Grain kernel damage during threshing: a comprehensive review of theories and models

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Abstract

Grain threshing is aimed at separating the grain from the inedible chaff. However, mechanical forces often damage grains, impacting their quality, market value, and germination ability. This comprehensive review examines theories and models developed to study and predict grain damage during threshing. These include contact theory, fracture mechanics models, discrete element modeling, and finite element analysis. This review delves into how these theories elucidate the influence of grain characteristics, such as moisture content and kernel size, on susceptibility to damage. It assesses how different machine parameters like threshing speed drum design and concave settings contribute to damage such as breakage, fissures, and internal cracks. We delve deeply into utilizing contact theory to estimate stress distribution when metal grains collide, employing fracture mechanics to understand crack initiation and propagation, and utilizing DEM and FEA to simulate how grains move within the thresher. By synthesizing knowledge from these modeling approaches, this review offers an understanding of the multifaceted nature of grain damage during threshing. They emphasize the significance of tuning settings and implementing suitable pre and post-threshing techniques to reduce waste and maintain top-notch grain quality for eating and seeding. This in-depth evaluation offers insights for scientists, engineers, and farming experts dedicated to enhancing the productivity and eco-friendliness of grain cultivation methods.

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Introduction

Grain threshing, the process of separating the edible part of cereal crops from the inedible chaff, is a critical step in post-harvest operations that can significantly impact the overall quality and yield of the harvested grain (Li and Thomas, 2014). Excessive mechanical damage to grains during the threshing process can lead to significant losses in the form of reduced grain quality, decreased germination rates, and diminished market value (Bucklin *et al*., 2013; Yasothai, 2020). In addition to the direct economic impact, grain damage can have far-reaching implications for food security and sustainability, affecting the harvested crop's availability, nutritional content, and storability.

To mitigate these challenges, researchers have developed a range of theories and models aimed at understanding the complex factors that contribute to grain damage during threshing and identifying effective strategies for minimizing such damage (Bucklin *et al*., 2013; Kroupa, 2003; Yasothai, 2020). Breakage of paddy grains poses a significant challenge within the rice sector, diminishing rice quality and market value. Grains often undergo damage from physical pressures during the threshing process. This damage reduces the number of whole grains available, which command higher prices and are preferred by consumers, simultaneously escalating processing expenditures and generating additional waste. To address these challenges, researchers have dedicated considerable effort to understanding and mitigating grain damage during threshing. This review provides a comprehensive overview of the various theories and models developed to explain and predict the occurrence of such damage. This review aims to provide a holistic understanding of the factors influencing grain damage by delving into the underlying physical, mechanical, and physiological principles. Furthermore, it examines the influence of external factors such as thresher design, operating parameters, and variations in grain characteristics. A thorough understanding of these aspects is crucial for developing effective strategies to minimize grain damage during threshing, leading to improved grain quality, reduced economic losses, and enhanced global food security.

Factors affecting grain damage

Grain damage can occur due to various factors, including the characteristics of the grains, machinery-related aspects, and mechanical factors, such as the speed of the cylinder, material feed rate, nip angle, and moisture levels. This article delves into how rice grains are affected by impact damage during threshing. Impact damage contributes to grain breakage during harvesting and handling processes (Chen *et al*., 2020). The extent of impact damage is mainly influenced by factors such as impact velocity, core alignment, angle of impact, and the surface involved.

Grain properties

Grains are the fundamental components of many agricultural products, and their physical characteristics, such as hardness, brittleness, and moisture content, play a crucial role in determining their quality, shelf life, and processing requirements. Theoretical models have been developed to understand and predict these properties, which are essential for efficient grain handling, storage, and utilization.

Hardness

Grain hardness measures the grain kernel's resistance to deformation or breakage (Yasothai, 2020). It is influenced by chemical composition, microstructure, and grain moisture content (Chaturvedi *et al*., 2020). Theoretical models for grain hardness often incorporate the concept of fracture mechanics, where the grain is treated as a brittle material that fails under applied stress (Chaturvedi *et al*., 2020). These models can predict the force required to rupture or break the grain, an essential parameter in dehulling machines and other processing equipment designs. In addition to mechanical properties, grain hardness is crucial in determining the quality and shelf life of various food products made from grains. Understanding the factors that influence grain hardness can help optimize processing techniques and ensure the desired characteristics in the final product. Researchers continue to study and refine theoretical models for grain hardness to enhance the efficiency and performance of grain processing technologies.

Brittleness

Grain brittleness, on the other hand, refers to the tendency of the grain to break or shatter into smaller pieces during handling and processing. Theoretical models for grain brittleness typically consider the internal structure of the grain, including the arrangement and strength of the cellulose fibers and the distribution of starch granules. These models can predict the likelihood of grain breakage and the size distribution of the resulting fragments, which is crucial for maintaining product quality and consistency (Bucklin *et al*., 2013; Mohammadi Shad and Atungulu, 2019). Grain brittleness is a complex and multifaceted property that can impact the overall quality of grains and grain-based products. Factors such as moisture content, temperature, and the presence of foreign materials can all influence the brittleness of grains. Understanding and controlling grain brittleness is essential for ensuring product integrity and minimizing waste in the food processing industry. By employing advanced modeling techniques and rigorous testing protocols, researchers and industry professionals can gain valuable insights into the factors contributing to grain brittleness and develop strategies to mitigate its adverse effects.

Grain moisture content

Moisture content is a critical parameter in the storage and handling of grains, as it directly affects the grain's susceptibility to spoilage, insect infestation, and other quality-degrading factors. Theoretical models for moisture content often incorporate the principles of thermodynamics and diffusion and can be used to predict the equilibrium moisture content of the grain under different environmental conditions, such as temperature and relative humidity (Batey, 2010; Bucklin *et al*., 2013; Chaturvedi *et al*., 2020; Fleurat-Lessard, 2016; Khan *et al*., 2017; Mohammadi Shad and Atungulu, 2019). Moisture content is one of the most critical grain-related factors affecting the extent of grain damage. The mechanical properties of grains, such as fracture toughness, elastic modulus, and brittleness, are closely related to moisture content (Chen *et al*., 2020). Studies have shown that cracking susceptibility first decreases with increasing grain moisture content and then increases above a specific moisture content (Looh *et al*., 2020). Low-moisture grains are more likely to break because they are more brittle, less elastic, and have lower fracture energy than higher-moisture grains (Chen *et al*., 2020).

The moisture content affects the mechanical properties of the grain, making it more susceptible to damage. Studies have been conducted to depict the effect of moisture content on barley and paddy grain damage during threshing operations. Results showed that grain moisture content affects stress distribution within the grain, with higher moisture content leading to increased stress concentrations and more significant grain damage (Ghasemi-Varnamkhasti *et al*., 2020; Looh *et al*., 2020). The moisture content of the grain is also a key factor influencing the extent of grain damage during threshing. Similarly, some researchers investigated the influence of moisture content on wheat grain damage during threshing (Chen, 2020). They found that overly dry or wet grain resulted in higher grain damage. The type of crop and type of grain can also influence the mechanism of grain damage during threshing. Another study investigated the influence of different threshing mechanisms on the quality of wheat and rice grains and found that the axial-flow rotor mechanism resulted in less grain damage in wheat than the tangential-flow rotor mechanism, while the opposite was true for rice (Gan *et al*., 2021). By understanding and applying these theoretical models, researchers and practitioners can develop more effective strategies for managing grains' physical properties, leading to improved quality, reduced waste, and enhanced efficiency in the agricultural industry.

Threshing mechanism design and operational parameters

Threshing mechanism design

The design of the threshing mechanism can also influence the extent of grain damage. A study by some researchers investigated the effect of different threshing mechanisms on wheat grain damage (Alotaibi *et al*., 2020). They found that the axial-flow rotor threshing mechanism resulted in less grain damage than the tangential-flow rotor threshing mechanism. The type of threshing unit in the combine harvester also influences grain damage. Compared to conventional combines, the cylinder speed is lower, and the concave spacing is more prominent in rotary combines, resulting in a lower percentage of damaged grain (Srivastava, 2006). In addition to machine parameters, other factors influencing grain damage include grain dwell time within the hull and orientation of the corn cobs during hulling. A longer dwell time in the firing crescent results in more significant impacts and longer reload times. The damage level increases almost linearly as the grains move further along the concavity. Figure 1 shows a simple illustration of the different threshing mechanisms.

Operation parameters

A study by Alotaibi *et al*. (2020) investigated the effect of different threshing parameters on wheat grain damage. They found that higher cylinder speed and concave spacing increased grain damage. According to Looh *et al*. (2020), cylinder speed significantly impacts grain damage. They observed that as cylinder speed increased from 697 to 1202 rpm, the broken grain fraction increased significantly from 0.0384% to 3.4052%. This can be attributed to the collision energy between grains and threshing rods increasing as the cylinder speed increases. The seeds were loaded with greater force and higher impact forces exerted on the crop during threshing at higher cylinder speeds (Greffeuille *et al*., 2007; Shirmohammadi and Charrault, 2018; Voicu *et al*., 2013).

Mechanical factors

Grain impact velocity

Grain impact velocity is a crucial parameter that significantly influences the degree of grain damage during the harvesting and post-harvest processing stages. Extensive research has been conducted to understand the relationship between impact velocity and damage levels for various grain species (Kumar and Kalita, 2017; Xie *et al*., 2020).

The type of threshing unit (conventional or rotary), drum speed, and conveyor speed are machine parameters that directly affect the grain impact velocity (Xie *et al*., 2020). Grains impacting at higher speeds are subjected to more significant shock loads, resulting in greater damage. Numerous empirical relationships have been established to correlate impact velocity and damage level for different grain species through single-grain impact experiments (Dobrzaski and Stpniewski, 2013; Liu and Yang, 2003; Xie *et al*., 2020).

