1,2]Xiaowei He, [1,2,*]Xufeng Wang, [3]Jianming Jian and [3]Shulin Hou

[1]*College of Mechanical and Electronic Engineering, Tarim University, Aral Xinjiang, 843300, China*
[2]*Modern Agricultural Engineering Key Laboratory at Universities of Education, Department of Xinjiang Uygur Autonomous Region, Aral Xinjiang, 843300, China*
[3]*College of Engineering, China Agricultural University, Beijing, 100083, China*

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Corresponding Author:
Xufeng Wang
College of Mechanical and Electronic Engineering, Tarim University, Aral Xinjiang, 843300, China
Email: wxfwyq@126.com

Abstract: The physical and mechanical properties of the newly "Zhongyousha No.1" and the traditional "Yousha" Chinese tiger nut varieties are studied. Several physical and mechanical properties of the two tiger nut varieties were determined as a function of moisture content (at five levels of 40.0, 32.0, 24.0, 16.0 and 8.0% wet basis). The physical and mechanical properties including length, width, thickness, geometric mean diameter, surface area, sphericity, compression rupture force, firmness, shear rupture force and shear strength. All tiger nut mechanical properties were significantly affected by moisture content ($P<0.01$). The results shows that the physical properties decreased linearly by decreasing moisture content. The compression rupture force increased linearly from the average of 175.56-208.77 N as moisture content increased from 8 to 40%. While for the shear rupture force and shear strength decreased linearly from the average of 109.73-91.72 N and 1.03-0.63 MPa, respectively. There is a quadratic relationship between firmness and moisture content from the average of 51.80-65.20 N/m. The compression rupture force in the vertical loading orientation is significantly greater than that of the horizontal, while the shear rupture force is higher in the vertical than horizontal. "Yousha" tiger nut possessed higher mechanical strength than "Zhongyousha No.1". The results can be used as design parameters for suitable harvesting machinery and food processing equipment.

Keywords: Tiger Nut, Physical Properties, Mechanical Properties, Moisture Content, Variety

Introduction

Tiger nut, which is native to Africa and Mediterranean countries, is widely distributed in the Nile Valley of Egypt (Pascual *et al*., 2000). It can be eaten raw and is considered to have a sweet and delicious taste (Alvares *et al*., 2017), with freshly harvested tiger nut characteristically having a snow white flesh and a delicate fragrance. Its rich nutrition has resulted in its development into beverages, milk powder, as well as food targeted at infants, young children and the elderly (Rosello-Soto *et al*., 2018). Tiger nut is also frequently used as an additive for ice cream and pastries (Cantalejo, 1997). In Africa, Spain and Mexico, tiger nut is also often used to make a cool, milky sweet drink, known as "horchata de chufa" in Spain and Mexico (Abdel-Nabey, 2001; Sanchez-Zapata *et al*., 2012). Tiger nut has recently been adopted as an oil-bearing economic crop, with its high tuber yield that is rich in oil (Ibitoye *et al*., 2018) awarding it the role of the "king of oil" in plants. In particular, it is a high-quality edible oil that is rich in monounsaturated fatty acids, minerals (particularly cholesterol-free) and protein (Ezeh *et al*., 2014; Oderinde and Tairu, 1988). Furthermore, tiger nut oil has been associated with the prevention of hyperlipidemia and cardiovascular diseases (Codina-Torrella *et al*., 2015).

There are many studies on the chemical and nutritional components of tiger nuts (Abdel-Nabey, 2001; Ibitoye *et al*., 2018; Rehab and El Anany, 2012). Research on the physical and mechanical properties of tiger nut is limited. Oyerinde and Olalusi (2013) measured the physical properties of yellow and brown tiger nut varieties under varying moisture content, demonstrating the larger size of the yellow tiger nut compared to the brown varieties. Ince *et al*. (2017) investigated the physical and compression properties of two Turkish varieties of tiger nut under varying moisture content and determined that the variety and loading direction have relatively little effect on firmness.

