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Review Article

Factors, Harms, and Control of Corn Kernel Breakage: A Review

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Abstract

Corn kernel breakage is an important cause of corn losses. Beginning at harvest, corn kernels are broken by collisions with farm machinery and equipment, drying induces increased kernel breakage susceptibility, and equipment transfers and grain loading generate collisions between corn kernels and with equipment, increasing the amount of broken kernels. Meanwhile, broken kernels increase the risk of insect damage, mold and mildew, as well as aggravate segregation during warehousing, which is detrimental to the safety and quality of corn storage. The causes of corn kernel breakage from harvest to storage are summarized, the water content is a key factor in the post-production quality and quantity of corn, the research results on kernel breakage in recent years are summarized, and suggestions are made for the research related to the reduction of corn kernel breakage rate.

INTRODUCTION

Corn is one of the food crops with the highest total production in the world and is one of the main food rations for human beings. To evaluate the quality of corn, in addition to color, capacity, and impurity content, the content of broken kernels is also an important indicator. According to the 2022/2023 U.S. Corn Harvest Quality Report (USGC, 2022), the overall average corn brokenness was 0.7%, the average total BCFM (broken corn and foreign material) was 0.9%, and 20.7% of the samples contained 1.0% or more broken corn. Corn goes through a number of stages between harvest and storage as shown in (Figure 1), including threshing, drying, conveying, drying, and storage, and the properties of the corn kernels change along with these steps. Corn harvesting and threshing processes commonly use instrumental processes, and kernels are highly susceptible to shattering when they collide with machinery [1-4]. When drying, the moisture content of corn kernels will drop dramatically, and some of the grain kernels will be crumpled due to the loss of water to produce stress accumulation internally, and cracks will appear [5,6]. When conveyed into the warehouse, the kernels are subjected to shock loads during instrumental transit, which is an important causative factor for corn kernel breakage [7,8]. In addition, ventilation and drying are carried out prior to storage, and high temperature and rapid drying are highly susceptible to cracking of higher-moisture grain kernels, which affects the processing quality of maize. Cracked kernels can withstand a decrease in the strength of the action, and the cracks are very easy to expand during subsequent processing, which in turn leads to grain breakage [9,10].

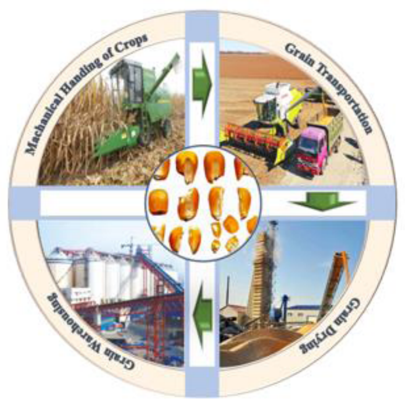

Figure 1 All stages of post-harvest corn are accompanied by crushing.

Breakage of corn kernels can cause difficulties in post-harvest production and storage. Complex segregation mechanisms such as sieving and impact separation after corn entry into the silo cause uneven mixing, stratification and segregation of intact and broken corn kernels in the form of distribution, resulting in uneven porosity distribution within the grain pile, which is exacerbated by uneven settlement caused by the self-weight of the grain [11,12], which ultimately leads to uneven distribution of the airflow resistance within the silo, and over drying of the low concentration pile and over wetting of the high concentration pile, which in turn induce the propagation of insects and molds. Breaking also changes the physicochemical properties of corn

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kernels thereby affecting the final quality of the product. Broken kernel surfaces are susceptible to infection and the growth of a variety of molds and pests, and the activity of molds and pests can lead to regional harborage of insects, condensation, and mold, and even to the entire silo [13-16]. Crushing of corn kernels likewise contributes to food waste [17]. This article reviews the causes and key factors of corn kernel breakage problems, grain storage risks induced by broken corn kernels, and the results of recent research on reducing corn kernel breakage, as well as recommendations on how to control corn kernel breakage and future research.

KERNEL BREAKAGE TYPE

The main types of kernel breakage are mechanical, thermal and biological breakage. Most of the mechanical breakage is due to impact, extrusion, shearing and rubbing between the seed grain and the instrument [18]. Thermal breakage is caused by the presence of temperature and moisture gradients within the seed grain, and uneven internal deformation after heating resulting in hygrothermal stresses [19]. Biological breakage is the breakage of seeds due to the propagation and activity of pests, molds as well as fungi [20].