For corn and soybeans, studies have shown that the impact damage becomes substantial when the impact speed exceeds 10 m/s (Dobrzaski and Stpniewski, 2013; Xie *et al*., 2020). Similarly, in the case of kidney beans, the proportion of damaged beans increased from 0. 17% to 32.88% as the impact speed increased from 5 to 15 m/s. Consequently, a commonly used method to reduce harvesting and post-harvest damage is to minimize the impact velocity of the grains. Therefore, a commonly used method to reduce harvesting and handling damage is to reduce the equipment's operating speed or feed rate; however, the capacity of the devices is also reduced. In practice, trial and error must find an operating condition that maximizes capacity and minimizes grain damage. Assume that the damage a grain sustains is directly proportional to its kinetic energy upon impact. Kinetic energy *(KE)* is given by Equation 1.

$$KE = \frac{1}{2}mv^2 \quad \text{(Eq. 1)}$$

where *KE* is kinetic energy; *m* is the mass of the grain; *v* is the impact velocity of the grain. If we assume that the mass of the grain remains constant, we can simplify the equation to $KE \propto v^2$.

This relation shows that kinetic energy is proportional to the square of the collision speed. Therefore, the higher the grain impact speed, the higher the kinetic energy and the higher the chances of grain damage occurring.

Angle of impact

The angle of impact, which refers to the angle between the direction of grain movement and the impact surface, is crucial in determining the extent of damage sustained by grains during handling and processing (Chen *et al*., 2020). Keller *et al*. (1972) reported that reducing the impact angle from 90 degrees to 45 degrees resulted in a 25% reduction in core damage when the grains impacted steel and urethane surfaces. However, the reduction was less pronounced for concrete surfaces (Baryeh, 2003). The effect of grain orientation on damage also varies by grain type, as grains' shape, structure, and composition differ across varieties. For example, soybeans experienced a reduction in kernel germination rate when impacted on the radicle, while cotyledon impact resulted in only minor damage (Keller *et al*., 1972; Jindal *et al*., 1979).

A semi-logarithmic relationship has been observed between the decrease in grain damage rate and the grain impact velocity (Baryeh, 2003). This suggests that higher impact velocities lead to disproportionate damage, emphasizing the importance of control-

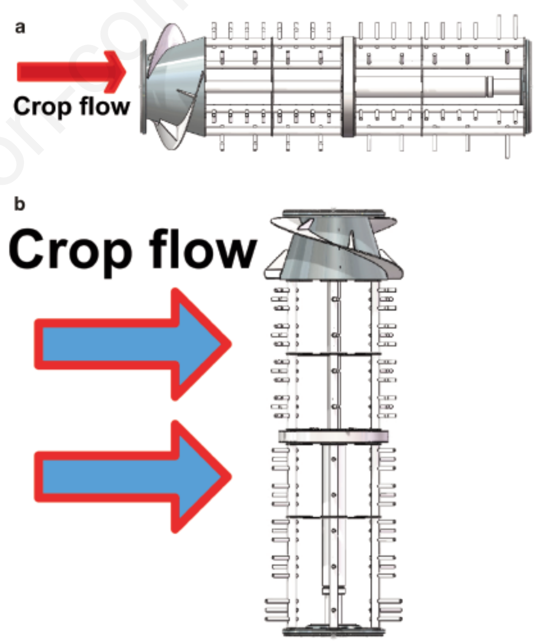

Figure 1. Illustration of material flow in two threshing mechanisms, where (**a**) is the axial flow and (**b**) is the tangential flow threshing mechanism

ling impact angles and velocities in grain handling processes.

Consider a simplified scenario where a grain impacts a surface at an angle. We will assume that the damage is directly proportional to the component of the impact velocity perpendicular to the surface. The kinetic energy of the grain can be divided into two components: one parallel to the surface ($KE_{\parallel}$)and one perpendicular to the surface ($KE_{\perp}$). The component of kinetic energy perpendicular to the surface is given by:

$$KE_{\perp} = \frac{1}{2}mv^2 \sin^2(\theta) \quad \text{(Eq. 2)}$$

where $KE_{\perp}$ is the kinetic energy component perpendicular to the surface; m is the mass of the grain; v is the impact velocity of the grain; θ is the angle of impact to the surface.

Eq. (2) shows that the component of kinetic energy perpendicular to the surface is proportional to the square of the grain impact velocity (v^2) and the square of the sine of the impact angle *($sin^2(\theta)$)*. Therefore, the angle of impact influences grain damage in the sense that the greater the angle *(θ)* between the grain trajectory and the surface normal, the smaller the perpendicular component of the kinetic energy *($KE_{\perp}$)*, and thus the possibility of grain damage also reduces. In this simplified model, factors such as grain properties, impact surface characteristics, and the interaction between the grain and the surface, which contribute to the overall outcome of grain damage, have not been considered.

Contact surface

Grain handling and processing can cause significant physical damage to the grains, affecting the product's overall quality and market value. One crucial factor that influences the extent of grain kernel damage is the type of contact surface during grain impacts. Previous studies have found that the material properties of the contact surface play a crucial role in determining the degree of damage sustained by the grains (Chen, 2020).

Specifically, impact tests have shown that grains striking a concrete surface experience more damage than grains striking a steel surface, and grain-on-grain impacts caused less damage than concrete or steel surfaces (Keller *et al*., 1972). These results indicate that grains impacting rougher and less resilient surfaces, such as concrete, suffer more damage than smoother and more elastic surfaces like steel.

The increased damage observed on rougher surfaces can be attributed to the higher stresses and greater stress concentrations generated at the grain-surface interface. For example, a study on micro-pitting and wear of rolling bearing steels found that the rougher surface underwent only mild wear, while the smoother surface experienced more severe damage modes like fatigue and plastic deformation. Similarly, studies on high-velocity grain impacts have shown that kernel damage is significantly influenced by the type of impact surface, with concrete causing more damage than steel or grain-on-grain impacts (Keller *et al*., 1972).

Understanding the mechanisms behind grain kernel damage due to contact surface properties is crucial for designing and optimizing grain handling processes to minimize quality losses. Predictive models that can account for the effects of impact surface properties would be valuable tools for the grain industry to assess and mitigate potential sources of kernel damage.

Let us consider a simplified scenario where a grain is being threshed against a surface, and the damage is related to the force exerted during the process. Let us assume that the amount of grain damage is proportional to the force applied to the grain during threshing. The force *(F)* can be expressed in terms of the pressure *(P)* exerted on the grain and the area *(A)* of contact: $F = P \times A$.

Where F is the force applied to the grain, P is the pressure exerted on the grain, and A is the contact area between the grain and the surface.

Let us consider the pressure *(P)* as the force applied per unit area: $P = \frac{F}{A}$. Assuming that the pressure is directly proportional to the grain damage, then we can obtain: *Damage* $\propto P$. Substituting the expression for pressure *P,* we obtain $\propto \frac{F}{A}$.

Since $F = P \times A$, we can substitute F back into the equation for damage as shown; *Damage* $\propto \frac{P \times A}{A}$. This simplifies to *Damage* $\propto P$.

This clearly shows that paddy grain damage is directly proportional to the pressure exerted during threshing. This model concludes that the contact surface affects grain damage through the contact area *(A)*. A larger contact area would spread the force over a larger area, potentially reducing pressure and minimizing damage. Conversely, a smaller contact area can cause more pressure and increase grain damage. In real-world scenarios, threshing processes involve various other factors, including grain properties, surface characteristics, and the dynamics of the threshing mechanism.

Mechanisms of grain damage

During the threshing process, which is a crucial step in separating the grain crops from their stalks or husks, different forces are exerted on the grains. These forces are crucial in separating the kernels from the rest of the plant matter. However, if these forces are not adequately controlled, they can also cause damage to the grains. The mechanisms of grain damage can be divided into three main force categories: impact and compression, shear and tensile forces, and abrasion and wear.

Impact and compression forces

The mechanical properties of grain kernels play a crucial role in the efficiency and quality of post-harvest processing operations, such as milling, hulling, and shelling (Greffeuille *et al*., 2007; Shirmohammadi and Charrault, 2018; Voicu *et al*., 2013). Understanding the theoretical implications of the forces acting on kernels during these processes is essential for optimizing equipment design and operating parameters. Grain kernels are subjected to various mechanical forces during processing, including compression, shearing, crushing, cutting, friction, and collision (Onwe *et al*., 2020; Shirmohammadi and Charrault, 2018; Voicu *et al*., 2013). These forces can have significant impacts on the physical and mechanical properties of the kernels, affecting their susceptibility to damage and the overall quality of the final product.

The moisture content of the kernels is a critical factor that influences their mechanical response to these forces. At lower moisture levels, kernels tend to be more brittle and prone to cracking or shattering under compression and impact. Conversely, higher moisture content can increase the pliability of the kernels, reducing the risk of mechanical damage but potentially affecting other processing characteristics (Onwe *et al*., 2020; Shirmohammadi and Charrault, 2018; Voicu *et al*., 2013). The design and operation of milling equipment play a critical role in determining the types and magnitudes of forces experienced by the grain kernels. For example, in industrial mills, the grinding process is driven by a combination of compression, shearing, and impact forces, which can result in the fragmentation of the kernels into a range of particle sizes and shapes. Similarly, in almond hulling and shelling operations, continuous compression and shear forces break the hull and shell layers and release the kernel (Shirmohammadi and Charrault, 2018). Careful consideration of the theoretical implications of these forces is essential for optimizing the mechanical processing of grain kernels. By understanding the relationships between kernel properties, moisture content, and the applied forces, researchers and engineers can develop more efficient and effective processing technologies that minimize kernel damage and maximize the quality of the final product (Onwe *et al*., 2020; Shirmohammadi and Charrault, 2018; Vishwakarma *et al*., 2018; Voicu *et al*., 2013).

Impact forces during threshing are essential for separating grains from plant matter, but excessive or uncontrolled impact can damage the kernels. This damage, characterized by cracks, splintering, or shattering, can occur at various stages, including harvest, transport, and processing when grains collide with other grains, threshing components (*e.g*., rotating knives, beaters), and other hard surfaces. Research has shown that the extent of impact damage correlates with impact speed and grain moisture content (Chen *et al*., 2020). For instance, a study on wheat found that drier grains were more susceptible to damage at higher impact speeds (Chen *et al*., 2020). Even after threshing, grain handling during separation and cleaning using oscillating screens or sieves can also inflict impact damage. The severity of this damage is determined by factors like the grain's speed and mass, as well as the nature of the impact surface. In a study of wheat impact damage, researchers found that grain damage increased with increasing impact speed and that the extent of damage depended on the moisture content of the grain.