Despite the physical and mechanical properties of agricultural materials playing a crucial role in the design of mechanical harvesting, sorting and processing equipment (Razavi and Edalatian, 2012; Kusumah *et al*., 2020), research on such properties for tiger nut is limited. Moisture content, loading direction and variety et al are the main factors, which affecting the physical and mechanical properties of agricultural materials (Su *et al*., 2019; Durguti *et al*., 2020). The physical and mechanical properties of fruits and vegetables are very necessary for the reasonable design of different processing equipment (Kusumah *et al*., 2020; Lae *et al*., 2019). China is currently lacking mature harvesting machines for tiger nut. Technical limitations commonly result in mechanical damage, including the breaking and stress cracking of tiger nut during harvest, which seriously affects its quality and economic value (Mlaviwa and Missanjo, 2019). This is attributed to the distinct physical properties of Chinese and foreign tiger nut varieties, with a specific lack of research on the former.

In this study, we measured the shear strength in different loading orientation of two Chinese tiger nut varieties, namely, an old variety denoted as "Yousha" and the new cultivar "Zhongyousha No.1", which has not been reported elsewhere. Furthermore, there is no published work focusing on the effect of moisture content on different properties of Chinese tiger nuts. Hence, this study was conducted to investigate the mechanical behavior and some physical properties of two different varieties of Chinese tiger nuts, the physical and mechanical properties including length, width, thickness, geometric mean diameter, surface area, sphericity, compression rupture force, firmness, shear rupture force and shear strength. The research results can be used to design, optimize and evaluate harvesting and processing machinery for tiger nuts, such as design of cleaning units and separating equipments and calculating the allowable load imposed on the oil extractors.

Materials and Methods

The test materials "Yousha" (Y) and "Zhongyousha No.1" (Z1) were grown in Nangong city, Hebei Province, China during the 2019 growing season in a randomized complete bock design at the China Agriculture University. The tiger nuts were harvest in October of the same year via a harvesting machine. Following harvest, the tiger nuts were washed and dried and tubers with uniform size, no damage and wormhole were selected as the test samples. Five moisture content treatments were applied to the two varieties, namely 40, 32, 24, 16 and 8% (w.b.), as well as the uniaxial compression and shear in two loading orientations.

The initial moisture content was determined by oven drying each variety at 105±2°C for 24 h (Razavi *et al*., 2007). In order to obtain different moisture content conditions, the samples were dried in a drying box at 80°C (GZX-9140MBE Electric thermostatic drying oven, Shanghai Boxun Industry Co., Ltd. Shanghai, China) and taken from the drying box and measured the mass every 30 min until the required moisture content was reached. Before each drying, take about 300 g tiger nut for drying experiment, the moisture content is followed by the application of the following formula (Balasubramanian, 2001):

$$m_f = \frac{m_i\left(100 - M_i\right)}{100 - M_d} \quad (1)$$

where, m_f and m_i are the dried and initial mass of the samples (g), respectively and M_i and M_d are the initial and desired moisture content (% w.b.), respectively.

The three key tiger nut dimension parameters of length (L, mm), width (W, mm) and thickness (T, mm) were measured using a Shenzhen BiaoKang SL01-22 digital vernier caliper with an accuracy of 0.01 mm (Fig. 1). The geometric average diameter, sphericity and surface area were calculated via the following formula (Altuntaş *et al*., 2005; Arslan and Vursavus, 2008; Mohsenin, 1970):

$$D_g = \left(LWT\right)^{1/3} \quad (2)$$

$$\Phi = \frac{D_g}{L} \quad (3)$$

$$S = \pi D_g^2 \quad (4)$$

where, D_g is geometric average diameter (mm), Φ is the sphericity (%) and S is the surface area (mm^2).