Mechanical Breakage

Mechanical harvesting: The popularity of mechanized harvesting of corn has been increasing, accompanied by the mechanical harvesting process of the kernel crushing problem has become a new challenge [21-25]. Mechanical harvesting of corn consists of two main parts: picking and threshing as shown in (Figure 2) and in (Figure 3). The current development of corn harvester mainly through the picking roller picking cobs, picking mechanism through the roller shaft on the stalk to realize the picking cob, therefore, the roller type, roller speed and the gap between the concave plate, will affect the harvesting of the kernel breakage rate [26,27]. The mainstream "roller plucking" mainly pulls corn cobs off the plant through a number of pairs of relatively rotating plucking rollers. During the process, the high-speed rotating cob picking rollers are in direct contact with the cobs, which can easily lead to serious cob injuries, kernel drop, and high breakage rate [28]. Geng A, et al. found that the impact force on the cobs in cob picking increases with the increase in cob diameter and the decrease in the gap of the cob picking rollers. In addition, the rotational speed of the picking rollers during spike picking is also closely related to the seed breakage rate, when the rotational speed of the picking rollers varies from 650 to 850 r/min, the cob loss rate and the seed breakage rate show a tendency of decreasing and then increasing with the increase of the rotational speed, which is due to the positive correlation of the cob damage rate and the seed breakage rate with the contact time between the cobs and the picking rollers [29].

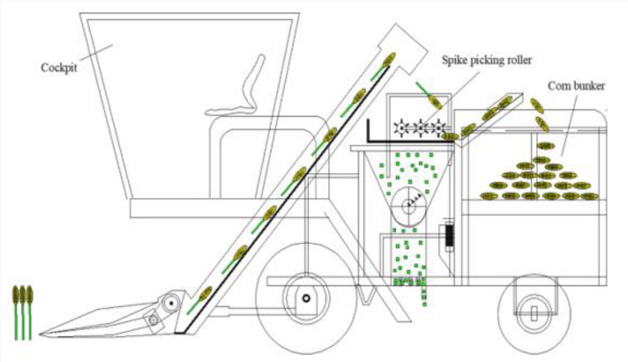

Figure 2 Structure and working line of corn combine harvester.

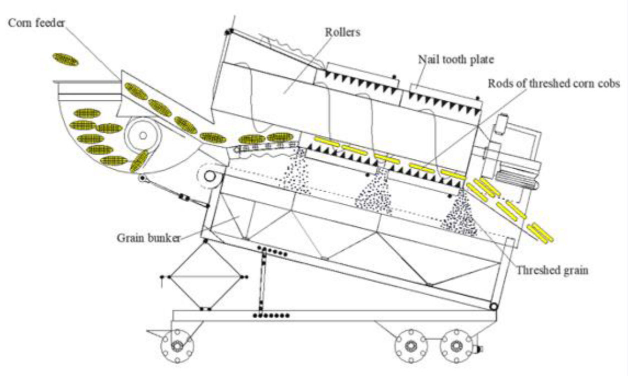

Figure 3 Structure and working line of corn thresher.

During threshing, the concave plates of the drum and the threshing elements on the drum in the threshing machine act on the cob to remove the kernels [30,31], and the corn cob is subjected to mechanical forces of pulling, rubbing, shearing, and impact [32]. The threshing force exerted on the cob by too slow a rotational speed or too large a plate spacing will make it difficult to meet the threshing conditions, and too high a rotational speed and a small plate gap will exert too much force on the cob, resulting in excessive kernel breakage. When corn threshing is carried out, the drum speed, drum diameter, ripple spacing, concave plate gap, feeding volume and feeding direction of the threshing machine have an effect on the threshing efficiency and breakage rate [33], and the results of the study show that reducing the drum speed is the most effective way to eliminate or reduce the kernel breakage, but the reduction of the drum speed also reduces the efficiency of threshing work [34].

The moisture content of corn at mechanical harvest is another key factor affecting kernel breakage [35], and studies have shown that the breakage susceptibility of corn first decreases with increasing moisture content and then increases above a certain moisture content [36,37], and harvest breakage is minimized when the moisture content of the corn is between 22 and 26%, and harvest breakage is greater when the corn has a low moisture content of 22% or a high moisture content of 26% [38,39]. When the moisture content of maize exceeds 26% during harvest, the plasticity of maize kernels is weakened and the compressive strength is reduced [40], and the moisture content continues to decrease after it falls below 13%, which results in a small increase in the plasticity of maize kernels, the compressive strength of maize kernels, and a small increase in compressive capacity [41]. Johnson, et al. [42] investigated the principles of mechanical threshing and found that the energy required for high moisture content kernels to be threshed was greater, and that their kernels were subjected to greater forces during threshing, and the breakage rate was significantly higher (0.5% at 20% moisture content of kernels, and more than 3.5% at 35% moisture content of kernels). The response trend between corn mechanical harvest crushing rate and water content was consistently positively correlated, and the relationship curve conformed to a quadratic parabolic shape [43]. The moisture content of corn kernels during harvesting directly affects the quality of corn machine harvesting, and excessive moisture content not only increases the corn kernel crushing rate during harvesting, but also has a great impact on the physicochemical properties of corn kernels, which is more prone to mold and insect problems [44].