The amount of impact damage a grain suffers depends on the speed and mass of the grain, as well as the surface over which the impact occurs. The kinetic energy of a grain can be deduced from Eq. 1. Xu *et al*. (2008) presented a theoretical analysis and finite element simulation of the impact damage caused by a threshing tooth on a grain of rice. Their study created models for the compression displacement, the maximum pressure distribution, and the critical velocity formula for impact damage.

Threshing involves the application of pressure to separate grain from its husk or straw. However, excessive compression during this process can damage grain, impacting quality and yield. For instance, the crop is compressed between a rotating cylinder and a concave in a combine harvester. While this force is essential for separation, excessive pressure within this compaction zone can deform or crush the grains. Compression damage can also occur during storage, transportation, and processing. The weight of the grain itself, especially in overloaded storage bins or transport containers, can cause deformation. Similarly, conveying grain through equipment like rollers and crushers can exert damaging pressure. This damage manifests as cracks and fissures in the grain structure, ultimately affecting its quality and reducing usable yield (Bian *et al*., 2015). The pressure determines the extent of damage applied, calculated as force (F) divided by the area (A) over which the force is distributed ($P=F/A$). Therefore, minimizing compression damage hinges on utilizing equipment designed for gentle handling, avoiding overloading, and optimizing machine settings to regulate the pressure exerted on the grain (Bucklin *et al*., 2013).

Shear and tensile forces

Grain detachment and damage in agricultural processing are critical concerns, as they can significantly impact product quality and yield (Khan *et al*., 2017; Mima and Oka, 1967; Mohammadi Shad and Atungulu, 2019). Understanding the role of shear forces and tensile stress in these processes is essential for designing effective grain handling and storage systems.

Shear forces play a crucial role in grain detachment, as they can cause grains to slip over one another along their interfaces (Liu and Shi, 2019). This phenomenon is particularly relevant in coarse-grained soils, where the typical failure mode is the loss of stability due to shear along the particle interfaces. Similarly, in grinding cereal seeds, such as wheat, the mechanical action of shear forces, along with compression, crushing, and friction, can lead to dividing grain particles into smaller fragments. Shear forces are also important in various industrial processes, such as milling, cutting, and mixing, where the manipulation of solid particles relies on applying these forces. Understanding the role of shear forces in grain detachment is essential for improving processes related to agricultural production, food processing, and soil mechanics. Consequently, research efforts focus on a better comprehension of shear forces and their impact on grain behavior.

In contrast to shear forces, tensile stress is less prevalent in granular materials like grains, as they are typically not subjected to significant tensile loading. However, tensile stress can still affect grain integrity, particularly during handling, transportation, and storage. To maintain grain quality and minimize detachment and damage, designing grain storage systems and handling equipment that can effectively manage the shear and tensile forces acting on the grains is crucial. This may involve optimizing the design of storage structures, such as silos and bins, to minimize the buildup of shear stresses, as well as the design of transportation and conveying systems to reduce the impact of shear and tensile loads on the grains (Bucklin *et al*., 2013; Khan *et al*., 2017; Voicu *et al*., 2013). Additionally, understanding the physical properties of grains, such as bulk density, particle density, and angle of repose, can aid in designing effective grain handling and storage systems. These properties can influence the behavior of grains under different loading conditions and should be considered when designing grain processing and storage equipment (Khan *et al*., 2017). Furthermore, proper knowledge of these physical properties can help prevent spoilage, clogging, and uneven distribution of grains during transportation and storage. Engineers can optimize equipment design to ensure smooth and efficient grain handling by understanding how grains interact with different surfaces and containers. This ultimately leads to improved productivity and overall operational efficiency in grain storage facilities. In addition, having a thorough understanding of grain's physical properties allows for developing innovative solutions to common challenges faced in the grain industry. By incorporating this knowledge into the design process, engineers can create systems that minimize waste, reduce energy consumption, and increase the overall profitability of grain storage operations. This emphasis on efficiency and sustainability is critical to ensuring the long-term success of grain handling facilities in a competitive market. Some threshing mechanisms utilize shear forces to separate grain from plant material. For example, the crop is pressed against a rotating cylinder fitted with rasps or teeth in a rasp bar cylinder system, effectively shearing the kernels away. However, these mechanisms can nick or damage the grain if not correctly adjusted. Shear damage occurs when a force parallel to the grain's surface causes it to slide or twist. This can occur during threshing, handling, and processing when grain is conveyed through equipment like augers and conveyors. Research has shown that shear damage can negatively impact grain quality. Minimizing shear damage requires using equipment designed for gentle handling, avoiding overloading conveyors and processing equipment, and optimizing the threshing mechanism. In the threshing mechanism, the rotor or cylinder and the concave plate create shear forces on the grain which can result in shear damage. The degree of shear damage depends on the shear stress and shear rate. Shear stress *(τ)* is calculated as the force applied *(F)* divided by the area over which it is distributed *(A)*: $\tau = F/A$. The shear rate *(γ)* is calculated as the velocity of the grain *(v)* divided by the distance over which the shear occurs *(x)*: $\gamma = v/x$. By carefully controlling these factors, grain damage during threshing and subsequent handling can be minimized.

Abrasion and wear

Grain processing and preparation for human consumption involves several stages, including threshing, which separates the grain from the plant material. During threshing, grains are subjected to various mechanical forces such as compression, shearing, crushing, cutting, friction, and collision, leading to abrasion and wear on the grain surfaces. The degree of abrasion and wear experienced by the grains depends on factors such as the threshing equipment's design, the grain's properties, and the operating conditions (Kumar Korram *et al*., 2018; Voicu *et al*., 2013).

The mechanical properties of the grain, such as its hardness, pliability, and moisture content, play a crucial role in determining the extent of abrasion and wear. Grains with higher moisture content tend to be more pliable and less susceptible to mechanical damage, while drier grains are more prone to abrasion and cracking. The amylose content of rice, for example, is associated with its textural attributes, such as hardness and stickiness, which can impact the grain's response to mechanical forces during processing. Rheological studies on cooked rice have also revealed insights into the viscous and elastic properties of the grain, which can further inform our understanding of its mechanical behavior.

In addition to the grain's intrinsic properties, the threshing equipment's design and operation can significantly influence the degree of abrasion and wear. The forces applied to the grain, such as compression, shearing, and friction, depend on the threshing mechanism's specific design and configuration. Grinding studies on cereal grains have shown that the nature and intensity of these mechanical forces can vary depending on the mill design, leading to differences in the resulting particle size distribution and shape (Voicu *et al*., 2013).

Understanding the theoretical perspectives on abrasion and wear mechanisms during threshing is crucial for optimizing grain processing technologies and improving the quality and recovery of the final product.

Friction plays a crucial role in threshing as it facilitates the separation of grain from plant matter. As the crop moves against the threshing elements, frictional forces help separate the grain. However, excessive friction can generate heat that causes the grains to burn or scar. Attrition can also occur, such as roughening or scratching the surface of the grains. Abrasion damage occurs when grains rub against each other or hard surfaces, such as the walls of storage tanks or processing equipment. This can result in the outer layer of the grain being removed, resulting in a loss of quality. To minimize abrasion damage, using equipment that reduces friction and avoids overloading storage containers is essential. As grain passes through the threshing unit, it rubs against various surfaces, which can cause abrasion damage. The degree of abrasion damage a grain suffers depends on the frictional force and the surface the grain rubs against. The following equation can be used to calculate the friction force: $Ff = \mu Ff$, where Ff is the force of friction, μ is the coefficient of friction, and Fn is the normal force. Overall, these equations help to provide a quantitative understanding of the mechanics of grain damage and can be used to optimize processing and handling techniques to minimize damage. In summary, the mechanics of grain damage can occur in different ways, including compression, impact, shear, and abrasion. The damage can result in reduced grain quality, lower crop yields, and economic losses.

Theoretical framework and types of grain damage

Theoretical framework

Mechanistic models

One of the critical theories in grain damage during threshing is the concept of "stress-strain" relationships, which describes the mechanical behavior of grains under the application of external forces (Kroupa, 2003). These models suggest that the extent of grain damage is directly related to the magnitude and distribution of stresses and strains experienced by the grain during the threshing process. For instance, studies have shown that the friction between the grain and the threshing components, as well as the impact forces experienced by the grain, can lead to the creation of microfractures and the weakening of the grain structure (Eyshi Rezaei *et al*., 2015; Yasothai, 2020). Furthermore, the orientation and velocity of the grain during threshing can also influence the distribution of these stresses and strains and, hence, the likelihood of grain damage. Another critical theory in this field is the concept of "energy dissipation," which examines the relationship between the energy input into the threshing system and the resulting grain damage (Kroupa, 2003). These models suggest that the efficiency of energy transfer during the threshing process is a critical factor in determining the extent of grain damage, as inefficient energy transfer can lead to the generation of excessive heat and localized high-stress zones that can compromise the grain structure (Eyshi Rezaei *et al*., 2015; Shirmohammadi and Charrault, 2018).

The theories and models highlighted above have provided valuable insights for developing strategies to minimize grain damage during threshing. These strategies include optimizing thresher design, using gentler grain handling techniques, and creating new technologies that utilize alternative mechanisms such as air-flow-based separation or ultrasonic vibration (Kroupa, 2003; Li and Thomas, 2014). Additionally, integrating advanced sensors and real-time monitoring systems has emerged as a promising approach for detecting and reducing grain damage during threshing operations.

The energy dissipation critical theory

Energy dissipation plays a crucial role in understanding the fracture mechanics and the conditions leading to breakage. The energy dissipation process during the impact of rice kernels can be discussed through various approaches:

Energy absorption and dissipation during impact. When a rice kernel is subjected to an impact, the kinetic energy from the impacting object (such as a mechanical component) is transferred to the kernel. This energy causes deformation of the kernel, which can either be elastic (temporary deformation) or plastic (permanent deformation), depending on the impact velocity and the properties of the rice kernel. The energy transferred during impact is dissipated in several ways; Internal friction within the material, elastic deformation, where part of the energy is stored and then released after impact (non-destructive impact), plastic deformation and crack propagation, where energy is consumed in creating new fracture surfaces and in permanent structural damage to the rice kernel and heat generation, where some of the energy is dissipated as heat due to internal material friction. At low velocities, the energy dissipated is insufficient to cause substantial damage, leading only to surface wear or minor abrasions. As velocity increases, more energy is transferred, and the rice kernel's ability to absorb and dissipate energy without fracturing reaches a limit, causing breakage.