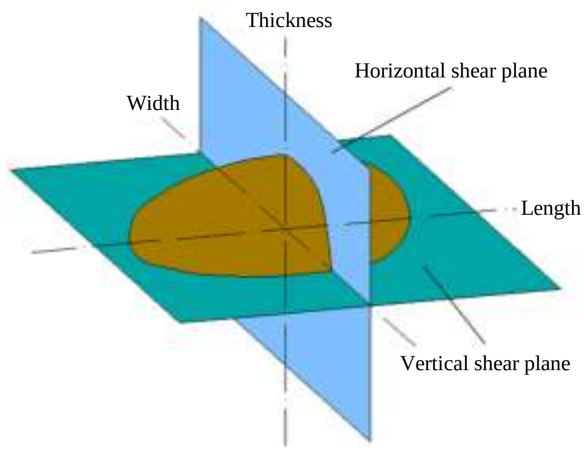

Fig. 1: Tiger nut dimension parameters and stress plane

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Uniaxial compression and shear tests were performed using a TMS Touch (Food Technology Corporation U.S.A), with a mechanical sensor range of 1000 N and resolution of 0.1 N. Uniaxial compression and shear tests were carried out in both the vertical and horizontal directions. The test sample was placed between the two plates at a compression and shear rate of 5 mm/min with an initial force recorded of 0.3 N. Each test was repeated 20 times at room temperature.

The uniaxial compression tests were implemented in order to determine the tiger nut firmness under compression. The diameter of the upper compression plate was 75 mm (Fig. 2). The firmness is expressed as the ratio of the compression force to deformation value at fracture (Khazaei *et al*., 2002):

$$Q = \frac{F}{D} \tag{5}$$

where, Q is the firmness (N/mm), F is the compression force at the rupture point (N) and D is the deformation at the rupture point (mm).

Fig. 2: Uniaxial compression test of tiger nut under different loading axis (a) vertical axis of tiger nut in line with loading orientation, (b) horizontal axis of tiger nut in line with loading orientation

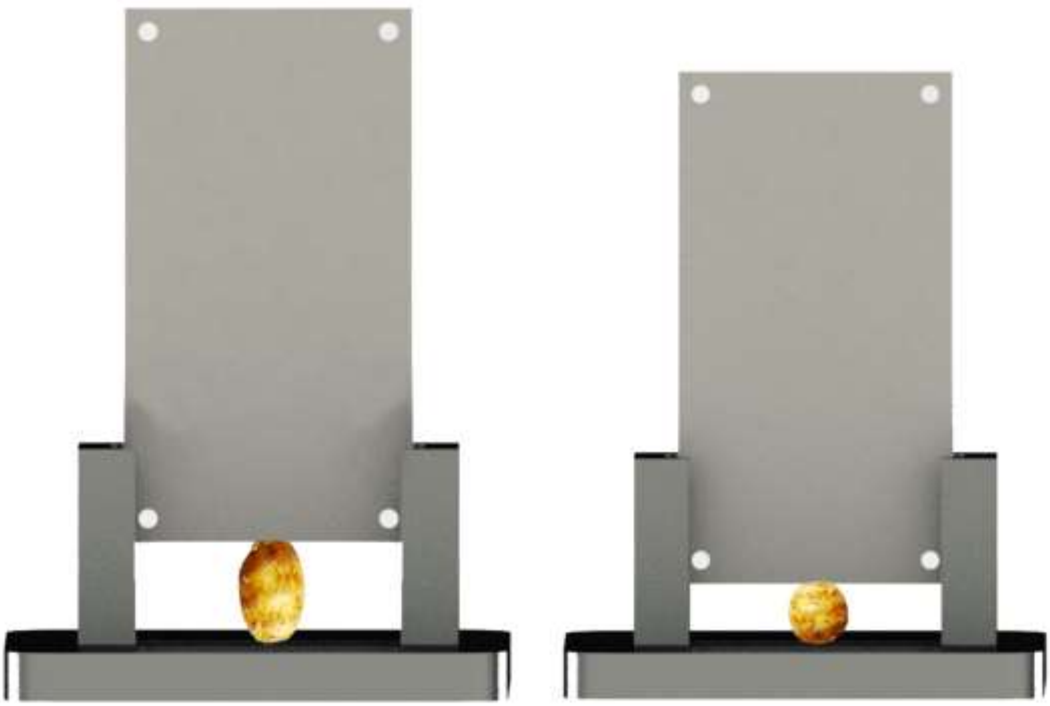

Fig. 3: Shear tests of tiger nut under different loading axis (a) vertical axis of tiger nut in line with loading orientation, (b) horizontal axis of tiger nut in line with loading orientation

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Shear tests were employed in order to determine the shear strength of the tiger nut under shear stress. The thickness of the upper shear plate used in the experiments was 1 mm (Fig. 3). The shear strength is expressed as the ratio of force to area at the splitting point (Tavakoli *et al*., 2009):

$$\tau_s = \frac{F}{A} \tag{6}$$

where, τ_s is the shear strength (MPa), F is the shear force at the fracture point (N) and A is the stress area (mm^2). The stress areas in the vertical and horizontal directions were determined as $A = \frac{\pi(L+W)^2}{16}$ and $A = \frac{\pi(W+T)^2}{16}$, respectively (Fig. 1).

