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Review Article

Determination Methods and Influencing Factors of Grain Mechanical Properties

Peng Gao[1,2,3] **Shuangqi Tian**[1,2,3] **Xing'ao Xue**[2,3] **and Jing Lu**[4]

[1]*National Engineering Research Center of Wheat and Corn Further Processing, Henan University of Technology, Zhengzhou 450001, China*
[2]*College of Food Science and Technology, Henan University of Technology, Zhengzhou 450001, China*
[3]*Food Laboratory of Zhongyuan, Luohe 462300, China*
[4]*Department of Molecular Sciences, Swedish University of Agricultural Sciences, P.O. Box 7015, Uppsala SE-75007, Sweden*

Correspondence should be addressed to Shuangqi Tian; tianshuangqi@haut.edu.cn

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Grain is extremely vulnerable to external loads during production and processing, resulting in the deterioration of grain quality. Deteriorated grain not only affects the economic value of grain but also affects the safety of storage. This has a very important relationship with the biomechanical properties of grains. It is of great significance to explore the mechanical properties of grain under different conditions and analyze the relationship between its physical and chemical properties and mechanical properties for improving its processing and eating quality. In this paper, the research methods of the mechanical properties of grains are reviewed. Various factors influencing the mechanical properties of cereals were analyzed. The relationship between the internal organizational structure of grain and its mechanical properties was discussed. This paper puts forward the shortcomings in the current research on the mechanical properties of grains and puts forward the prospect and analysis of its importance in future development in order to provide a reference for reducing crushing in the grain processing process.

1. Introduction

Grain refers to the seeds of gramineous plants, including rice, wheat, maize, millet, sorghum, and other grains. The staple foods processed from grains provide most of the energy and protein and are widely cultivated around the world [1]. However, in today's highly mechanized popularization, grain will be subjected to various mechanical forces in production and processing. These forces can cause irreversible damage to the grain, causing the grain to deform and even leading to the fracture of the grain [2]. According to the nature of the force, it can be roughly divided into the following categories: the friction between threshing and the machine, the impact force between harvesting and the machine, and the extrusion force [3–5]. When these external forces exceed the limit that the grain can withstand, the grain breaks. Ruptured grains not only affect the physical and chemical properties of grains but also increase the difficulty of grain storage [6]. These biomechanical problems in the processing process will directly affect the quality and economic effects of grain. Therefore, the mechanical parameters such as rupture force and rupture energy of grain under external load are clarified, and the relationship between the organizational structure and mechanical properties of grain is studied. It can provide technical parameters for mechanical processing equipment, which is of great significance in reducing the loss of grain in harvesting, transportation, storage, and processing. For example, based on the theoretical and mechanical properties of buckwheat, the threshing unit of the thresher can be optimized to improve the cleaning efficiency of the buckwheat thresher [7]. By combining the compression tests, compression-relaxation tests, insertion-relaxation tests, and stretch tests, the threshing rate of maize kernels was obtained. By establishing an artificial neural network model, the mechanical properties of maize kernels were used to predict the breakage rate

[8]. The study of the differences in mechanical properties of different threshing directions of maize provides a theoretical basis for the design of mechanized threshers [9]. These are inseparable from the study of the mechanical properties of grains.

The research on the mechanical properties of grain can be divided into dynamic mechanical and static mechanical properties. Dynamic mechanical research refers to the mechanical response of materials under alternating stress (alternating strain), that is, the relationship between mechanical properties (modulus and internal friction) and temperature and frequency. The static load's mechanical properties refer to the changes in the mechanical behavior of the grain after the slow loading of the external force in the static state. At present, the research on the mechanical properties of grain is mainly based on static load mechanics. The changes in the mechanical behavior of grains under compression, shear, and other forces were explored [2, 10]. The values used to characterize the static mechanical properties of cereals include elastic modulus, contact stiffness, damage strength, shear strength, yield strength, crushing force, and crushing energy [11]. In recent years, studies have found that the mechanical properties of grains were affected by many factors, and the antidamage ability of different grains was different [12]. In this paper, the factors affecting the mechanical properties of grain were summarized by summarizing the current research methods on the grain's mechanical properties. The relationship between the mechanical properties of grain and its processing quality was analyzed, and the research status of the mechanical properties of grain was expounded.

2. Research Methods of Mechanical Properties of Grain

The study of the grain's mechanical properties can provide data support for the design and parameter optimization of processing machinery, transportation, and storage, as well as the evaluation of grain quality. As early as the 1970s, the mechanical properties of grain had been studied. The results of the mechanical behavior of rice under quasi-static compressive load showed that the moisture content had a great influence on the mechanical properties of rice. The yield point and maximum compressive strength of the sample decreased with the increase in moisture content [13]. With the continuous development of science and technology, the research on the mechanical properties of grains is becoming more and more extensive, and the methods are becoming more and more perfect. In order to explore the mechanical properties of grains, the methods used by researchers mainly include experimental methods, mathematical calculation methods, and finite element analysis methods.