Transportation: The use of precarious roads for transportation, excessive speed, old trucks or body failures, lack of qualification of drivers, and damage to the tools of transportation equipment lead to corn being subjected to crushing, collisions, impacts, insects and molds that can cause kernel breakage during transportation operations [45]. R Paulsen, et al. measured the breakage of two shipments of maize transported from Toledo to Rotterdam and from Peoria to Mexico, respectively, and the average rate of breakage increased from 3.6% to 15% from Toledo to Rotterdam. In the transportation from Peoria to Mexico, the average rate of breakage increased from 1.2% to about 5.3% [46]. The transportation chain is subjected to multiple equipment transports, where corn is subjected to repeated actions and high percentages of breakage occur [47,48]. Mainstream corn transportation machines include belt conveyors, Pneumatic conveyors, bucket elevators, and scraper conveyors, and (Figure 4) lists the commonly used handling machines. Corn transportation will use a large number of these machines, and the extrusion and collision between materials generated by machine constraints can damage the kernels [49,50], and the excessive speed of equipment transportation during transportation operations can lead to high-speed, violent impacts between corn kernels and conveying and storage equipment, resulting in kernel breakage [51]. JM Boac, et al. used a bucket elevator to transport 25 tons of corn for corn transportation breakage tests and found that the average breakage rate increased by 3.83% compared to the pre-transportation period [52]. Mwaro WB, et al. calculated the amount of particle breakage that occurs in bulk corn kernels transported through a drag chain conveyor with a steel plate, and the results showed that a drag chain conveyor with a steel plate can result in bulk corn kernel breakage up to 2.63%. The kernel breakage rate increased with decreasing belt loading and decreasing moisture content. Corn kernel breakage also increased with repeated handling [53].


a. Belt Conveyor b. Bucket elevator b. Scraper conveyor

a. Pneumatic Conveyor b. Screw Conveyor

Figure 4 Several common corn transportation apparatus.

In addition to this, corn kernels dropped during transshipment or transferred between different equipment resulting in height differences, such as when unloading corn kernels from combines to wheelbarrows or filling storage bins, are subjected to impact loading, resulting in breakage of corn kernels with higher moisture content, whereas corn kernels with lower moisture content show better impact tolerance [54]. The results of drop impact tests conducted on corn, soybeans and wheat showed that mechanical damage to grain kernels increased with increasing drop height [55], which was attributed to the fact that grain kernels gained greater velocity with increasing drop height, which resulted in greater impact forces [56]. In drop impact experiments, the velocity of the grain stream may exceed the final velocity of individual grains when the drop height exceeds 15 m because the resistance acting on individual grains is not exactly the same when the grain stream falls as a whole [57]. In addition, intergranular constraints are an important factor in the different behavior of granular flows with respect to the impact characteristics of individual grains [58]. When the granular flow is impacted, it causes secondary impacts between particles under the influence of rebound angle and rebound velocity [59]. Secondary impacts also cause breakage.

Mechanical breakage model: Mechanical breakage is the main form of post-production corn shattering that occurs, mostly due to corn kernels being subjected to forces that exceed their own strength. Mechanical breakage is a more serious problem than thermal and biological breakage. The control of kernel mechanical shattering can be predicted by studying the mechanical properties of kernels and building mechanical models for targeted prevention and control [60-62]. The index generally used to indicate the damage resistance of seed grains is the fracture force or critical damage energy [63,64], and seed grains exhibit different mechanical properties under dynamic and static loading. Under static loading conditions, the fracture force or critical damage energy can be measured by a uniaxial compression test [65], during which a single corn kernel is slowly compressed between two parallel plates until the kernel breaks [66]. The value of critical breaking force or critical energy of corn has been studied more [67-69] and can be found in the published literature. There are also several studies using three-point bending tests and compression tests to determine the breaking force of kernels [70,71]. Under dynamic loading, such as when impact forces are applied, the seed grain is subjected to large transients, and there are two main ways to study the impact breakage characteristics of seed grains, which are categorized as multi-particle impact breakage and single-particle impact breakage. Multi-particle impact breakage test needs to be combined with empirical knowledge to analyze the crushing mechanism, and it is difficult to reveal the seed kernel breakage characteristics in detail, and single-particle impact breakage test can be equipped with a high-speed camera to record the crushing process in detail, and a large number of scholars have established the grain impact damage model through the single-particle impact test [72,73].