We analyzed the effects of five moisture content levels and two varieties on the physical properties of tiger nut. In addition, the impacts of the five moisture contents, two varieties and two stress orientations on the mechanical properties (e.g., fracture force, fracture point displacement, firmness, shear strength and energy absorption) were also analyzed. Duncan's multiple range test was employed to compare the mean values of the parameters. Furthermore, we performed polynomial fitting with water content as the independent variable and fracture force as the dependent variable. SPSS Statistics 20 (IBM) was used for the data analysis and Origin 8.6 (OriginLab) was applied to view and plot the results.

Results

The mean value and standard deviation of the physical property parameters from the two varieties of Chinese tiger nut are summarized in Table 1. Also, the linear regression analysis (with generic form of $a + b*(M_c)$) are presented in Table 2. It is showed that the change of physical properties can be related to be the moisture content. In this study, the effect of moisture content on the physical properties of two tiger nut were found to be significant for length, width, thickness, geometric mean diameter, surface area and sphericity (P<0.01). With the exception of sphericity (P = 0.628), the effect of variety on all other physical parameters was significant (P<0.01).

The axial dimension, including Length (L), Width (W) and Thickness (T) of Chinese tiger nut measured at five moisture content from 8 to 40% (w.b.) are shown in Table 1. The slope of regression equation for the axial dimensions of the tiger nuts is positive (Table 2). More specifically, the length, width and thickness of the Y and Z1 varieties were reduced by (6.3 and 8.8%), (11.7 and 13.7%) and (24.2 and 23.3%) respectively, with the reduction in the thickness being the most prominent. The statistical analysis also showed that the moisture content had significant effect (P<0.01) on all axial dimensions (Table 3). The reason for this increase may be due to the penetration of water in the intercellular space, resulting in the protrusion of the sample. In addition, the geometric mean diameter of the tiger nut decreased with moisture content by 14.6 and 15.5%, respectively. The slopes of regression lines for axial dimensions versus moisture content of variety Y were greater than variety Z1. To give more detail, the length, width and thickness of Y were 1.37, 1.21 and 1.05 times that of Z1. This may be because the variety Y is larger flesh. In this respect, the water absorbed by the variety Y interstices was more than that of variety Z1intersticesto achieve the same moisture content.

The changes of surface area with the tiger nut moisture content are shown in Table 1. Table 2 shows the change in the slope of the trend lines of the surface area with moisture content. The coefficient of the equation shows that the change rate of surface area with moisture content is very large. Duncan's (Ince *et al*., 2017) multiple range test results demonstrate that the Y variety lengths belong to the same group statistically for all five moisture content levels, with no significant differences between values.

Table 1: Tiger nut physical properties (mean ± standard deviation) determined from experiments

		Moisture content (% w.b.)				
Properties	Variety	40	32	24	16	8
Length (mm)	Y	15.33±1.10^{a}	14.92±0.82^{a}	14.70±0.88^{a}	14.44±0.88^{a}	14.36±0.99^{a}
	Z1	14.48±0.89^{a}	14.08±1.19^{ab}	14.01±0.75^{ab}	13.35±0.77^{ab}	13.20±1.04^{b}
Width (mm)	Y	14.45±0.75^{a}	13.82±0.85^{ab}	13.32±1.00^{b}	13.17±0.87^{b}	12.76±0.97^{b}
	Z1	13.87±1.07^{a}	13.26±0.84^{a}	12.89±0.61^{ab}	12.09±0.95^{b}	11.97±0.91^{b}
Thickness (mm)	Y	11.89±0.58^{a}	10.84±0.90^{b}	10.69±0.67^{b}	9.98±0.95^{bc}	9.01±0.98^{c}
	Z1	11.27±0.98^{a}	10.82±0.88^{a}	9.41±0.90^{b}	9.13±0.99^{b}	8.64±0.80^{b}
Geometric mean diameter (mm)	Y	13.80±0.52^{a}	13.05±0.37^{b}	12.78±0.55^{bc}	12.36±0.54^{cd}	11.79±0.61^{d}
	Z1	13.12±0.82^{a}	12.63±0.69^{ab}	11.92±0.52^{bc}	11.36±0.73^{c}	11.09±0.74^{c}
Surface area (mm^2)	Y	599.06±45.29^{a}	535.64±30.07^{b}	513.74±44.55^{bc}	480.70±41.92^{cd}	438.08±44.85^{d}
	Z1	542.28±69.09^{a}	502.15±54.40^{ab}	446.93±38.71^{bc}	407.05±51.02^{c}	387.61±52.74^{c}
Sphericity (%)	Y	90.25±4.19^{a}	87.66±3.88^{ab}	87.03±3.32^{ab}	85.74±3.83^{ab}	82.36±5.53^{b}
	Z1	90.64±2.64^{a}	89.88±3.64^{a}	85.15±3.51^{b}	85.18±4.54^{b}	84.09±3.40^{b}