2.1. Experimental Method. The experimental method was a commonly used method for studying the mechanical properties of grains. The materials testing machine or texture analyzer can be used to simulate the different loads that grains are subjected to during production and processing and to analyze the changes in their mechanical properties. The mechanical indexes of grain, such as rupture force, rupture energy, elastic modulus, and compression displacement, were measured directly. The experimental method has a strong applicability and can be used to measure the mechanical properties of most grains, such as maize, wheat, and rice [14–16]. Appropriate experimental methods can be selected for research needs and research objects. Table 1 lists several test methods for measuring the mechanical properties of the grain. Using the experimental method to determine the mechanical properties of grain is convenient and fast, and data accuracy is high. However, due to the large differences between grain individuals, the repeatability of the data obtained by the experimental method is poor, and a large number of experimental results are often needed to ensure the stability of the data.

2.2. Finite Element Analysis. The finite element method (FEM) is an efficient and discrete numerical method, which is widely used in engineering design and scientific research [24]. It is widely used in granaries. In addition to analyzing the transfer of grain heat, airflow, and water in silos, it can also study the bulk density of grain in silos. As a key factor in predicting grain pressure in silos, it plays a vital role in food security storage [25, 26]. By establishing a finite element model to analyze the mechanical properties of grains, the internal stress-strain distribution of grains under different ballasts can be obtained [27]. Based on the mechanical properties of compression, the finite element analysis of soybeans was carried out. The results showed that there were differences in the internal stress distribution of soybean grains when soybeans were compressed under different placement methods. This is greatly related to the contact area of the compression plate. The finite element simulation results are consistent with the compression test results, which can better explain the crack distribution of soybean when it is compressed [28]. The finite element model of wheat grain can better simulate the stress distribution inside wheat grain during storage. Studies have shown that the stress on the side of wheat grain during storage is about three times to that on the bottom [29]. Compared with other experimental methods, the microscopic mechanical properties of grains under external loads can be obtained by establishing a finite element model, which reflects the distribution law of the internal stress of grains. Combined with the results of the experimental method, the mechanical behavior of grains under different conditions can be better explained.

2.3. Mathematical Algorithm. In addition to the two experimental methods mentioned above, researchers often use mathematical calculations to obtain mechanical indicators such as the elastic modulus and failure stress of grains and further analyze the relationship between grain deformation and its mechanical properties. When the grain is compressed, the contact area between the indenter and the grain is elliptical, and the failure stress of the grain can be

Table 1: Experimental method to explore the mechanical properties of grains.

Research object	Instrument	Experimental method	Factor	Reference
Maize	Tension/compression testing machine	Compression test	Moisture content	[17]
Wheat	Texture analyzer	Shear test	Loading rate	[18]
Rice	Self-made machine	Impact test	Impact velocity	[19]
	Texture analyzer	Three-point bending	Drying condition	[20]
Millet	Assembled apparatus	Wear test	Friction media	[21]
Soybean	Universal testing machine	Compression test	Moisture content	[22]
Sorghum	Grain hardness tester	Compression test	Moisture content	[23]

calculated according to the contact area and the magnitude of its rupture force [30]. Taking maize as an example, when it is compressed, the semimajor axis (a) and semiminor axis (b) of the contact surface area can be calculated by using the following equations:

$$a = m\left[\frac{3F(K_1+K_2)}{2}\left(\frac{1}{R_U}+\frac{1}{R'_U}+\frac{1}{R_L}+\frac{1}{R'_L}\right)^{-1}\right]^{1/3}, \quad (1)$$

$$b = n\left[\frac{3F(K_1+K_2)}{2}\left(\frac{1}{R_U}+\frac{1}{R'_U}+\frac{1}{R_L}+\frac{1}{R'_L}\right)^{-1}\right]^{1/3}, \quad (2)$$

where m and n are constants, and K_1 and K_2 are calculated by using the following formula:

$$K_1 = \frac{1-\mu^2}{E},$$
$$K_2 = \frac{1-\mu_2^2}{E_2}, \quad (3)$$

where μ and μ_1 are Poisson's ratio of maize and compression plate and E and E_2 are the elastic modulus of maize and compression plate, respectively [31]. In general, the elastic modulus of the plate is much higher than that of the grain, so $K_2 = 0$ can be used in the calculation process. Now, the contact area can be calculated according to the elliptic area formula as follows:

$$A = \pi ab. \quad (4)$$

The contact surface stress is calculated by using the following formula [32]:

$$S = \frac{1.5F}{A}. \quad (5)$$

As a physical quantity describing the elasticity of an object, elastic modulus (also known as Young's modulus) can well reflect the difficulty of object deformation. The general definition of elastic modulus is the ratio of stress to strain in this direction. From a macroperspective, elastic modulus is a measure of the ability of an object to resist elastic deformation. From a microperspective, it is a reflection of the bonding strength between atoms, ions, or molecules [33]. The elastic modulus of wheat grains can be determined by the stress-strain curve under lower deformation. The specific calculation formula is as follows:

$$E = \frac{\sigma}{\varepsilon} = \frac{P/A}{D_e/H}, \quad (6)$$

where E (MPa) is the elastic modulus, P (N) is the pressure on wheat, A (mm^2) is the size of the contact area, D_e (mm) is the elastic deformation of wheat grain during compression, and H (mm) is the initial height of wheat [34]. In addition to calculating the ratio of stress to strain, the calculation of the elastic modulus of grain can be carried out according to the following formula:

$$E = \frac{0.338F(1-\mu^2)}{D^{3/2}}\left[K_U\left(\frac{1}{R_U}+\frac{1}{R'_U}\right)^{1/3}+K_L\left(\frac{1}{R_L}+\frac{1}{R'_L}\right)^{1/3}\right]^{3/2}, \quad (7)$$

where E is the apparent elastic modulus, F is the compression force, μ is Poisson's ratio, K_U and K_L are the constant of 1.3531, D is the compression displacement, R_U and R'_U are the maximum and minimum curvature radius of the maize kernel, and R_L and R'_L are the maximum and minimum radius of the curvature of the indenter. In the compression test, the calculation method of elastic modulus is also different due to the different loading modes and contact areas of the indenter, including single plate contact, parallel plate contact, and spherical indenter on a curved surface [35]. The uniaxial compression test is the most commonly used method to calculate the elastic modulus of grain, but some researchers use other methods to determine the elastic modulus of the grain. For example, the elastic modulus of grain was measured by an acoustic wave experiment. The results show that the elastic modulus of grain can be predicted within a certain range of water content. The experiment provides a new idea for the determination of the elastic modulus of grain.

3. Mechanical Properties of Grain

3.1. Characterization of Static Mechanical Properties of Grain. The static mechanical properties of cereals are usually studied by using a material universal testing machine or a texture analyzer. During the grain static loading mechanics experiment, the grains are fixed on the plate and remain motionless, and the slowly descending indenter exerts a force on the specimen. As the loading indenter descends, the force acting on the grain increases, and when the force exceeds the limit that the grain can stand, the grain ruptures. By analyzing the force-displacement curve from the time the indenter touches the grain until the grain breaks, the amount of rupture force and energy that need to be absorbed by the grain to break can be obtained [18]. Rupture force and rupture energy are the most intuitive physical quantities to represent the damage resistance of grains, so these two mechanical indexes are often used in the research process to further analyze the relationship between the mechanical properties of grains and their quality traits. In addition, the indicators used to characterize the mechanical properties of grains also include shear force, bending stress, elastic modulus, yield strength, and crushing stress [36].

3.1.1. Compression Mechanical Properties. The compression force is one of the most common external loads on grain. Under pressure, the grains are prone to deformation and structural changes. When the pressure exceeds the limit that the grain can withstand, the grain is broken, which affects the safety of grain storage [37, 38]. The experimental device of grain compression mechanical properties is shown in Figure 1. The grain was fixed on the stage to keep still, the upper-pressure indenter decreased slowly at a fixed rate, and the force-displacement curve was obtained under the action of pressure. Mechanical indexes such as rupture force, rupture energy, and compressive displacement can be obtained by analyzing the force-displacement curve [39, 40]. During the compression process, the loading rate of the indenter would affect the mechanical properties of the grain. Therefore, a constant loading rate should be ensured during the experiment [18].