Critical energy threshold. The study identified a critical energy threshold that determines whether the rice kernel will break under impact. This threshold is defined as the amount of energy that the kernel can absorb without undergoing catastrophic failure. When the impact energy surpasses this threshold, the kernel experiences internal damage leading to cracks and breakage. The critical velocity at which the kernel breaks is tied directly to this energy threshold. For example, studies have found that rice kernels with varying moisture contents had different energy thresholds (Han *et al*., 2021):

- Rice with higher moisture content could absorb more energy before breaking, showing a higher critical energy threshold.
- Rice with lower moisture content had a lower threshold, making it more susceptible to breaking under impact.

Energy dissipation and crack formation. At higher impact velocities, studies showed that stress concentration occurs at specific points in the rice kernel, leading to the formation of meridian cracks or radial cracks (Han *et al*., 2021; Thamburaja *et al*., 2019). The dissipation of energy during this process involves the propagation of stress waves from the point of impact. These stress waves travel through the material, with energy being dissipated as the cracks extend and propagate. This crack propagation consumes a significant portion of the energy, which is why the number and complexity of cracks increase with velocity. In high-velocity impacts, more energy is dissipated through the creation of multiple crack surfaces and the disintegration of the kernel into several fragments.

Role of elastic and plastic deformation. Finite element method (FEM) simulations conducted by other researchers helped visualize how energy dissipation varies between elastic and plastic deformation regimes (Han *et al*., 2021). In elastic deformation, part of the energy is stored in the material's structure and is released once the impact force is removed, meaning no permanent damage occurs. However, in plastic deformation, energy is irreversibly dissipated in changing the structure of the material, leading to permanent damage and the initiation of cracks. The study found that as the impact velocity increased, the rice kernel moved from primarily elastic deformation to plastic deformation, resulting in more energy being dissipated in the form of permanent structural changes.

Energy dissipation in high-velocity impacts. In high-velocity impacts, a significant amount of energy is dissipated in the form of intense local damage at the point of contact. The rice kernel often disintegrates due to the rapid propagation of stress through the material. Previous study noted the formation of a conical stress region below the contact area, where oblique and radial cracks form (Han *et al*., 2021). This pattern of energy dissipation is characteristic of brittle materials, where the energy causes the material to fragment rather than deform smoothly. As a result, the kernel breaks into multiple pieces, with the energy being used up to create new surfaces and spreading cracks throughout the kernel.

Energy dissipation and impact repetition. In real-world applications, such as in rice processing, grains are often subjected to repeated impacts. The study briefly mentions that repeated impacts can lead to fatigue failure, where the energy dissipation during multiple impacts weakens the material over time. Even if each impact does not exceed the critical energy threshold, the cumulative dissipation of energy through microcracks can eventually cause the kernel to fail. This highlights the importance of understanding both single-impact and cumulative energy dissipation for reducing rice breakage during processing.

In any impact or deformation process, the total mechanical energy involved can be divided into energy that is stored (elastic energy) and energy that is dissipated (plastic deformation, fracture, heat, *etc*.). The energy balance is expressed as:

$$E_{total} = E_{elastic} + E_{dissipated} \quad \text{(Eq. 3)}$$

where E_{total} is the total energy imparted to the system (*e.g*., through an impact); $E_{elastic}$ is the energy stored elastically in the material, which can be recovered; $E_{dissipated}$ is the energy lost through irreversible processes such as plastic deformation, crack propagation, and heat.

The energy dissipated corresponds to the entropy production in the system. The critical energy needed to cause fracture in a material can be related to the energy dissipated in creating new surfaces (fracture surfaces). This is often described using Griffith's energy criterion for fracture (Griffith, 1921), where the critical energy release rate, G_c, determines when a crack will propagate.

$$G_c = \frac{2\gamma}{E} \quad \text{(Eq. 4)}$$

where G_c is the critical energy release rate (J/m²) the amount of energy required to propagate a crack; γ is the surface energy of the material (J/m²); E is the Young's modulus (Pa) of the material, which determines its stiffness.

For a system experiencing impact, the impact energy imparted must exceed this critical energy release rate for the material to fracture. If the impact energy is below this threshold, the material will not fracture, but may still experience plastic deformation. In thermodynamics, entropy generation is directly related to the irreversibility of a process, such as plastic deformation or fracture. The total entropy change ΔS in a system is given by the relationship (Callen, 1985):

$$\Delta S = \frac{\Delta Q}{T} \quad \text{(Eq. 5)}$$

where ΔS is the change in entropy (J/K); ΔQ is the heat generated or energy dissipated in an irreversible process (J); T is the absolute temperature (K) at which the process occurs.

In the context of fracture, the energy dissipated in forming new crack surfaces is associated with an increase in entropy. The greater the energy dissipated in the form of plastic deformation or crack growth, the greater the entropy generation in the system. This increase in entropy represents the irreversible nature of material failure. The plastic work done on a material during deformation is also associated with energy dissipation. This can be expressed as:

$$W_{plastic} = \int \sigma \, d\varepsilon_{plastic} \quad \text{(Eq. 6)}$$

where $W_{plastic}$ is the plastic work done on the material (J); σ is the stress (Pa); $\varepsilon_{plastic}$ is the plastic strain.

This plastic work contributes to energy dissipation, leading to an increase in temperature, material degradation, and entropy production. From an entropy approach, the fracture can also be described by the second law of thermodynamics, where the total entropy in the system must increase during fracture. The condition for crack propagation can be written as:

$$\frac{dG}{dt} < 0 \text{ and } \frac{dS_{total}}{dt} > 0 \quad \text{(Eq. 7)}$$

where G is the Gibbs free energy of the system; S_{total} is the total entropy of the system.

The system's entropy increases as energy is dissipated through crack propagation and plastic deformation. The entropy production rate can be used to predict the onset of material failure, with higher entropy generation signaling the imminent fracture of the material.

In the case of high strain rates (such as impacts), a portion of the energy dissipated during plastic deformation is converted to heat. This raises the temperature of the material locally and affects the overall energy dissipation rate (Lemaitre and Chaboche, 1990):

$$\Delta E_{dissipated} = \Delta E_{plastic} + \Delta E_{thermal} \quad \text{(Eq.8)}$$

where $E_{dissipated}$ is the total energy dissipated; $E_{plastic}$ is the energy dissipated due to plastic deformation; $E_{thermal}$ is the energy dissipated as heat.

This heating can further influence the material properties, potentially lowering the critical energy required for fracture as the material becomes more ductile at higher temperatures.

Combining the concepts of energy dissipation and entropy, the total dissipated energy due to fracture in a dynamic system can be written as (Eshelby, 1951; Rice, 1968):

$$E_{dissipated} = G_c . A \times T \Delta S \quad \text{(Eq. 9)}$$

where G_c is the critical energy release rate; A is the area of the new crack surfaces; T is the temperature; ΔS is the entropy change associated with the energy dissipation process.

This equation provides a thermodynamic framework for evaluating the total energy dissipated during crack propagation, incorporating both mechanical and thermodynamic aspects of fracture (Langer, 2008). In the entropy approach to energy dissipation and fracture, the energy imparted during an impact or deformation process is either stored elastically or dissipated through plastic deformation, crack formation, and heat generation. The critical energy threshold for fracture is related to the energy needed to create new surfaces, while the energy dissipation leads to entropy generation, representing the irreversibility of material failure. Understanding these concepts allows for a deeper analysis of how materials break under dynamic loading conditions, such as in the impact tests on rice kernels. Figure 2 shows the crack formation and propagation process in rice grains.

Energy dissipation plays a major role in the fracture behavior of viscoelastic materials like grain kernels. In viscoelastic systems, mechanical energy is not fully recovered during deformation, leading to dissipation through internal processes such as heat generation, molecular rearrangement, and irreversible structural damage. Understanding this dissipation is essential for modeling grain damage, as it drives the progression from reversible deformation to irreversible fracture. Thamburaja *et al*. (2019) outlined the critical energy dissipation theory, focusing on the thermodynamically consistent modeling of viscoelastic materials. An entropy-based approach can enhance grain damage and fracture modeling under viscoelastic deformation. The dissipation process increases entropy, which can be related to the internal energy changes and fracture initiation. By accounting for the increase in entropy during damage evolution, a more robust model can be developed to predict when viscoelastic grains transition from elastic deformation to fracture (Thamburaja *et al*., 2019).

$$\Gamma_{\phi} = \phi_0 \left(\frac{G^*}{G_c}\right)^{\beta} \left[-\frac{\partial G}{\partial \phi}\right] \geq 0 \quad \text{(Eq.10)}$$

where Γ is the rate of dissipation per unit volume; ϕ_0 is the reference damage generation rate; G^* is the local driving force for damage (related to the Gibbs free energy); G_c is the critical energy release rate (a material parameter); β is a power-law coefficient governing the rate of damage progression. This equation ensures that damage is irreversible, driving the material towards fracture as energy is dissipated.

Computational and experimental models

Alongside these theoretical frameworks, researchers have also developed a range of computational and experimental models to simulate and predict grain damage during threshing. These models often incorporate grain properties, thresher design, and operating parameters to ensure a more holistic understanding of the complex interactions involved in the threshing process (Kroupa, 2003; Li and Thomas, 2014). For instance, finite element analysis (FEA) models have been used to simulate the stresses and deformations

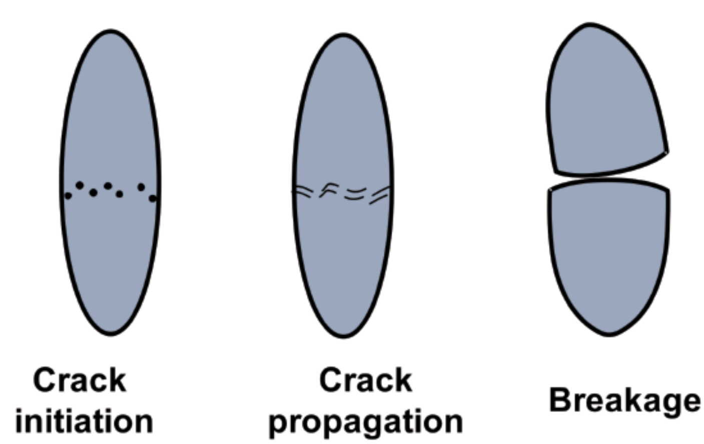

Figure 2. Crack initiation, propagation and breakage in rice grain during multiple impacts.

experienced by grains during threshing, enabling the identification of critical stress points and the optimization of thresher designs (Bian *et al*., 2015; Fleurat-Lessard, 2016; Khan *et al*., 2017; Nuttall *et al*., 2017).