Quasi-static load model: The static strength of corn kernels can be estimated from the fracture force and critical damage energy measured by bending and compression tests. Zoerb and Hall (1960) determined the basic mechanical and rheological properties of corn [74]. These properties include compressive strength, modulus of elasticity, maximum compressive stress, shear stress and stress relaxation. They also evaluated the modulus of elasticity (defined as the energy required to deform a corn kernel to its yield point) and the modulus of toughness (defined as the energy required to deform a corn kernel to its maximum compressive force) in compression tests. The values of the modulus of elasticity and modulus of toughness of corn were also roughly estimated. sheleff and Mohsenin (1969) investigated the effect of moisture content on the mechanical properties of corn [75] by uniaxial compression of individual kernels of corn at moisture contents ranging from 6.5% to 28% (dry basis). Linear ultimate load, apparent modulus of elasticity and modulus of deformation were determined using cylindrical indenter, spherical indenter and parallel plate, respectively, and each of the evaluated parameters decreased with increasing kernel moisture content. Hammerle and Mohsenin (1970) determined the tensile relaxation modulus of corn cuticular endosperm as a function of time, temperature and moisture content [76]. By superimposing rate sensitivity and time-temperature, the authors found that corn kernel cuticular endosperm had a flatter curve in relation to tensile relaxation modulus at temperatures ranging from 5.0°C to 69.4°C and moisture contents ranging from 13% to 27%. Su, et al. (2019) determined the extreme points of kernel stress for different shapes of corn kernels and for the same kernel with different stress sites, and determined that corn kernel maximum stress was most likely to cause kernel breakage in the abdomen [77]. The bending stress mathematical modeling of corn kernels enables the assessment of the deformation limits of the kernels when subjected to loads, such as stresses during kernel transit, pressures under stacking loads, and the extent to which the kernels are affected by moisture content, temperature, and time when stored in bins. In addition, the numerical data obtained from the results of bending and compression tests can help to provide more insight into the cracking damage to corn kernels caused by bending and compression phenomena that may be encountered during the relevant harvesting or sowing stages.

Impact model: Impact damage is another major cause of grain breakage during harvest and transit. The degree of impact damage is mainly influenced by impact velocity (for corn, impact damage is more significant when the impact velocity is greater than 10 ms^{-1} [78]), moisture content, impact angle and impact surface. The instantaneous loading rate of impact is much higher compared to static compression and bending [79]. In order to evaluate the ability of seeds to resist impact damage, researchers have introduced a seed quality index known as breakage sensitivity [80]. However, breakage sensitivity can only provide an estimate of the extent of damage, and the actual damage depends on the physical properties of the seed kernel as well as the degree and number of times the seed kernel has been loaded, which cannot be predicted by breakage sensitivity [81]. In order to relate kernel breakage to impact loading, many researchers have modeled breakage using single kernel impact tests. K (1979) built a small rigid hammer mill and used it to determine kernel damage due to impact. The results were described in terms of breakage rate and were used to evaluate the effects of sieve size, milling speed, kernel size, moisture content, and temperature on breakage rate, and it was found that corn kernel impact breakage was strongly correlated with moisture content (impact damage was least when the moisture content of corn kernels was 25%, and increased rapidly with increasing or decreasing moisture content), and it increased significantly with increasing particle size as well as with decreasing temperature [82]. S (1983) used an experimental setup with a purely random impact loading mode to predict the impact damage of corn kernels under real working conditions, linking the breakage susceptibility to the moisture content of the kernel and the loading rate. Fu, et al. (2009) defined the critical impact velocity at which breakage of a kernel occurs (the critical velocity is defined as the minimum impact velocity at which one or more cracks are observed within the kernel) [83]. Long (2022) established a DEM model of corn kernel and determined that the head of corn kernel has a strong capacity to withstand impact loads through high-precision simulation [84]. These models have improved researchers' understanding of seed kernel impact damage factors, and in addition, these studies have greatly contributed to the development and improvement of devices that may produce seed kernel breakage.

Thermal Breakage

Dry: Harvested corn with high moisture content needs to be dried, which removes some of the pest eggs and molds from the surface of the corn kernel and keeps the corn at an appropriate moisture content, which is more conducive to subsequent storage and other processes [85-89]. However, the drying process is also accompanied by drying damage or even breakage of corn kernels. From the microscopic level, corn kernel drying is a dynamic process of heat and mass transfer, and the structure of corn kernels generally consists of seed coat, endosperm, and embryo, and the heat transfer coefficients (thermal conductivity) and moisture diffusion coefficients of each of the three parts are different, and in the process of drying, the internal wrinkles occur in the parts due to the lack of coordination of the heat as well as the mass transfer, resulting in the internal During the drying process, the uncoordinated transfer of heat and mass from each part leads to internal wrinkles and structural damage, which is further exacerbated by the uneven change in moisture content of the grain due to the different moisture diffusion coefficients [10,90-94]. The main reasons for kernel breakage are:

A. Excessive drying temperature makes corn kernels expand, generating internal accumulated stresses, destroying the internal structure of the kernel and increasing its susceptibility to breakage [89,95].

B. Excessively fast drying rate makes the rate of internal moisture transfer to the surface of the grain smaller than the rate of surface moisture evaporation, generating a large moisture gradient inside the grain, which results in differences in volume shrinkage [96,97].