There are differences in the compressive mechanical properties of different grains. Table 2 shows the magnitudes of compressive rupture force and rupture energy of several common grains. The antidamage ability of grains was maize > soybean > rice > wheat > sorghum. The maximum compressive rupture force of maize was in the range of 374.18 N~629.72 N. The compressive rupture force of rice was the smallest in the range of 23.54 N~38.19 N. The ability of grains to resist damage varies depending on the orientation. Taking maize kernels as an example, the compression rupture force was horizontal > lateral > vertical. This was due to the difference in the contact area between the indenter and the grain under different compression orientations. When placed horizontally, the contact area between the grain and the indenter is large, and the force is dispersed on the surface of the grain, so the grain has a high compressive rupture force at this time [44]. On the side of maize kernel, the proportion of the horny endosperm was higher than that of the floury endosperm. The horny endosperm tissue had a high bonding strength and hardness and was not easy to be destroyed. Therefore, the side compression rupture force was larger. When the top surface is compressed, the indenter first contacts the embryo of the maize kernel. This part was the main part of the life activities of maize kernels, and it is also the weakest part of the antidamage ability of kernels. At the same time, the proportion of the floury endosperm at the top of the maize kernel was higher than that of the horny endosperm, so the maize kernel had the lowest compressive rupture force when standing [45, 46]. The difference in the compressive mechanical behavior of grains was closely related to their physical and chemical properties. The relationship between the physical and chemical properties of grains and their mechanical properties will be further discussed in the following sections.

3.1.2. Bending Mechanical Properties. The determination of grain bending mechanical properties can be used to characterize the ability of grain to resist bending loads during production and processing. The commonly used experimental method of bending mechanical properties is the three-point bending test, which can be used to test the bending strength, fracture energy, and other indicators of materials [47]. At the beginning of the experiment, the material was placed on two fulcrums at a certain distance, and a downward load was applied from the center above the material. Two equal moments were formed between the three contact points of the material, so that the material breaks at the midpoint [20]. The experimental device is shown in Figure 2. The results of the multipoint bending test of intact brown rice and rice with cracks in the husk showed that the flexural strength and failure energy of intact rice were much higher than those of damaged rice. As drying continued, the rice grains became stronger and tougher. Under lower moisture content conditions, intact brown rice had a higher apparent elastic modulus, flexural strength, and fracture energy [48]. In addition, the three-point bending breaking force of brown rice increases with the increase in rice maturity, and the yield of the first rice has a certain correlation with the breaking force of rice grains [49]. Although there was no relevant research, this should be related to the change of protein and starch content in rice during maturation. Compared with other mechanical indexes, the bending crushing force of rice can better reflect its crushing characteristics, which provides an important basis for reducing the breakage rate and rice cracks in rice processing.

3.1.3. Shear Mechanical Properties. The shear characteristics of grain are very important engineering data in the study of grain crushing, threshing, and antibreaking ability under seed harvest [50]. The determination of the mechanical properties of materials under shear force is one of the basic experimental methods for the mechanical property test of materials. The grain was placed on a central suspended-loading platform before the start of the shear test of the grain. The upper indenter was a blade indenter. When the indenter was in contact with the grain, the force-displacement curve was recorded. The experimental device is shown in Figure 3. The shear mechanical test results of rye grains showed that when the water content of rye grains increased from 10% to 20%, the average shear force decreased from 60.8 N to 31.4 N. This is due to the swelling of the endosperm after absorbing water, resulting in a decrease in the shear strength of the grain [51]. There are some differences in the shear resistance of different wheat varieties. The research results of hard wheat varieties and soft wheat varieties showed that the shear resistance of hard wheat was significantly higher than that of soft wheat, but

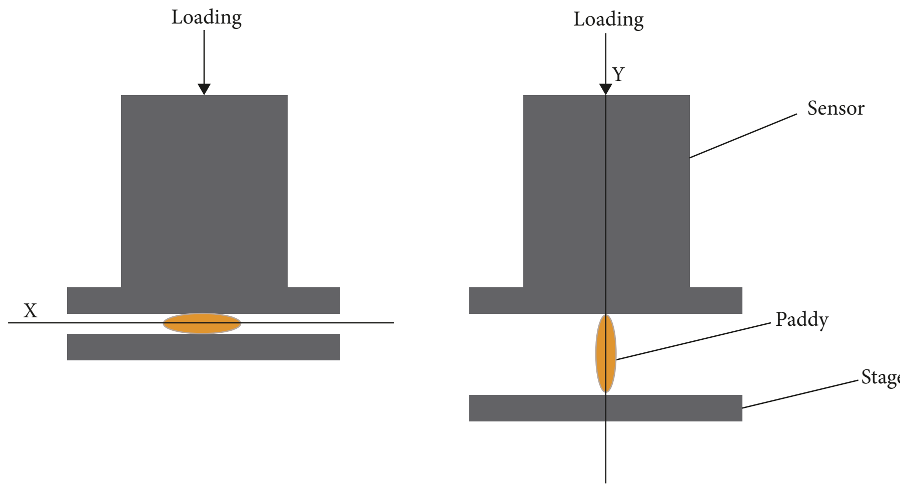

Figure 1: Compression test device schematic diagram.

Table 2: Different grains' compression rupture force.