Table 2: Parameters of linear regression analysis ($a + b*(M_c)$) with their respective coefficient of determination (R^2) and RMSE for physical properties of two types of Chinese tiger nut versus dimensionless moisture content

	Y				Z1			
Property	a	b	R^2	RMSE	a	b	R^2	RMSE
Length (mm)	14.030	0.030	0.9486	0.1026	12.84	0.041	0.9452	0.1443
Width (mm)	12.290	0.051	0.9600	0.1506	11.33	0.062	0.9655	0.1710
Thickness (mm)	8.495	0.083	0.9590	0.2501	7.77	0.087	0.9399	0.3205
Geometric mean diameter (mm)	11.350	0.059	0.9792	0.1252	10.42	0.067	0.9828	0.1285
Surface area (mm^2)	400.400	4.711	0.9747	11.1097	335.90	5.056	0.9782	11.0340
Sphericity (%)	81.300	0.221	0.9395	0.8203	81.65	0.223	0.8622	1.2990

Table 3: The parameter test results of physical properties

Properties	Length	Width	Thickness	Geometric mean diameter	Surface area	Sphericity
Moisture content(MC)	0.002^{**}	0.000^{**}	0.000^{**}	0.000^{**}	0.000^{**}	0.000^{**}
Variety(V)	0.000^{**}	0.000^{**}	0.001^{**}	0.000^{**}	0.000^{**}	0.628^{ns}

*, **: Significant at the levels of 5 and 1%, respectively. ns: Not significant

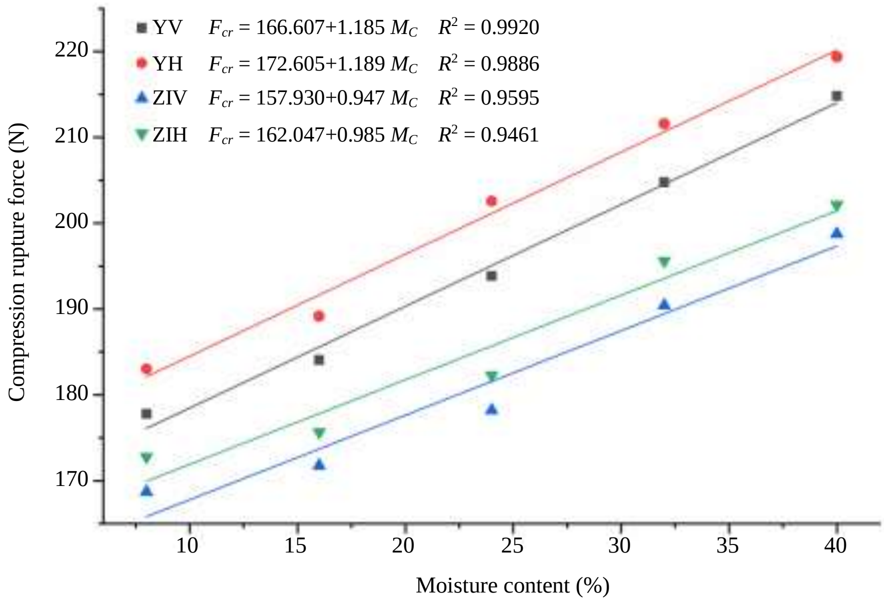

Fig. 4: Effect of moisture content on the compression rupture force (F_{cr}, N) of Chinese Tiger nut

Sphericity, which represents the shape characteristics of the material, also decreased with moisture content by 8.7 and 7.2%, respectively. The regression equation of the relationship between sphericity and moisture content is represented in Table 2. The results show that sphericity decreases linearly with decrease of moisture content. Table 3 shows that the lack of differences in the sphericity parameters between the Y and Z1 tiger nut varieties (P = 0.628).