C. Uneven drying makes the drying process of grain grain temperature gradient, grain surface layer first drying, and grain center part of the moisture to diffuse, then continue to pass the hot air, drying efficiency is reduced, and easy to produce broken [98].

Drying temperature, drying rate, moisture content and temperature gradient: In the process of thermal drying, drying temperature is an important index that affects the drying quality of grains [99,100]. Many researchers have studied the deformation characteristics of corn kernels in thermal drying, and the force-deformation curves of corn kernels show linear changes at different temperatures, and with the increase of drying temperature corn kernels begin to appear rupture phenomenon [89,96,101]. The drying process is most concerned about the drying rate, the faster drying rate can bring more revenue space, however, with the increase of drying rate, the percentage of kernel stress rupture also increases [102]. Maintaining a reasonable drying rate is the key to ensure drying efficiency and corn quality. The initial moisture content of the kernel during drying is also an important factor that should not be ignored. Moisture content acts on the heat and mass transfer process during kernel drying, and is related to kernel drying effectiveness and breakage rate, and kernels of corn with high moisture content undergo greater volume changes during drying, and are more susceptible to breakage due to water dissipation and kernel crumpling [103,104]. In addition, the components of the corn kernel, such as the pericarp, hard endosperm, soft endosperm, and germ, have different water dissipation efficiencies, and it has been found that differences in changes in the moisture content of the internal structure of the corn kernel under the same drying conditions can trigger a moisture gradient and create stresses that can crack when the destructive strength of the corn kernel is exceeded [105-107]. The effect of temperature gradients during drying can also lead to corn kernel breakage, and temperature gradients caused by non-uniform drying environments or non-consistent drying rates can cause kernel cracking during drying [97], with temperature gradients typically arising within approximately 20 seconds after the start of drying and disappearing after 2 to 3 minutes [97,108]. Intermittent drying is an effective way to reduce the temperature gradient, and cracking due to excessive hygrothermal stress can be avoided by keeping the grain kernels in closed bins for a certain period of time, which makes it possible to maintain low moisture and temperature gradients within the kernels through natural heat and moisture transfer.

Dry kinetics: Considering the effects of the above factors, equations describing the change in moisture during drying of grain kernels can be obtained and the emergence and expansion of cracks can be predicted from the change in moisture content, on which the drying kinetics are based. Drying kinetics studies the relationship between the amount of moisture removal and various governing factors in the drying process. The study of drying kinetics is mainly the mathematical simulation of the thin-layer drying (thin-layer drying refers to the drying process in which the surface of the material layer of less than 20mm is completely exposed to the same environmental conditions, and it is the basis for the study of the deep-bed drying characteristics) curves to obtain the equation of the thin-layer drying. Since the 19th century, researchers have used the Fick's law of diffusion for describing the drying behavior of the material [109], which is used to describe the drying behavior of the material under the assumptions of the uniformity and isotropic, the resistance to flow of moisture within the material is uniformly distributed, the diffusion coefficient D is independent of the local moisture content, and the volume contraction of the material is negligible, Fick's second law will be simplified as:

$$\frac{\partial X}{\partial \tau} = D\frac{\partial^2 X}{\partial x^2} \tag{1}$$

where X is the wet fraction ratio (defined as the ratio of the free wet fraction to be removed to the initial wet fraction at a certain moment); τ is the drying time; D is the diffusion coefficient/$m^2 \cdot s^{-1}$; and x is the diffusion distance/m.

For an infinitely large flat plate (thin sheet layer material) with uniform initial moisture distribution, mass transfer symmetric about the center, and instantaneous equilibrium state of moisture content on the surface of the sample with the surrounding drying medium, the initial and boundary conditions can be determined, from which the theoretical equations of thin-layer drying, i.e., the diffusion equation, can be obtained:

$$M_R = \frac{X - X_c}{X_0 - X_c} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\times\exp\left[\frac{-(2n+1)^2\pi^2 D\tau}{4L^2}\right] \tag{2}$$

where MR is the moisture ratio at a certain moment; L is half of the thickness of the infinite flat plate/m.

Lewis [109] proposed a thin-layer drying rate equation similar to the Newton cooling rate equation for convective heat transfer and derived the Lewis equation:

$$M_R = \frac{X - X_c}{X_0 - X_c} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\times\exp\left[\frac{-(2n+1)^2\pi^2 D\tau}{4L^2}\right] \tag{3}$$

where k is the drying constant/s^{-1}.

Page [110] modified equation (3) to obtain the Page equation for thin layer drying of grains:

$$M_R = \exp(-k\tau^n) \tag{4}$$

Karathanos [111] tabulated the first three terms of Eq. (2) into three exponential equations to obtain a semi-theoretical equation for thin-layer drying, which is simple in form and meets the accuracy requirements of the engineering:

$$M_R = a_1 \exp(-k_1\tau) + a_2 \exp(-k_2\tau) + a_3 \exp(-k_3\tau) \quad (5)$$

where a_1, a_2, a_3, k_1, k_2, and k_3 are empirical constants.