Over the last decade, attempts have been made to develop mechanistic models for predicting grain kernel damage during handling processes. While empirical models are built on direct observation, measurement, and extensive data, mechanistic models describe the process based on an understanding of physics or chemistry. For example, grain kernel damage has been modeled using the finite element method (FEM) to give detailed force and deformation analysis on kernels. In FEM, the kernel is divided into a collection of connected elements, each of which follows a specified stress-strain relationship. According to Lizhang *et al*. (2013), the deformation of the system of elements is determined from Newton's laws numerically. They used FEM to simulate the impact between a threshing tooth and a single rice kernel. Based on stress analysis in a single kernel, the critical velocity corresponding to the critical tensile stress (minimum stress that causes permanent plastic deformation or cracks) was predicted to be 29.5 m/s (Chen *et al*., 2020; Lizhang *et al*., 2013). The simulation prediction was close to the experimental result of 30 m/s. Another investigator modeled the compression of individual and bulk Jatropha curcas seeds in a container. The results indicated that the coefficient of friction between seeds and between a seed and the container played a significant role in the initial stage of the pressing process (Chen *et al*., 2020; Paulsen *et al*., 2019). The authors observed that the information provided by the FEM model helps optimize the design of oil-pressing machines to increase energy efficiency.

In addition to finite element analysis, other computational models, such as discrete element method simulations, have recently gained popularity. DEM models treat grains as discrete particles interacting with each other and the threshing components through contact forces. These models can simulate the flow and behavior of large grains within a thresher, providing insights into the bulk material handling aspects of the threshing process.

Some researchers have developed a non-local fracture-based finite-strain theory for modeling fracture in viscoelastic materials and implemented it in the Abaqus FEM program. They can generate mesh-density-independent and mesh-type-independent stress-strain responses and cracking profiles using the element failure method. Notably the works of Thamburaja *et al*. (2019): the key concept from their new computational framework for damage in viscoelastic solids revolves around the accurate simulation of crack propagation in viscoelastic solids, which is achieved through a computational framework that integrates both the time-dependent mechanical behavior of viscoelastic materials and fracture mechanics principles. To understand the crack propagation process in viscoelastic solids, we have to discuss the viscoelastic behavior of grains, the simulation approach, energy dissipation and the fracture criteria.

Viscoelastic behavior. Viscoelastic materials exhibit both elastic (instantaneous) and viscous (time-dependent) deformations. Under mechanical loading, the material response includes immediate elastic deformation followed by gradual viscous flow, which influences crack growth behavior.

Simulation approach. The crack propagation in viscoelastic solids is simulated using finite element methods (FEM). These methods incorporate the viscoelastic material model, which accounts for the time-dependent stress-strain relationship. The model is coupled with fracture mechanics to capture the onset and growth of cracks.

Energy dissipation. In viscoelastic materials, energy dissipation occurs due to internal friction during deformation. This dissipation is crucial in the crack propagation process because it delays the fracture, providing a more accurate representation of the crack growth rate over time.

Fracture criteria. The computational framework utilizes a fracture criterion based on stress intensity factors (SIF) or energy release rates, which are used to predict when and where cracks will initiate and propagate.

The stress-strain relationship for viscoelastic materials can be summarized using the following equation derived from linear viscoelastic theory, as described in sources like Christensen's "Theory of Viscoelasticity" (Christensen, 1982) and is a foundational concept in time-dependent material behavior (Thamburaja *et al*., 2019).

$$\sigma(t) = E_0\epsilon(t) + \int_0^t E(t-\tau)\frac{d\epsilon(t)}{d\tau}d\tau \qquad \text{(Eq.11)}$$

where $\sigma(t)$ is the stress; $\varepsilon(t)$ is the strain; E_0 is the instantaneous elastic modulus; $E(t-\tau)$ is the time-dependent modulus.

The fracture of viscoelastic materials, like grain kernels, has been explored in detail by Thamburaja *et al*. (2019) using a finite-deformation constitutive theory. This approach models fracture as the loss of mechanical resistance in a material due to the failure of its elements, capturing viscoelastic behavior through a novel, non-local, and rate form-based theory.

Viscoelastic materials like grain kernels have a combination of elastic (spring-like) and viscous (dashpot-like) responses. The elastic portion recovers after deformation, while the viscous portion resists motion depending on the strain rate. Thamburaja *et al*. (2019) modeled this through two links: an elastic link (link 1) and a viscous link (link 2), which are parallel (Eq. 11 and 12) (Thamburaja *et al*., 2019):

$$\frac{1}{1-\emptyset}\dot{S}_1 = C_1\left[\dot{E}\right] - \frac{1}{(1-\emptyset)^2}S_1 \qquad \text{(Eq.12)}$$

$$\frac{1}{1-\emptyset}\dot{S}_2 = C_2\left[\dot{E}\right] - \frac{\emptyset}{(1-\emptyset)^2}S_2 - \frac{1}{k}\left(\frac{\sigma}{\sigma_0}\right)^q C_2[S_2] \qquad \text{(Eq.13)}$$

where ϕ represents the damage measure; C_1 and C_2 are elastic moduli; σ_0, k, and q are material constants for viscous deformation. Fracture occurs when the Gibbs free energy G^* exceeds a critical threshold G_c. The total Gibbs free energy is expressed as:

$$G = \frac{1}{1-\emptyset}\sum_{i+1}^{2} G_i^* \qquad \text{(Eq.14)}$$

Thamburaja *et al*. (2019) established both local and non-local fracture criteria. In the local case, damage is triggered when $G^* \geq G_c$. For non-local fracture, the driving force for damage is averaged over a fracture process zone, incorporating the influence of neighboring points. This mitigates mesh dependence in simulations and better represents physical crack growth. These models can be adapted for grain fracture simulations, where the viscoelastic nature of the kernels under different threshing methods influences crack initiation and propagation. Kroupa (2003) proposed a computational model for predicting grain damage during threshing. The model used machine vision to analyze corn kernel images and quantify mechanical damage as the percentage of the kernel surface area stained green. This approach allowed for automated, objective damage measurement of damage, and could be used to evaluate the performance of different threshing systems. Another study examined the mechanical properties of almond kernels under varying moisture content levels. The researchers found that kernel moisture content significantly affected the pliability and susceptibility to damage during hulling and shelling operations. Maintaining optimal moisture content was shown to increase the recovery of undamaged kernels. Additionally, experimental studies have been conducted to validate these computational models and to investigate the effects of various parameters on grain damage, such as the impact of different thresher designs, operating speeds, and grain moisture content (Khan *et al*., 2017; Kroupa, 2003; Nuttall *et al*., 2017). These studies typically involve laboratory-scale threshing experiments using controlled conditions to isolate the effects of specific parameters. Data on grain damage, such as the percentage of broken or cracked grains, is collected and analyzed to evaluate the performance of different threshing configurations and to develop empirical relationships between operating parameters and grain damage.

The discrete element method has emerged as a valuable tool for analyzing the behavior of grain systems. DEM simulations enable tracking individual kernel movements, calculating contact forces between kernels and boundaries, and determining kernel accelerations using Newton's Laws. This method has been applied to study grain damage in various scenarios, including compression, conveying, and milling. Another approach, the lattice element method, bridges the gap between DEM and the finite element method and has been used to simulate fracture in materials like wheat endosperm. While mechanistic models like DEM and LEM offer deeper insights and broader applicability than empirical models, they require a strong understanding of the underlying physics and can be computationally demanding.

In summary, computational and experimental models have been created to quantify and comprehend grain damage during post-harvest processing. Factors like moisture content, mechanical forces, and biological degradation are crucial. By utilizing these models, processors can enhance equipment and handling methods to minimize damage and maintain the quality of grain products.

Analysis of the different types of grain damage

While threshing is essential for separating grains from the harvested crop, it can also damage various grains, significantly impacting the final product's quality and yield. Factors such as the timing of harvesting (Yasothai, 2020), the type of equipment used (Kumar Korram *et al*., 2018), and environmental conditions can all contribute to the extent of grain damage during this critical stage of the rice production process.

Two different threshing methods (manual or mechanical) can cause breaks, cracks, bruises, and abrasions in seeds, resulting in abnormal seedlings of questionable planting value. The main types of grain kernel damage are mechanical, thermal, and biological (Chen *et al*., 2020). Mechanical damage can be categorized into two types based on the visibility of the damage: external and internal. External mechanical damage includes visible cracks, breaks, or abrasions on the grain surface, while internal mechanical damage refers to unseen fissures or fractures within the kernel.

Thermal damage is caused by the excessive heat generated during threshing, which can denature proteins and cause biochemical changes in the grain (Bishaw *et al*., 2007; Kumar Korram *et al*., 2018; Sreenivasulu *et al*., 2015). This damage often results in chalky or discolored grains that are undesirable for consumers (Sreenivasulu *et al*., 2015). Biological damage is caused by microbial growth or insect infestations that can occur when the harvested grains are not properly dried or stored.

External damage includes open cracks in the grain and kernel breakage, while internal damage lies underneath the pericarp and cannot be detected without unique instrumentation (Chen *et al*., 2020; Paulsen *et al*., 2019). The percentage of broken kernels is used to estimate the level of mechanical damage, mainly because the quantification process is simple and fast; however, it does not consider all types of mechanical damage.

Internal damage refers to the fine cracks within a kernel's endosperm underneath the pericarp. Among all cereal grains, only rice and corn have internal severe damage problems, which are commonly referred to as fissures (rice) or stress cracks (corn) (Paulsen *et al*., 2019). The major causes of internal damage are thermal and moisture stresses induced by rapid ambient temperature and moisture changes, especially during drying and rewetting processes (Cnossen, 2012; Lizhang *et al*., 2013; Paulsen *et al*., 2019). Internal damage can also occur due to impact during mechanical harvesting and handling processes. The formation and propagation of internal stress cracks depend on the kernel's structure, composition, and variety (Chen *et al*., 2020; Wang and Jeronimidis, 2008).