Variety	Placement	Rupture force (N)	Rupture energy (mJ)	Reference
Maize	Horizontal	374.18~629.72	31.42~154.72	[41]
	Lateral	92.54~144.70	54.19~304.33	
	Vertical	69.84~163.05	342.99~778.83	
Wheat	Horizontal	48.51~88.96	36.33~50.19	[42]
	Horizontal	154.62~287.98	—	
Soybean	Lateral	114.71 ± 197.67	—	[28]
	Vertical	90.80 ± 172.05	—	
Rice	Horizontal	99.15~154.42	15.57~31.81	[40]
	Vertical	23.54~38.8	12.42~24.13	
Sorghum	Horizontal	50~75.26	—	[43]

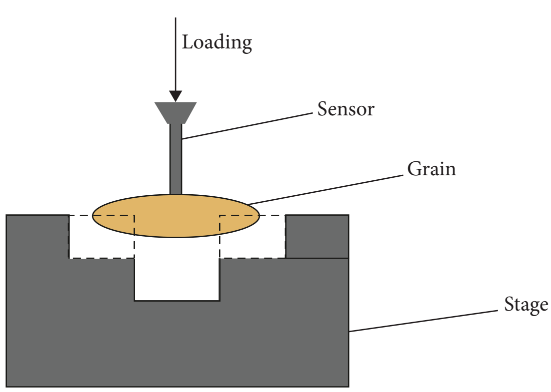

Figure 2: The schematic diagram of the three-point bending experimental device.

the water content had no significant effect on the shear energy of the two varieties of wheat [52]. When wheat grains were sheared at lower moisture content, the shear deformation of wheat was small. In the case of high water content, the wheat grains gradually ruptured during the shearing process, and the deformation was large. The shear energy of wheat depends on the shear force and shear deformation. Although the high moisture content led to the decrease in wheat shear force, the shear deformation increased with the increase in water content, so the moisture content had no significant effect on the shear energy of wheat [18].

3.2. Grain Dynamic Mechanics. Dynamic mechanical properties are used to study the law of stress and strain changes of materials under the action of changing forces. An important direction of grains' dynamic mechanics research was the influence of the impact force on grain's mechanical properties. The impact force refers to the force that suddenly increases and then disappears rapidly between two objects during a collision. It is characterized by short action time and large force value. The study of impact mechanical properties is of great significance for reducing the crushing rate of grain in the process of warehousing.[53]. When the grain is put into the warehouse, the higher the warehouse, the greater the impact of grain contact with the ground, and the higher the grain crushing rate. The research on the impact mechanical properties of grain was often combined with the experimental results of compression mechanics.. Based on the results of the compression test and impact test, a mathematical model for predicting seed breakage was established [54]. The experimental results on the impact force of rice show that there was a velocity threshold when the

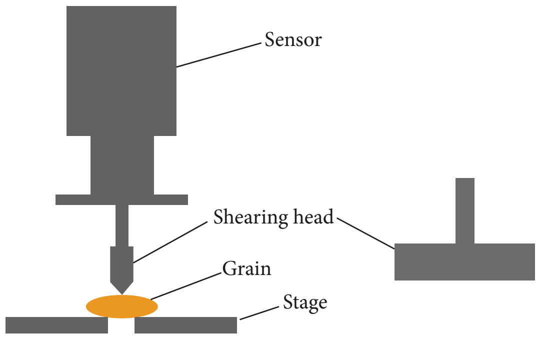

Figure 3: Shear mechanics test diagram.

grain was broken by the impact force, and the grain will not break below the velocity threshold. The probability of grain rupture tends to be stable with the increase in impact velocity [19, 55]. According to the size of the impact rupture force, the appropriate adjustment of the grain storage height can effectively reduce the grain crushing rate and improve the utilization rate of grain resources.

3.3. Grain Viscoelasticity. The viscoelasticity of food refers to the characteristics of both viscosity and elasticity when food materials are subjected to force. It mainly studies the distribution law of internal stress and strain of materials and the relationship between them and external forces. Common food materials such as bread and dough are the research objects of food viscoelasticity [56, 57]. Due to the complex deformation of food during chewing, it is usually subjected to the shear and compression of the teeth and tongue at the same time. Viscosity and elasticity will affect the taste of food. Therefore, it is of great significance to explore the viscoelasticity of food for understanding the changes in food's physical properties and human chewing bionics. The research on grain viscoelasticity can be divided into two categories: dynamic viscoelasticity and static viscoelasticity. Dynamic viscoelasticity refers to the phenomenon that the strain and stress of the material change with time under the action of alternating stress or alternating strain. Static viscoelasticity studies the stress relaxation and creep properties of materials under constant stress or strain. Thus, we explored the compression deformation of the object under the action of external force [58].