Also listed in (Table 1) are a number of equations for drying kinetics for different grains, and with appropriate assumptions and modifications, some of these equations can be applied to predict damage and fragmentation during drying of corn kernels.

Biological Breakage

Storage is a crucial link in the whole post-production chain of maize, and microbial and pest infestation is a major threat to the safety of maize storage. The burrowing nature of pests can lead to the shattering of corn kernels [116]; microbial infestation can lead to the development of diseases in corn in storage bins, weakening of corn kernels, and increased risk of shattering [117].

Injurious insect: Storage pests include as many as 20 species of Coleoptera, Lepidoptera, and Ixodes [118-121], as listed in (Table 2). In order to accurately investigate the problem of corn kernel breakage caused by corn storage pests, researchers have proposed the concept of infection index to calculate the degree of infestation of the pests [122,123]. It has been investigated that after 5-6 months of storage without protective measures, the average breakage rate of stored maize affected by pests can reach 75.85%, with losses ranging from 51% to 85% [124]. The degree of pest infestation is closely related to the temperature and humidity of the storage bin, and in the case of the maize weevil population, 30°C and 75% RH are the optimal environments for its growth on stored maize [125]. Kernel hardness is also a key factor for insect resistance and is influenced by moisture content [124,126]. Moisture content above 16% reduces corn kernel strength [127] and makes it more susceptible to infestation by corn storage pests. In addition, given the soft nature of the kernel and the proximity of nutrients to the kernel, adult pests feeding on corn kernels are biased to penetrate the flatter side, which is more likely to cause through cracks, resulting in breakage and shattering of the kernel [119].

Table 1: Drying Kinetic Model.

Equation type or researcher	Model Name	Drying equation
Semi-Theoretical		
Henderson [112]	Single diffusion model	$M_R = a\exp(-k\tau)$
Jha P [113]		$M_R = \frac{8}{\pi^2}\exp[\frac{-\pi^2 k\tau}{4L^2}]$
Sharaf E [112]	Double diffusion model	$M_R = a_1\exp(-k_1\tau) + a_2\exp(-k_2\tau)$
Sacilik k [114]		$MR = A_1\exp(-k\tau) + A_2$
Midilli A [115]		$MR = A_1\exp(-k\tau^n) + A_2\tau$
Karathanos [111]	Triple diffusion model	$M_R = a_1\exp(-k_1\tau) + a_2\exp(-k_2\tau) + a_3\exp(-k_3\tau)$
Semi-empirical		
Lewis [109]	Lewis model	$\frac{}{\partial\tau} \quad \frac{}{\partial x^2}$
Page [110]	Page model	$M_R = \exp(-k\tau^n)$
Overhults [112]	Modified Page Model	$M_R = \exp\left[-(k\tau)^n\right]$
Wang [112]	Modified Page Model	$M_R = a\exp(-k\tau^n)$
Empirical		
Thompson [112]		$\tau = a\ln M_R + b(\ln M_R)^2$
Wang [112]		$M_R = 1 + a\tau + b\tau^2$

Table 2: Common storage pests.

Name	Category	Susceptible Products
Flour mite	Sarcoptiformes; Acaridae	Cereals, cereal products
Pulse weevil	Coleoptera; Bruchidae	Many pulses including kidney bean
Pulse beetle		Many pulses
Dried fruit beetle		Dried fruits, groundnut
Rice moth	Coleoptera; Nitidulidae	Rice, maize, soybean
Rusty grain beetle	Lepidoptera; Galleridae	Maize, wheat
Flat grain beetle	Coleoptera; Laemophloeidae	Maize
Tropical warehouse moth		Rice, maize, mung bean
Long-headed flour beetle	Lepidoptera; Phycitidae	Maize
Merchant grain beetle	Coleoptera; Tenebrionidae	Oilseeds, groundnut
Saw-toothed grain beetle	Coleoptera; Silvanidae	All cereals, pulses, spices
Indian meal moth		Rice, wheat, maize
Australian wheat borer	Lepidoptera; Phycitidae	Paddy, rice, maize, sorghum
Granary weevil	Coleoptera; Bostrichidae	Rice, wheat, maize
Rice weevil	Coleoptera; Curculionidae	Rice, maize, wheat
Maize weevil		Maize, also other cereals
Angoumois grain moth		Paddy, wheat, maize
Red flour beetle	Lepidoptera; Gelechiidae	All cereals, starch, pulses
Confused flour beetle	Coleoptera; Tenebrionidae	Flour, wheat, maize
Khapra beetle		All cereals