Grain damage may be classified into two categories: visible and invisible. Visible damage, cracked or broken grain, is usually measured on a volume basis by sieving a standard sample in a 2 mm slotted mesh screen; 5% of cracked grain in a consignment is generally regarded as the maximum acceptable level. Invisible damage applies to sound grain that fails to germinate (Roberts and Arnold, 1966).

Physical damage to rice grains during threshing operations, such as breakage, cracking, and splitting, is a significant concern for rice producers and processors. These damages can lead to reduced quality, lower market value, and decreased consumer satisfaction.

Breakage

Rice grain breakage during threshing is a complex phenomenon affected by a combination of factors affecting the extent of the damage. The complex blend of these factors provides a comprehensive understanding of how breakage occurs and valuable insight into possible mitigation strategies. At the heart of the process is the interplay of mechanical forces, where impact and friction play a central role. When rice stalks are threshed, they are subjected to continuous impact and friction against threshing components such as threshing bars or concave plates. These interactions create significant forces that resonate through the grains, creating the potential for breakage. The nature of these forces is complemented by the rapid separation techniques used in modern beating operations. Although these techniques speed up separation, they also increase the risks associated with grain breakage due to the speed of movement.

The moisture content of rice grains is a critical mediator in this process. High humidity makes the grains more elastic, making them prone to deformation and breakage due to mechanical stress. In addition, the characteristics of the rice variety play an essential role. Varieties differ in their inherent structural flexibility; some are genetically more fragile, making them more sensitive to mechanical forces applied to them. Adding complexity to the equation, thresher settings act as significant factors. Improperly adjusted equipment can increase the force on the blades, increasing the likelihood of breakage. Factors such as rotor speed, concave clearance, and settings must be carefully calibrated to balance effective separation and minimize blade damage.

The presence of foreign substances in the threshing cylinder cannot be underestimated. Debris, such as rocks or soil, disrupts the uniform distribution of forces, creating localized stress points that compromise the integrity of the blades. This, in turn, affects the quality of the seeds. Poor-quality seeds with defects or lesions already have a weakened structure that makes them more susceptible to breakage.

Grain breakage models

Modeling grain breakage during combined threshing is complex due to many interacting factors such as crop characteristics, harvester design, operating speed, etc. One approach is to consider the stress that occurs during the threshing of the grain. A simplified model can relate grain stress to its probability of breakage. Here is the basic conceptual equation:

$$P_{breakage} = k.\frac{\sigma}{\sigma_{max}} \quad \text{(Eq.15)}$$

where $P_{breakage}$ is the probability of grain breakage; k is a constant that depends on factors like crop type, grain properties, and harvester design; σ is the stress experienced by the grain; σ_{max} is the maximum stress a grain can withstand before breaking.

Rice grain breakage during threshing is a complex issue influenced by numerous factors, including impact and frictional forces, grain properties, and machine settings. Innovative mitigation strategies are being developed to combat this, focusing on minimizing the forces that lead to breakage. For instance, incorporating rubber or flexible components into threshing devices can absorb shocks and reduce friction, thereby protecting the grains. Optimizing machine settings based on a thorough understanding of force interactions can minimize grain stress.

Research has demonstrated that broken rice grains exhibit undesirable characteristics like reduced elongation and increased stickiness during cooking, ultimately affecting the texture and sensory experience. By understanding and addressing the intricate mechanisms of grain breakage, these innovative solutions aim to optimize threshing processes and ensure a higher-quality rice product. Studies have shown that breakage can significantly affect rice quality. For example, a study (Bao, 2019) evaluated the effect of breakage on the cooking quality of rice. The researchers found that broken rice grains exhibited reduced elongation and increased stickiness compared to intact grains, impacting cooked rice's overall texture and sensory attributes.

Cracking

The cracking of rice grains during the threshing process occurs due to a complex interaction between mechanical forces and the internal vulnerabilities of the grains themselves. This multifaceted process can be decomposed into several interrelated factors contributing to grain splitting. The relentless impact and compressive force applied to the rice grains as they pass through the threshing equipment is at the heart of this process. The granules are caught between the dynamic movement and the static surfaces of components such as rasp bars or concave plates, exerting high pressure on them. These forces create an environment ripe for structural compromise and set the stage for a potential fissure. More complexity, friction, and friction emerge. The blades, which must constantly rub against the striking components, are exposed to abrasive forces that wear away their outer protective layers. These layers, which act as a natural defense against damage, can gradually wear away, making the blades more susceptible to cracking.

Moisture content is a critical modulator of this process. Grains with increased moisture levels show reduced structural integrity, become flexible, and tend to deform due to mechanical stress. Moisture enhances the effects of impact, compression, and friction, effectively lowering the cracking threshold. The characteristics of the variety bring a new layer of influence. Rice varieties have distinct structural characteristics; some have thicker shells or an inherently firmer texture, while others have more delicate qualities. Varieties with thinner skin or structural weakness are susceptible, and their susceptibility to cracking increases due to the mechanical stress of threshing.

Foreign materials play an essential role, which are often imperceptible but impressive. Rocks, soil, and other debris cause irregularities in the threshing process, causing localized stress points that concentrate forces in some grain regions. These stress concentrations are a precursor to cracking, especially in grains already weakened by other factors. Inadequate machine settings increase the risks. Improper gaps between components or rotor speeds that are too high will result in uneven force distribution where certain areas of the blades are under more pressure. This unevenness increases the likelihood of cracking if the blades stick with disproportionate tension. Seed quality is an important aspect. Blades with existing defects or damage may split. Such low-quality seeds, already weakened by cracks or weak points, are at the limit of mechanical attack by the thresher.

Grain cracking model

Modeling grain cracking in combine harvesters during threshing involves considerations similar to grain splitting and understanding the mechanical forces and interactions that lead to grain cracking. Here is a simplified model that considers some of the critical factors: Let us consider a simple model that relates the probability of grain cracking P_{crack} to various factors:

$$P_{crack} = \frac{k\,.\,F_{compression}}{E} \quad \text{(Eq.16)}$$

where k is a proportionality constant; $F_{compression}$ is the compressive force experienced by the grain due to the threshing mechanisms; E is a material property related to the grain's resistance to cracking. This model suggests that the probability of grain splitting is proportional to the compressive force exerted on the grains by threshing components and inversely proportional to the breaking strength of the grain. However, this is a simplified representation, like the grain-splitting model. In reality, grain cracking is influenced by grain moisture content, variety, threshing component structure, machine settings, and the interaction of compression and shear forces.

Working conditions should not be underestimated. High-performance requirements or suboptimal equipment maintenance raise the stakes, increase the forces acting on the blades, and accelerate cracking. Mitigation requires a holistic approach. Fine-tuning the machine settings ensures equal distribution of force, careful removal of foreign bodies, and careful monitoring of moisture content to reduce the risk of cracking. Carefully selecting rice varieties based on their structural characteristics provides a preventive layer of protection. By recognizing the complex web of interrelated factors, it is possible to create a harmonious balance that minimizes the cracking of the rice grains during threshing and protects the integrity of the harvested crop.

Splitting

Splitting involves the separation of rice grains into two or more pieces along their lengthwise axis. The process of rice grain splitting during threshing operations is a complex interplay of mechanical forces, inherent grain characteristics, and operational dynamics. This phenomenon can be elucidated through a sequence of interconnected events culminating in grain splitting.

As the threshing machinery engages, rice stalks or panicles are thrust into the mechanized process, setting the stage for the cascade of events. The impact and pressure generated within the machinery constitute the initial impetus for grain splitting. The grains, nestled within their protective husks, are wedged between moving components like rasp bars, concave plates, and stationary surfaces. This confrontation of forces initiates the critical interplay that underlies splitting.

Moisture content emerges as a pivotal factor in the process. Grains imbued with higher moisture levels transform, making them more susceptible to splitting. The combination of mechanical pressure and moisture's softening effect creates an environment conducive to structural vulnerability. Misalignment or improper adjustment of threshing equipment can cause excessive force on the grains, leading to splitting. Rice varieties with long and slender grains are prone to splitting, harming rice quality and market value. Previous researchers assessed the effect of splitting on the cooking quality of rice. The researchers found that split grains exhibited reduced elongation and increased stickiness compared to intact grains, similar to broken grains (Chaturvedi *et al*., 2020). This highlights the importance of minimizing splitting to maintain desired cooking properties.

Grain splitting model

Modeling grain cracking during the threshing phase of a combine requires an understanding of the mechanical forces and interactions between grains and threshing components. Although the complexity of this process may require a combination of empirical data, field observations, and theoretical considerations, here is a simplified model that includes a few key factors: Consider a simple model that combines the probability of grain splitting P_{split} with several factors:

$$P_{split} = \frac{k \,.\, F_{impact}}{E} \quad \text{(Eq.17)}$$

where k is a proportionality constant; F_{impact} is the impact force experienced by grains due to the threshing mechanisms; E is a material property related to the grain's resistance to splitting.

This model suggests that the likelihood of grain splitting is directly related to the impact force exerted on the grain by the threshing components and inversely related to the grain's resistance to splitting.

In reality, grain cracking can be affected by grain moisture content, grain variety, threshing component design, and machine settings. More accurate model development can incorporate experimental data to establish the relationship between impact force and rupture probability, consider the effects of moisture content and grain properties, and the dynamics of threshing components and their interactions with grains.

Efforts are underway to develop improved threshing technologies to minimize physical damage. For example, rubber rollers or axial flow threshers apply less force to the grains during separation. These technologies have shown promising results in reducing breakage, cracking, and splitting compared to traditional threshing methods. Proper equipment maintenance, calibration, and operator training are crucial in minimizing physical damage. Regular inspection of threshing equipment, adjustment of settings according to grain characteristics, and ensuring optimal moisture content are essential practices.

Physical damage, such as breakage, cracking, and splitting during threshing operations, can significantly impact rice grains' quality and market value. Rice producers and processors must optimize threshing techniques, adopt improved technologies, and implement proper maintenance practices to minimize these damages and ensure high-quality rice for consumers.