3.3.1. Static Viscoelasticity. The study of the static viscoelasticity of cereal is widely used in the study of the rheological properties of wheat dough and starch gel. The differences in physical properties of grains were analyzed by compression or shear tests combined with mechanical indexes such as grain elastic modulus, shear modulus, and loss modulus [59]. In addition to these studies on the viscoelasticity of starch gel or dough, there is also a certain relationship between the rupture behavior of grains and their viscoelasticity [60, 61]. The maximum rupture force of wheat and rye showed a strong correlation with their viscoelasticity. The viscoelasticity of grains is strongly related to their composition, especially the water content. Moisture content affects the viscoelasticity of grain to a great extent, the most important of which is the elastic modulus of grain [62]. The uniaxial compression experiment of wheat further verified this result. With the increase in water content, the elastic work of wheat grain decreased during compression, and the plastic work increased with the increase in water content. The total work in the compression process was reduced by 80% [63]. Molenda and Stasiak reported that the elastic constants (elastic modulus E and Poisson's ratio) of wheat, rye, barley, oats, and rapeseed are determined by the linear phase of the sample loading curve. The increase in moisture content will lead to a decrease in the elastic modulus of the grain [64]. The size of the elastic modulus reflects the strength of the material's resistance to deformation, so it is feasible to analyze the fracture behavior of grains by grain viscoelasticity.

3.3.2. Dynamic Viscoelasticity. Dynamic mechanical analyzer (DMA) is widely used in the study of the dynamic viscoelasticity of materials. During the measurement, the sample will be affected and controlled by the periodically changing mechanical stress. The relationship between the mechanical properties of viscoelastic materials and time, temperature, or frequency is obtained. Dynamic mechanical analysis is of great significance for evaluating the tensile properties, viscosity, and elasticity of wheat dough and can better predict the fermentation stability of dough [65, 66]. Through the study of the dynamic viscoelasticity of grain, the dynamic storage modulus, loss modulus, and loss tangent can be obtained. The experimental results of stress relaxation and frequency scanning of different varieties of maize showed that the varieties had no significant effect on the viscoelasticity of maize kernels [41]. The moisture content affects the stress relaxation behavior of maize kernels to a certain extent. The loss modulus and loss tangent under high moisture content are higher than those under low moisture content. The storage modulus of maize kernels decreased with the increase in moisture content [67, 68]. The experimental results of the creep properties of highland barley kernels show that the creep strain increases with the increase in moisture content. For the dynamic viscoelastic analysis of grains, the generalized Maxwell model can better fit the experimental data of stress relaxation and the curve of relaxation modulus [69, 70]. However, how to combine the viscoelasticity of grains in actual production and how to dynamically analyze the changes in the mechanical behavior of grains under external loads are still important problems that researchers need to solve urgently.

3.4. Other Mechanical Properties. The research on the mechanical behavior of grain is not limited as abovementioned. The friction coefficient of grain varies greatly on the surface of different materials. Generally speaking, the coefficient of static friction on different surfaces is manifested in concrete > galvanized steel > wood [71]. Low surface roughness could greatly reduce the wear of the grain surface and reduce the energy consumption of grain during processing. As an important index to characterize the mechanical properties of grain, hardness plays an important role in the processing and grinding processes. There were many methods for measuring grain hardness, but it was a common method to obtain grain hardness through a puncture test. Hardness is closely related to the grinding performance of the grain, which is of great significance to determine the final processing performance [72, 73].

Although research on the mechanical properties of grain has been greatly developed, there were few studies on the comprehensive consideration of the mechanical properties of grain. Considering the mechanical properties of grains in many aspects, a comprehensive consideration can be made for grain from harvest to final sale, so that the loss of grain in the middle of each link can be minimized, and its economic value can be better maintained.

4. Influencing Factors of Grain Mechanical Properties

4.1. Raw Materials and Geometric Properties. The internal organizational structure of grain is complex, the material composition of each part is different, and the mechanical strength is also different. The structural composition and density of cells are important factors affecting the mechanical behavior of grains [74]. Common grain's mechanical strength is usually expressed as maize > soybean > wheat > rice [75, 76]. The maize kernel is composed of three parts: seed coat, endosperm, and embryo. Compared with other grains, maize has a larger geometric size. The maize kernels have a larger surface flatness than other grains. Therefore, when subjected to external loads, the force required for maize to break is greater than that of other grains. Soybean has a higher oil content and viscosity than other grains, which increases its fracture energy. The shape characteristics of wheat and rice lead to low mechanical strength [40]. In addition to its own shape, the triaxial size also affects the mechanical properties of grains. There is a strong correlation between the thickness and grain hardness of different varieties of wheat, and the change in size will cause a change in wheat hardness. The greater the thickness, the higher the hardness of wheat [15]. The increase in thickness will reduce the flatness of wheat, and similar findings are found in rice. The rupture force of rice is affected by the combined action of three-axis dimensions. The rice particles with a higher flattening ratio and smaller elongation ratio seem to have a greater compression rupture force (flattening ratio: thickness/width; elongation ratio: width/length) [55].