Same letters within a column denote means that are not significantly different at the 0.01 significance using Duncan's multiple range test.

Figure 4 displays the compression rupture force (F_{cr}) results of the two tiger nut varieties under different moisture contents. The compression rupture force of both varieties significantly exhibited a linear decrease from the average of 175.56-208.77 N (P<0.01) as the moisture content was reduced.

For both varieties, the compression rupture force in the vertical loading orientation (mean values for both varieties 188.31 N, respectively) is significantly bigger (P<0.01) than that in the horizontal loading orientation (mean values for both varieties 193.41 N, respectively). This can be attributed to the larger stress area in the horizontal orientation compared to that of the vertical orientation eventually. Across all moisture content, the compression rupture force varied between 168.68 and 214.81 N in the vertical loading orientation and 172.76 and 219.36 N in the horizontal loading direction. According to the results of the tests, the effect of variety on the compression rupture force was significant (P<0.01).

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Figure 5 presents the Firmness (F) determined for the two tiger nut varieties under different moisture contents. The firmness values of the tiger nut at rupture point decreased nonlinearly as the moisture content decreased. The reason for this is the high decrease in deformation at low moisture content levels. Significant differences (P<0.05) in firmness were observed between the two varieties.

Firmness values in the vertical and horizontal loading orientations ranged from (59.94 and 76.34 N/mm) and (41.73 and 57.71 N/mm), respectively. The firmness values in the horizontal loading orientation were approximately 1.5 times larger than those of the vertical loading orientation and this difference was significant (P<0.01). The effect of moisture content on firmness was also statistically significant (P<0.01).

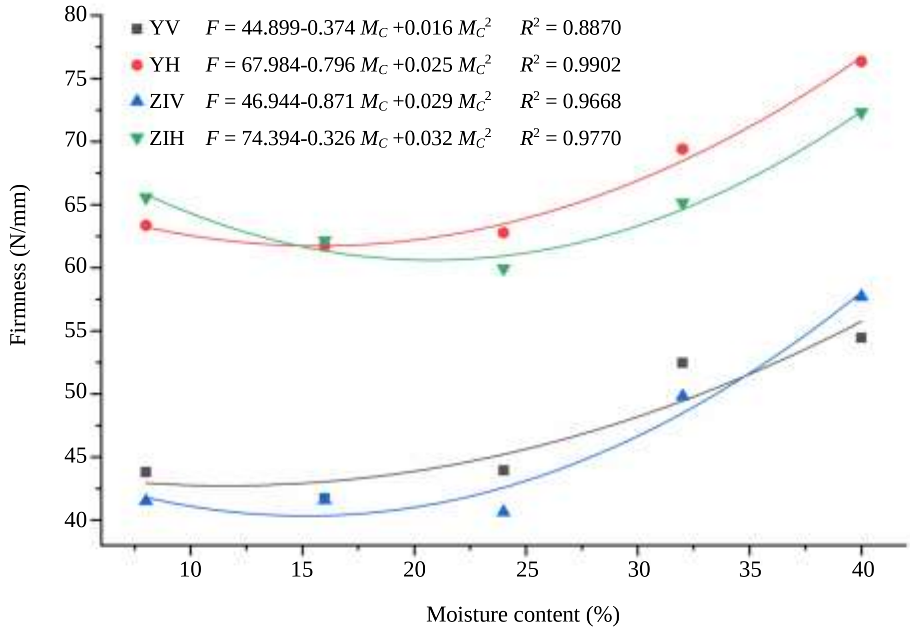

Fig. 5: Effect of moisture content on the firmness (*F*, Nmm) of Chinese Tiger nut