Mathematical expressions of theoretical models of grain damage

Analytical models

Grain breakage is critical in various agricultural and industrial processes, from milling and processing to storage and transportation. Understanding the underlying mechanisms and developing accurate predictive models is essential for optimizing these systems (Bucklin *et al*., 2013; Maindarkar *et al*., 2014). One of the critical aspects of grain breakage is the influence of the grain's physical and mechanical properties, which can vary significantly depending on the grain type, moisture content, and other factors (Polikarpova and Mizikovskiy, 2020). Several grain breakage models have been proposed, each focusing on different aspects of the problem and utilizing various mathematical approaches.

The Sukumaran and Rajashekhar model provide a comprehensive framework for predicting grain breakage based on the grain's mechanical properties, such as hardness, compressive strength, and impact resistance. The model employs a statistical approach, incorporating the Weibull distribution to account for the inherent variability in grain characteristics. The mathematical expression for the model is given by:

$$P_b = 1 - exp\left(-\left({}^{F}/_{F_0}\right)^{n}\right) \quad \text{(Eq.18)}$$

where P_b is the probability of breakage and has a value between 0 and 1 where 0 indicates no breakage and 1 indicates complete breakage; n is the number of impacts, and this refers to the number of times the grain is subjected to a force that could cause breakage; F is the applied force on the grain. This could be the force exerted during milling, handling, or any other process that could cause breakage. F_0 is the characteristic breakage force of the grain. This is a material property that represents the grain's resistance to breakage. A higher F_0 indicates a more robust grain.

The model has been successfully applied to various grains, including wheat, maize, and rice, and has shown good agreement with experimental data (Nuttall *et al*., 2017).

Another prominent model is the Kitsunai and Arakawa model, which focuses on the role of moisture content in grain breakage. This model considers the viscoelastic behavior of the grain and how it changes with moisture content, leading to a modified form of the Sukumaran and Rajashekhar models. The mathematical expression for the Kitsunai and Arakawa model is given by:

$$P_b = 1 - \; exp(-an^b \; x \; MC^c) \quad \text{(Eq.19)}$$

where P_b This represents the probability of grain breakage; ranging from 0 (no breakage) to 1 (complete breakage); n signifies the number of impacts the grain experiences, which could lead to breakage. MC is the grain's moisture content, a crucial factor influencing its viscoelastic behavior and susceptibility to breakage. Now, let us address the other symbols in the equation: a, b, and c. These are not simply variables but model parameters that must be determined experimentally. They reflect the relationship between moisture content, number of impacts, and breakage probability for a particular type of grain. Think of it this way: while *n* and *MC* are conditions you can control in an experiment, *a*, *b*, and *c* are inherent characteristics of the grain that dictate how it responds to those conditions.

The Kitsunai and Arakawa model emphasizes that moisture content plays a significant role in breakage behavior, and these parameters help quantify that relationship. This model has shown good predictive capabilities for various grains, particularly in scenarios where moisture content plays a significant role (Maindarkar *et al*., 2014; Oli *et al*., 2016).

In addition to these models, other approaches focus on specific aspects of grain breakage, such as the Saad and Mallick model (Nuttall *et al*., 2017), which incorporates the effect of grain orientation during impact, and the Miu and Martynenko model, which considers the influence of grain geometry and size distribution. These models provide a more comprehensive understanding of grain breakage and offer valuable tools for optimizing various agricultural and industrial processes. For instance, the Saad and Mallick model considers the grain's orientation during impact and its influence on the probability of breakage. The mathematical expression for this model is seen in Eq. 8.

$$P_b = 1 - exp(-kn\, x\, sin^2\theta) \quad \text{(Eq.20)}$$

where P_b is the probability of the grain breaking, ranging from 0 (no breakage) to 1 (sure breakage); *k* is a constant parameter specific to the grain type and its material properties. It reflects how susceptible the grain is to breakage in general; *n* represents the number of impacts the grain experiences; θ is the angle between the direction of the impact force and the grain's central axis (imagine a line running through the longest part of the grain).

The model cleverly uses $sin^2(\theta)$ to account for how the impact angle influences breakage. For example, when $\theta = 0°$, the impact is directly on the grain's tip, $sin^2(\theta) = 0$, suggesting a lower probability of breakage. If $\theta = 90°$, The impact is perpendicular to the grain's longest side, $sin^2(\theta) = 1$, indicating a higher likelihood of breakage. The Saad and Mallick model highlights that the impact angle is crucial in predicting breakage for grains with irregular shapes.

This model has shown good agreement with experimental data, particularly for grains with elongated or irregular shapes, where the orientation of the grain during impact can significantly affect the likelihood of breakage (Maindarkar *et al*., 2014).

On the other hand, the Miu and Martynenko model focuses on the influence of grain geometry and size distribution on breakage probability. This model accounts for the heterogeneous nature of the grain population by incorporating the variability in grain dimensions and shapes. The mathematical expression for this model is:

$$P_b = 1 - exp\left(-\left({}^{d}/_{d_c}\right)^n\right) \quad \text{(Eq.21)}$$

where; P_b represents the probability of a grain breaking, ranging from 0 (no breakage) to 1 (guaranteed breakage); *d* refers to the diameter of an individual grain. The model acknowledges that within a batch, you will have grains of varying sizes; d_c is the critical diameter, a key parameter specific to the type of grain. It represents a threshold: grains with diameters larger than d_c are likelier to break under stress; *n* is another parameter specific to the grain type. It reflects how sharply the breakage probability increases as the grain diameter surpasses the critical diameter (d_c). A higher value of 'n' indicates a more sudden increase in breakage probability. While not included in the Miu and Martynenko model, μd (mean grain diameter) and σd (standard deviation of grain diameter) are essential for understanding the overall breakage behavior of a collection of grains. They describe the size distribution within the grain batch. The Miu and Martynenko model emphasizes that a realistic prediction needs to consider this size variation, as it is unlikely that all grains will have the same diameter. This approach has proven effective in predicting the breakage behavior of grains with diverse size and shape characteristics, providing a more comprehensive understanding of the factors influencing grain breakage (Maindarkar *et al*., 2014).

Vogel and Peukert described the relationship between particle breakage probability and impact velocity using the generalized dimensional analysis method and the detailed fracture mechanical model. The mathematical model is as follows (Vogel and Peukert, 2003):

$$P = 1 - exp\left\{-f_{Mat.}Kx\left(\frac{V^2}{2} - W_{m,min}\right)\right\} \quad \text{(Eq.22)}$$

where *P* is the breakage probability; is the material parameter (kg/J · m); *k* is the number of impacts; *x* is the initial particle size (m); *V* is the impact velocity (m/s); and Wm, min characterizes the threshold energy (J/kg) which a particle can take up without fracture.

Figure 3 shows the variation of rice breakage probability with impact velocity. It is obvious that the breakage probability of rice increases with the increase of impact velocity. When the impact energy exceeds the energy threshold, the rice kernel will have a certain probability of breaking. Below this energy threshold breakage does not occur, only surface wear is produced (Figure 4a) which can be attributed rather to attrition than to particle fracture. There is a similar phenomenon in other types of particles (Vogel and Peukert, 2003). Figure 4a shows an example of the first mode of breakage, *i.e.* surface wear under low impact velocity. After statistical analysis, when the impact velocity is low (generally speaking, the impact velocity is less than 10 m/s), the microcrack cannot propagate and penetrate in time (Han *et al*., 2006). The macroscopic characterization is that only minor damage to the rice kernel in the form of surface wear occurs due to high local stress. Although the macroscopic breakage behavior is not observed, the internal structure of rice kernel may have changed. Previous study suggested the strength of particles decreases slightly after repeated impact at a lower velocity (Han *et al*., 2006). From the standpoint of energy, Tavares and Carvalho (Tavares and Carvalho, 2007) explained that the energy required for breakage of particles decreases with the accumulation of damage after repeated impact.

Similarly, some researchers carried out a series of low-energy repeated impact tests and obtained the same result. They realized that rice kernel is not only an agricultural material but also a discontinuous medium (Han *et al*., 2021). Some natural microcracks inevitably exist inside the rice particles. After low-energy repeated impacts, these natural microcracks are conducive to the initiation, propagation and coalescence of macrocracks, which results in a decrease in particle strength (Han *et al*., 2021). It suggests that the breakage of rice kernel strongly depends upon the strength, the weaker the strength, the more likely crack growth tends to occur and the easier the breakage. Therefore, the breakage probability of the rice kernel will increase with an increasing number of impacts under the condition of low-velocity impact. This is also the reason that rice will be subjected to repeated stress in each processing environment to produce more broken rice.

Comparative analysis of the different analytical models

Comparing these analytical models is essential for choosing the right tool for the job. Here is a breakdown of their strengths, limitations, and predictive capabilities:

Sukumaran and Rajashekhar model. This model is relatively simple and easy to implement. It accounts for the inherent variability in grain strength using the Weibull distribution. This model is suitable for scenarios where impact force is a dominant factor. It is suitable for estimating breakage probability under repeated impacts, mainly when focusing on the grain's material strength. However, its limitations are that it does not explicitly consider moisture content, grain shape, or size distribution, which can be significant factors in real-world applications.

Kitsunai and Arakawa model. The core strength of this model is that it directly incorporates moisture content, a crucial factor influencing grain breakage. It builds upon the Sukumaran and Rajashekhar model, adding a layer of complexity. This model is well-suited for situations where moisture content is a significant concern, such as grain drying or storage. The limitation is that it requires experimental determination of multiple parameters (*a, b, c*), which can be time-consuming. This may not be as accurate for extremely dry or wet grains, where the relationship with moisture content is less predictable.

Saad and Mallick model. This model explicitly considers the impact angle, which is crucial for irregularly shaped grains. It provides insights into how grain orientation affects breakage susceptibility. The Saad and Mallick model is valuable for processes where grain orientation during impact is difficult to control, such as milling or transport. Its core limitation is that it may not be as

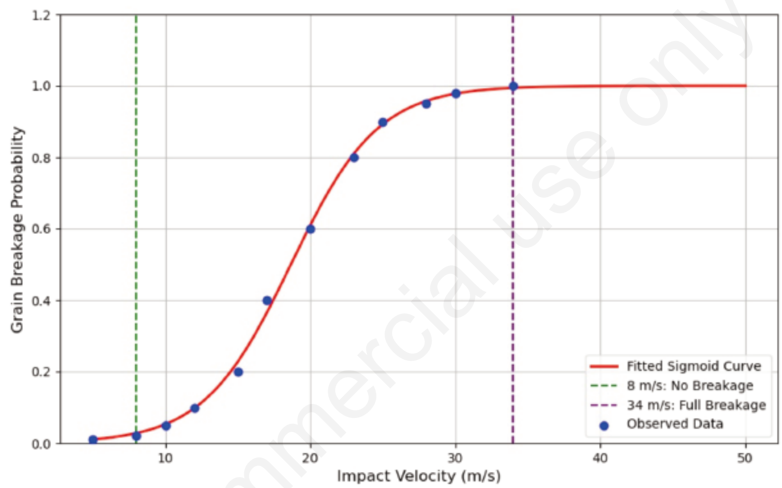

Figure 3. Correlation between impact velocity and grain breakage probability of rice grains undergoing multiple impacts.