4.2. Grain Endosperm. Endosperm is the main component of grains, and the bonding force between its parts has a great influence on the mechanical properties of endosperm [77]. Endosperm is essentially a complex mixture of starch granules and protein groups. According to their different structures, they can be divided into the horny endosperm and floury endosperm. The horny endosperm contains high amylose content, and the starch granules exist in the form of polyhedral. It is closely combined with the protein group, the internal cavity of the tissue is small, and it has high hardness. The floury endosperm's starch granules are mainly spherical, not closely arranged, and have a large cavity volume inside. Therefore, its hardness is lower than that of the horny endosperm [45]. Grains can be divided into cutin grains and powder grains according to the proportion of the horny endosperm and floury endosperm. Due to the high content of the horny endosperm, cutin grains often have high grain hardness. In dry wheat grains, there was a positive correlation between grain hardness and cutin rate. Wheat with a higher cutin rate had higher hardness [78, 79]. Maize kernels also have similar experimental results. According to the proportion of the horny endosperm and floury endosperm, maize can be divided into flint corn, floury corn, sweet corn, dent corn, popcorn, and so on [80]. The force required for the rupture of maize kernels is proportional to the content of the horny endosperm. Maize kernels with high horny endosperm content tend to have higher mechanical strength [81]. The proportion of horny endosperm of flint corn is higher than that of other kinds of maize, so flint corn has higher damage resistance than other varieties [82].

4.2.1. Protein. Although protein does not account for a high proportion of the total composition of some grains, it also has a certain effect on the mechanical properties of grains. The protein content and composition are different in different endosperms. The contents of total protein and insoluble protein in the horny endosperm were higher than those in the floury endosperm and sorghum grain. The content of α-zein in the horny endosperm was higher than that in the floury endosperm in maize grain [83, 84]. The mechanical properties of grains are also affected by the endosperm structure during the test, and compared with the protein composition, the mechanical properties of grains have a strong correlation with the total protein content [85]. A large number of studies have shown a positive correlation between wheat hardness and protein content. The higher the protein content, the harder the wheat grain [41, 86]. The degree of vitreous affects the hardness of wheat grains. In addition to environmental conditions, vitreous is also affected by the genes that control grain hardness. Vitreous was positively correlated with protein content, so the hardness of wheat grains showed a strong correlation with protein content [87]. This phenomenon that protein content is affected by gene regulation and ultimately affects the mechanical properties of grains has similar experimental results to maize grains. The higher kernel hardness of flint corn is also related to its protein content [88]. The microstructure of the grain fracture form verified the contribution of high protein content to grain hardness. The microstructure of the broken grains was characterized by the fracture of the connection between the starch granules and the protein matrix or the fracture of the protein matrix or the fracture along the boundary of the starch granules [45]. This fracture pattern indicates that the thicker the protein matrix covering the surface of the starch granules is, the less likely it is to break.

4.2.2. Starch. Similar to protein, starch, as one of the main components of cereal endosperm, affects the mechanical properties of cereals by affecting the hardness of the endosperm. According to the different molecular structures, starch can be divided into amylose and amylopectin. Although both of them are polymers of glucose, their physical and chemical properties are quite different. Previous studies have shown that the content of amylose is positively correlated with the hardness of maize endosperm. The higher the amylose content, the higher the hardness of the endosperm [89, 90]. The shape and size of starch granules in different cereals were different. The starch granules of wheat, rye, and barley were spherical and discoid. In addition to the starch structure, the morphology of starch granules has also been proven to be related to the mechanical properties of cereals [82, 91]. The starch granule morphology of the maize horny endosperm is different from that of the floury endosperm. The starch granules in the floury endosperm are mostly spherical and loosely packed in the protein matrix. The starch granules in the horny endosperm showed a dense accumulation of polyhedral. The starch granules in the corn horny endosperm bind more tightly than the starch granules in the floury endosperm after being squeezed by the protein matrix. This compactness increases the density of the endosperm and thus the firmness of the endosperm. The observation results of the microstructure of maize endosperm also confirmed this conclusion. The starch granules in the cuticle endosperm were more tightly bound to the protein matrix than those in the silty endosperm, so the hardness of the horny endosperm was higher than that of the floury endosperm [92]. There was a positive correlation between amylose content and grain rupture force in grains [93]. However, some researchers have shown that the amylose/starch ratio is more representative than the amylose content itself in explaining the effect of starch composition on grain hardness [94]. This has a very important guiding significance for evaluating the change in the mechanical behavior of the grain grinding process.