Microorganisms: Microbial invasion is one of the main causes of quality deterioration in maize [4,20,128-130]. In particular, fungal contamination, fungal infestation of stored maize can lead to heat generation, mold production, and increased susceptibility of maize kernels to breakage [131]. Heat treatments such as roasting using temperatures above 150°C during grain storage can reduce mycotoxin levels [132-134]. However, despite treatment with high temperatures or other means, the fungal damage to grain can only be suppressed, not eliminated [135]. The reason is that, on the one hand, microorganisms can be transmitted and infected to grain through various media such as air, dust, rodents, insects and mites, tools and so on [136]; on the other hand, microorganisms have a significant characteristic of fast growth and reproduction [137]. In the grain storage environment, the respiration of the grain itself and the activity of bacteria release large amounts of heat and moisture [138-140], which provide conditions for pests to survive; pests destroy intact grain kernels, making the starch of the corn kernel as well as other internal constituents more accessible to microorganisms, and also increasing the risk of microbial infection [4,15,16]. On the other hand, a variety of pests themselves carry microorganisms [141,142] and act as carriers to transport them to the site of infection [143]. Bio fragmentation of grain particles in storage silos is essentially caused by the interaction and interaction of various organisms for survival activities in an unfavorable storage environment.

CORN BREAKAGE HARM

Changing the Stacking Characteristics

Corn is a typical bulk agricultural material. It participates in commercial trade, processing and storage on the scale of grain pile. When corn grains are broken, the appearance of broken grains will change the physical properties (unit weight, porosity, angle of repose) of corn grain pile [144-148]. The unit weight value is the reference basis for calculating the pressure exerted on the wall of the silo or bulk silo by the corn stored in the silo. The angle of repose is a basic parameter to determine the flow characteristics of corn storage and processing, which affects the layout of hoppers, pipes, covered silos, ventilation process and the design of air flow distribution [146]. Porosity will affect the heat and mass transfer rate during aeration and drying. The appearance of broken kernels will reduce the porosity of corn and increase the angle of repose. The increase of angle of repose will increase the rolling friction coefficient of corn kernels, directly affect the feeding rate, and change the stacking characteristics of corn kernels, which is directly related to the storage quality of corn kernels and the pressure distribution at the bottom of the warehouse [149]. In addition, broken grains will fill the grain gap, resulting in an increase in bulk density [144], the stress borne by the warehouse wall from the grain pile is increased, which increases the storage risk. Similarly, the decrease of porosity will lead to the change of grain bulk density [150], In turn, it will cause changes in the pressure distribution at the bottom of the grain pile, and increase the stress value of corn grains at the bottom [151], the possibility of crushing grains at the bottom will also increase. In storage, the change of grain storage environment is affected by temperature, humidity, self pressure and other factors [11,12].

Accelerate Segregation

Corn is a non-homogeneous aggregation of grain kernels, and the different collision forces, gravity and air resistance between broken and intact kernels during binning can cause the redistribution of corn grain pile components, resulting in the formation of segregation phenomena [152]. The segregation phenomenon leads to redistribution of intact and broken kernels in the spatial location, which biases the aggregation of large and small kernels, respectively, within the corn [153]. The aggregation of broken kernels will lead to uneven airflow in the bulk grain pile, and corn in low airflow locations will not be cooled or dried, resulting in high moisture and temperature in some areas, making it more susceptible to pests and molds. On the other hand, the segregation phenomenon also reduces the porosity of the grain pile and affects the ventilation effect [154,155]. A large number of studies on grain segregation phenomenon have been carried out at home and abroad, and some scholars have investigated the occurrence mechanism of segregation phenomenon during binning from the perspective of kinetics [156]. Broken corn kernels are captured by the larger pores between the kernels in the process of sliding along the surface of the grain pile, so that the concentration of broken kernels near the vicinity of the unloading opening directly underneath is higher, while the larger intact kernels slide farther away, and the final result is that the broken corn kernels are concentrated in the center area, while the intact corn kernels are distributed in the surrounding area. As the drop height increases, the more severe the phenomenon of automatic grading of grain kernels becomes [157]. It has also been found that when corn falls through the discharge opening, collision occurs, and after the impact of large and small kernels, the initial horizontal velocity obtained by the large mass corn kernel and the small mass corn kernel are different, which produces segregation phenomenon [158]. Different mechanisms of particle grading during grain bin entry have been investigated, including agglomeration, airflow, chipping, rebound, displacement, embedding, fluidization, impact, penetration, push-off, rolling, sieving, sliding, and trajectory [159-164]. However, according to this review, although researchers have derived general laws of seed segregation through experimentation and analysis, there are fewer specific models that can predictably describe the segregation behavior.