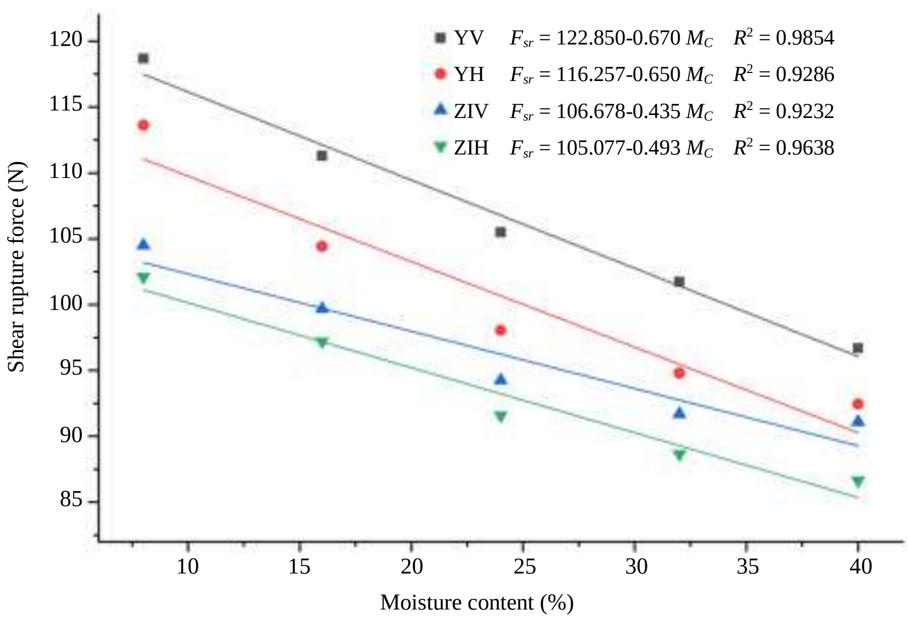

Fig. 6: Effect of moisture content on the shear rupture force (F_{sr}, N) of Chinese Tiger nut

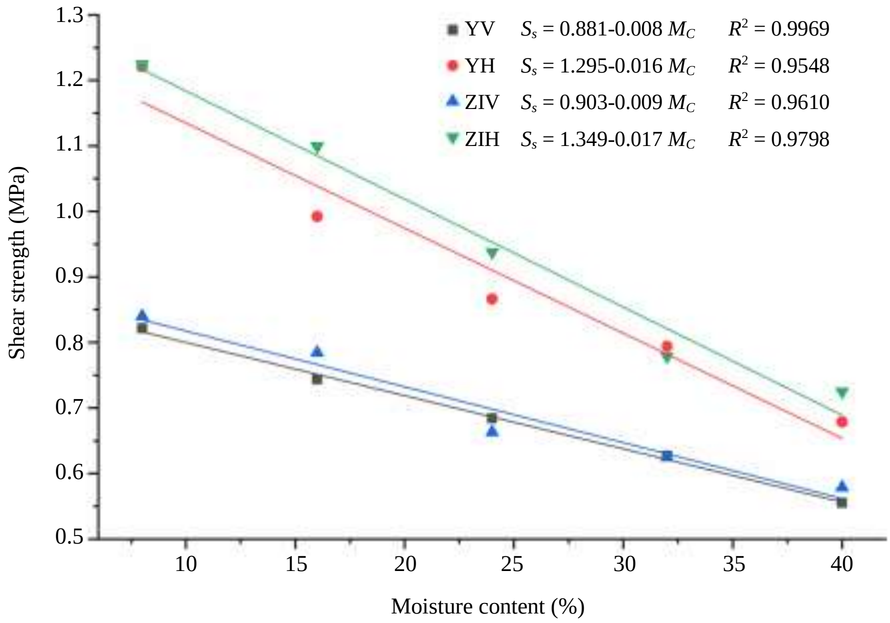

Fig. 7: Effect of moisture content on the shear strength (S_s, MPa) of Chinese Tiger nut

Figure 6 presents the shear rupture force (F_{sr}) of the two tiger nut varieties under different moisture contents. The shear rupture force increased as the moisture content decreases for both varieties and loading orientations. This may be explained by the differences in moisture content, the lower the moisture content, the firmer and the internal structure of tiger nut. The shear rupture forces of the two varieties were significantly higher ($P<0.01$) in the vertical than horizontal loading orientation, ranging from (91.09 and 118.69 N) and (86.66 and 113.63 N), respectively. The test result demonstrates that the effect of moisture content, loading orientation and varieties on the shear rupture force was significant ($P<0.01$). This is because the shear cross-sectional area of horizontal loading orientation is smaller than that of vertical loading direction.