4.3. Moisture Content. The difference in water content will not only affect the basic physical properties of grain and the safety of grain storage but also affect the mechanical properties of grain and the damage resistance [9, 95]. Studies have shown that under conditions of high moisture content, the mechanical strength of grains is low, and they are more likely to deform or even rupture when subjected to external forces. The compression test results of broad bean under different water content and compression directions show that the rupture force of any axis along the three axes is highly dependent on the water content. There is a significant negative correlation between water content and rupture force [96]. This is because, under conditions of high moisture content, the endosperm cells in the grain will absorb water and fill the internal voids, making the grain structure expand. This not only affects the physical properties of grains, such as 1000-grain weight, bulk density, and true density, but also makes the endosperm texture softer, which in turn reduces the mechanical strength of the grain [97]. The microstructure of oats was different under different water contents. When the water content was low, the starch granules in oat grains were closely arranged. At this time, the grains have higher mechanical strength. With the increase in water content, starch and protein in grains will swell to different degrees. Due to the presence of -NH_3 and -COOH groups in the protein, its water absorption capacity is stronger than that of starch granules. Therefore, when the moisture content of the grains increases, the internal starch-protein network system becomes irregular, and this irregular starch-protein system weakens the mechanical properties of the grains [98]. Therefore, the grains should be dried in time after harvest. Reducing the moisture content can not only prolong the storage time and reduce the harm of microorganisms in the storage process but also prevent mildew [99]. Higher grain mechanical strength under low moisture content is of great significance for reducing the damage of grain during processing..

4.4. Other Influencing Factors. In addition to the differences in the grain itself, external conditions such as storage and processing methods will also affect the mechanical properties of the grain. In order to ensure the safety of stored grain, it is often necessary to reduce the moisture content by drying before the grain is put into storage. However, drying temperature, drying time, and drying method also have an impact on the mechanical properties of grains. This is mainly due to the influence of different drying processes on the internal stress cracks of grains [100]. Different drying conditions will cause changes in the internal stress of grains, which will affect the mechanical properties such as fracture force and fracture energy [101]. High-temperature drying can make rice obtain higher bending strength and fracture energy and make the grains stronger and tougher, while thelower-temperature drying conditions will reduce the bending strength of rice grains and have a certain impact on the yield [16]. In addition, the mechanical behavior of grains will also change during the storage process. The storage time and pressure will also affect the mechanical properties of rice grains. The mechanical properties of rice grains are linearly related to the storage pressure. The compressive capacity decreases with the increase of storage pressure, and the length of storage time will also affect the damage resistance of grains [32]. The reason for this phenomenon is due to the grain after-ripening phenomenon under long-term storage conditions. In this process, the contents of protein, starch, and free fatty acids in grains will change, which leads to the change in grain mechanical behavior. In addition, during the storage process, the grains are squeezed by the surrounding grains, and the closer they are to the bottom of the granary, the greater the extrusion pressure. Compared with the compression of a single grain, the mechanical properties of stacked maize grains are different from those of a single grain [39]. Therefore, it is of great significance to analyze the mechanical properties of grains by using a triaxial test to explore the change of stress in grain piles under pressure.

5. Conclusion and Prospect

So far, the research on the mechanical properties of grain still needs further development. The mechanical properties of grain have a great influence on its processing quality. Although there are various research methods on the mechanical properties of grain, the mechanical properties of grain under different conditions are simulated by shear, compression, bending, and other experimental methods, and the mechanical indexes such as rupture force, rupture energy, and elastic modulus of grain are obtained. However, the relationship between the mechanical properties of grain and its physical and chemical properties and even the unified mechanical determination method of grain has not been standardized. Most research on the mechanical properties of grain is limited to the static force change, while the research on the mechanical properties of grain in the process of circulation is still limited. How to apply the experimental mechanical indexes to solve practical problems, reduce the loss in the process of grain processing, and reduce mechanical damage is an urgent problem to be solved. At the same time, the systematic discussion of many factors affecting the mechanical properties of grains and the use of various experimental methods are of great significance for reducing the grain breakage rate and improving the grain utilization rate.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Peng Gao conceptualised the study, developed the methodology, wrote the original draft, and validated the study. Shuangqi Tian administered the project and wrote, reviewed, and edited the study. Xing'ao Xue investigated and supervised the study. Jing Lu supervised and wrote, reviewed, and edited the study. All the authors have read and agreed to the published version of the manuscript.

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