Downgrade

Corn trade is an important part of international agricultural trade, and the trade value of corn is measured by the grades assigned by countries. Corn kernels are friable compared to other grain kernels [55], and broken corn kernels are an unfavorable factor for grade classification in corn trade. Different countries have different definitions for the brokenness of corn kernels, as shown in (Table 3), and the definition of brokenness of corn kernels in China is the percentage of kernels that are less than four-fifths of the average length of intact corn kernels in the kernel specimen. In China's corn quality standards, the rate of broken kernels is taken as one of the important factors for grade classification, and corn is divided into five grades, in which the first-grade to the fifth-grade corn has to satisfy the rate of damage kernels, respectively less than or equal to 4%, 6%, 8%, 10%, and 15%. The United States in the corn grading standards set five levels, the same, broken rate is also regarded as an important index of corn grading, first to fifth grade corn were required to damaged grain rate shall not be higher than 3%, 5%, 7%, 10%, 15%, broken grain rate shall not exceed 3%, 5%, 7%, 10%, 15%. The Canadian Grain Commission divides corn into five grades, and the rate of damaged grains in these five grades must not exceed 3%, 5%, 7%, 10%, 15%, and the rate of broken grains must not exceed 2%, 3%, 5%, 7%, and 12%, respectively.

CONCLUSION

This paper reviews the types of breakage, causes of breakage, factors affecting breakage, hazards of breakage, and models used to predict breakage that occur in the post-production process of

Table 3: Breakage rate requirements for maize grading in three countries.

Country		Grading parameters		
U.S. Grade Number		**Heat-Damaged Kernels (%)**	**Damaged Kernels Total (%)**	**Broken Corn and Foreign Material (%)**
1		0.1	3.0	2.0
2		0.2	5.0	3.0
3		0.5	7.0	4.0
4		1.0	10.0	5.0
5		3.0	15.0	7.0
Canada Grade Number	**Density (g/l)**	**Heat-Damaged Kernels (%)**	**Damaged Kernels Total (%)**	**Broken Corn and Foreign Material (%)**
1	688	0.1	3.0	2.0
2	666	0.2	5.0	3.0
3	644	0.5	7.0	5.0
4	622	1.0	10.0	7.0
5	580	3.0	15.0	12.0
China Grade Number	**Density (g/l)**	**Mildew grain (%)**	**Damaged Kernels Total (%)**	
1	720	2.0	4.0	
2	690		6.0	
3	660		8.0	
4	630		10.0	
5	600		15.0	

corn. Most of the research on corn post-production mitigation has dealt with losses due to corn kernel shattering, and a variety of factors contribute to the occurrence of shattering from the beginning of corn harvest. Mechanical harvesting is the link where most of the crushing occurs, and there are many related studies, especially on damage reduction by agricultural equipment; in the subsequent link, drying induces breakage, which is essentially due to the reduction of breakage sensitivity resulting in the kernels being more susceptible to breakage, and the breakage of corn kernels is more difficult to observe in this link, and the change of critical stress value of corn kernels is usually used for predicting the likelihood of breakage; the breakage of corn kernels during the warehousing link, which can be used for prediction; and the breakage of corn kernels during the storage link, which can be used for prediction. The breakage of corn kernels in the binning process can be attributed to collision and extrusion, which is easy to observe, and the mechanism of breakage is related to dynamics and kinematics, which is a more complicated factor to be considered in the related research. To summarize the different mechanisms of corn kernel breakage in each link, all of them are closely related to the moisture content. High moisture content of corn in the mechanical harvesting period will increase the breakage rate; low moisture content of corn in the drying period will make the corn kernel more brittle and reduce the sensitivity to breakage.

To solve the problem of corn kernel breakage, it is necessary to start from each link. Mechanical harvest breakage problem should focus on the two main factors leading to mechanical harvest breakage, on the one hand, to strengthen the professional quality training of operators, research and development of more simple operation, more powerful agricultural equipment; on the other hand, to reasonably formulate the harvesting plan, to ensure that the corn is in the harvest under the safe moisture content. The solution to the problem of drying-induced corn kernel breakage is more inclined to the use of new drying technology, reduce the drying time of corn kernels to reduce the possibility of damage to the internal structure of corn kernels, and at the same time to control the moisture content of corn kernels at an appropriate level to reduce the risk of over-drying and breakage of corn kernels. For the problem of broken corn in the warehouse, it is necessary to optimize the operation line of corn in the warehouse, reduce the number of equipment transfer, reduce the possibility of collision and extrusion of corn kernels and mechanical equipment; it is also necessary to carry out a reasonable operation of the warehouse, avoiding the empty warehouse into the grain, increasing the curvature of the corner of the skidding pipe, reasonable design of the unloading device, and comprehensively consider the difference in the height of the fall of corn kernels in different warehouses, and as far as possible reduce the horizontal initial velocity of the fall of the corn kernels. The initial horizontal speed of the falling corn kernels is minimized as much as possible. In the whole corn processing link, corn moisture content has been throughout, is to determine the corn in different parts of the processing can guarantee the quality of important factors, but also to determine whether the corn can meet the important parameters, make a proper detection of moisture content on the corn in all aspects of the quality of an important significance.

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