Figure 7 presents the Shear strength (Ss) of the two tiger nut varieties determined for different moisture content values. The shear strength increased as the moisture content decreased, reaching a maximum of 1.22 MPa for both varieties at the moisture content of 8%.

Furthermore, the shear strength in the horizontal loading orientation was significantly greater ($P<0.01$) than that in the vertical orientation, with ranges of (0.68 and 1.19 MPa) and (0.56 and 0.84 MPa), respectively. The test result reveals the variety on the shear strength to be significant ($P<0.05$).

Discussion

The result indicated that the axial dimensions are increased with the increasing of moisture content. Ince *et al*. (2017; Oyerinde and Olalusi, 2013) have reported similar trends for two tiger nut varieties. Abano and Amoah (2011) reported that the dimension of black variety of tiger nut ranged from 13.71 to 16.16 mm in length, 12.46 to 14.51 mm in width, 10.40 to 11.94 mm in thickness and 11.80 to 13.69 mm in geometric mean diameter for moisture content from 17 to 32% (w.b.). These values are close to the general value of Chinese tiger nut variety Y. Our sphericity values are slightly larger than those of (Abano and Amoah, 2011; Ince *et al*., 2017). Compared with foreign varieties, the sphericity value of Chinese tiger nut is larger. The results of the current study demonstrate the lack of differences in the sphericity parameters between the Y and Z1 tiger nut varieties ($P>0.05$), while significant differences were observed for other physical parameters ($P<0.01$) and the sphericity decreases linearly with decrease in moisture content. These results indicated that the different size circular holes could be used to sieving particle for different varieties of tiger nut. At the same time, the size of the screen of tiger nut should be considered in different harvest periods. In particular, the tiger nut length, width, thickness, geometric average diameter, surface area and sphericity, decreased with moisture content. The thickness exhibited the most obvious reductions (24.2 and 23.3% for Y and Z1, respectively) as the moisture content decreased from 40 to 8%. The effect of moisture content on length, width, thickness, average diameter, sphericity, surface area was significant ($P<0.01$).

All tiger nut compression and shear mechanical properties were significantly affected by moisture content (P<0.01). The compressive fracture force and firmness decreased with the moisture content, while the shear rupture force and shear strength increased. Therefore, at high water content, it can resist compression, but not shear. It is suggested to harvest, package or transport when the moisture content of Chinese tiger nuts is more than 30%. The compression rupture force and shear rupture force of the Y variety were greater than those of the Z1 variety, reaching 219.36 and 118.69 N. The effect of varieties and loading orientation on the compression rupture force, firmness, shear rupture force and shear strength were significant (P<0.05). Our results demonstrate that the moisture content, variety and loading orientation have a significant impact on the physical and mechanical properties of tiger nut. Thus, the influence of moisture content, variety and loading orientation should be comprehensively considered in the design of harvest machinery and food processing equipment. This study evaluated the physical and mechanical properties of Chinese cultivar tiger nut and provides reference data to develop suitable conditions for harvesting, storing and handling of tiger nut.

It should be noted that only some physical and mechanical properties of Chinese tiger nuts obtained in this study. In further research, the contact parameters of Chinese tiger nuts and different materials should be researched and the influence of root and stem of tiger nuts under actual working conditions should be considered.

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Author’s Contributions

Long Wang and Can Hu: Designed and performed the experiments work.

Wensong Guo, Xiaowei He and Xufeng Wang: Participated to collect the materials related to the experiment.

Jianming Jian and Shulin Hou: Revised the manuscript.

Ethics

The authors declare their responsibility for any ethical issues that may arise after the publication of this manuscript.

Conflict of Interest

The authors declare that they have no competing interests. The corresponding author affirms that all of the authors have read and approved the manuscript.

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