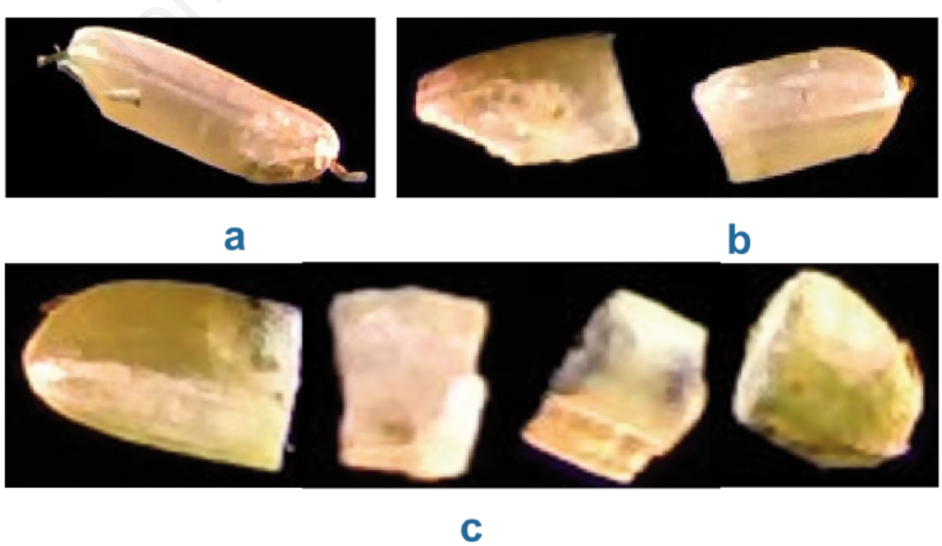

Figure 4. Different breakage modes of rice grains undergoing multiple impacts, where (**a**) is surface wear, (**b**) is a single fracture point, and (**c**) is multiple breakage points.

accurate for grains with more uniform shapes where orientation plays a lesser role.

Miu and Martynenko model. The main strength of this model is that it accounts for the size distribution within a grain batch, acknowledging that not all grains are identical. This also introduces the concept of critical diameter, highlighting size as a key factor. This model helps predict the overall breakage behavior of a heterogeneous grain population, particularly in milling and grinding operations. However, this model requires knowledge of the grain size distribution, which might not always be readily available. In summary, choosing the "best" model depends heavily on the specific application and the most critical factors. The Kitsunai and Arakawa model might be most suitable if moisture is a primary concern. The Saad and Mallick model would be better if grain shape and impact angle were critical. For scenarios involving a wide range of grain sizes, the Miu and Martynenko model would be more appropriate. Often, a combination of these models or modifications tailored to specific situations might be necessary for the most accurate predictions.

Theoretical approaches to mitigating grain damage

The agricultural industry faces a critical challenge in maintaining the quality and integrity of cereal grains throughout the postharvest handling process. Technological advancements and innovative approaches are being explored to address grain damage, microbial contamination, and nutritional degradation.

Machine design optimization

Machine design optimization is crucial for developing high-performing, reliable, and cost-effective machines, especially in agriculture, where minimizing grain damage during threshing is paramount. Designing efficient threshing components necessitates a delicate balance between adequate threshing and minimizing grain damage. As you pointed out, the design process for mechanical elements is inherently iterative and heavily reliant on the designer's experience and intuition. While the internet has broadened access to information and manufacturer-provided design procedures, current computer applications struggle to replicate the nuanced decision-making of a human designer.

Several limitations plague current Computer-Aided Design applications. Many CAD applications restrict design exploration by limiting parameter control, forcing designers to work with fixed values. This inherent rigidity hinders the discovery of unconventional designs and optimization possibilities. Moreover, while adept at calculations and rule-based modeling, CAD systems struggle to emulate human designers' intuitive decision-making and experience-based judgment. Further exacerbating these challenges is the difficulty CAD systems face in accurately modeling the complex interactions between components and forces inherent in mechanical designs, making it challenging to account for all potential failure modes. However, promising advancements offer potential solutions. Integrating AI and machine learning algorithms into CAD applications could help bridge the gap between human intuition and computational power. By analyzing vast datasets of designs, material properties, and manufacturing processes, AI can assist designers in making more informed decisions. Generative design, an iterative AI process, can explore a broader range of design possibilities within specified constraints and performance criteria, potentially leading to more innovative and optimized designs. Furthermore, advanced simulation and analysis tools can provide designers with a virtual testing ground to evaluate their designs under various conditions, identify potential weaknesses, and optimize accordingly. The future of mechanical design lies in a collaborative approach that leverages the strengths of human designers and intelligent computer systems. This synergy, combining human intuition with computational power, holds the key to developing more efficient, innovative, and robust designs for critical agricultural tasks like threshing.

Emerging trends have observed and driven disruptive innovations in electrical machine design optimization (Bramerdorfer *et al*., 2018). Techniques such as sophisticated emerging methods for modeling machine characteristics, reducing the number of required finite element (FE) simulations, and nonlinear modeling of optimization targets as functions of design parameters can lead to significant time and computational efficiency gains (Bramerdorfer *et al*., 2018, 2016; Rao and Pawar, 2020).

Design optimization of mechanical system components is challenging due to the complex design constraints and mixed-type design variables involved. Rao algorithms have demonstrated promising performance in optimizing the design of selected mechanical system components, with the designs obtained using these algorithms outperforming those obtained using other optimization algorithms in previous studies.

Machining process optimization is another critical aspect of machine design, as it can significantly impact the final product's performance, reliability, and cost-effectiveness. By incorporating predictive models and optimization techniques into the design process, engineers can develop more robust and efficient machines that are better equipped to withstand the demands of their intended applications.

Pre-threshing treatments

Pre-threshing treatments play a crucial role in the post-harvest handling of grain crops, as they can significantly impact the quality and damage characteristics of the final product. The present study aims to provide a theoretical analysis of the potential effects of various pre-treatment methods on the extent of grain damage during subsequent processing steps.

One key aspect is the relationship between physical parameters and grain damage. Factors such as initial height, tuber mass, and impact material have been shown to influence the maximum and minimum acceleration experienced by the grain, which can directly translate to the extent of damage. Analyzing these relationships can help inform the design and optimization of pre-treatment equipment and processing machinery to minimize undesirable grain degradation.

For instance, research has demonstrated that maintaining the optimal moisture content of the grain can increase the kernel's pliability and reduce its susceptibility to mechanical damage during hulling and shelling operations (Shirmohammadi and Charrault, 2018). This suggests that pre-wetting or conditioning the grain before processing may be an effective strategy to preserve quality.

Additionally, studies on other cereal crops have highlighted the potential of physical post-harvest treatments, such as thermal processing or irradiation, to inhibit the growth of spoilage microorganisms and extend the shelf-life of the final product (Schmidt *et al*., 2018). However, the authors caution that a single treatment may be insufficient to decontaminate the grain fully, necessitating the development of combined approaches to harness synergistic effects.

Overall, the theoretical analysis presented in this review underscores the importance of carefully considering the impact of pre-threshing treatments on grain quality and damage characteristics. By incorporating a multifaceted understanding of the underlying physical and biological mechanisms, researchers and industry stakeholders can work towards optimizing pre-processing steps to ensure the delivery of high-quality, minimally damaged grain to consumers (Panasiewicz *et al*., 2009).

Post-threshing handling

Post-harvest handling is a critical stage in crop production, as it directly impacts the final quality and marketability of the harvested produce. Proper post-harvest management is essential for ensuring that agricultural products reach the market in the best possible condition, preserving their quality, taste, flavor, texture, and nutritional value. Post-harvest losses can occur due to various factors, including physical damage (e.g., bruising), inadequate cooling, and poor handling practices (Cole *et al*., 2018; Valenzuela, 2023).

In the developing world, post-harvest losses tend to occur between the grower and the market rather than at the consumer level, in contrast to the developed world. These losses are often exacerbated by factors such as harvesting at improper maturity, rough handling, poor packaging, lack of protection from water loss, inadequate transportation, and limited access to cooling or cold storage facilities. Reducing post-harvest losses is critical in increasing food availability and sustainability, particularly as the global population is expected to exceed 9 billion by 2050 (Toivonen *et al*., 2014).

Advances in post-harvest preservation and quality management techniques, such as drying, heat treatment, high-pressure processing, and fermentation, can help mitigate post-harvest losses and ensure the safety and accessibility of the food supply (Cole *et al*., 2018; Valenzuela, 2023). Additionally, implementing good post-harvest handling practices, including proper logistics and infrastructure support, can significantly reduce the loss of fresh produce during the distribution process (Cole *et al*., 2018).

One critical aspect of post-harvest handling is the need to minimize physical damage to the harvested produce, particularly in the case of grains like maize. Rough handling, such as excessive threshing or inappropriate transportation, can lead to bruising, cracking, or other forms of kernel damage, which can compromise the quality and shelf life of the product (Kaur *et al*., 2019). Developing and implementing gentle handling practices, such as careful threshing, controlled conveying, and optimized storage conditions, can help preserve the harvested grains' integrity and minimize post-threshing losses (Kaur *et al*., 2019).

Conclusions and suggestions for future research

This comprehensive review examined existing theories and models concerning grain damage during threshing, highlighting the complex interplay of factors influencing this critical issue. Key theoretical findings emphasize the significance of grain properties such as moisture content, kernel size, and variety, which significantly influence susceptibility to mechanical damage**.** Machine parameters such as threshing speed, drum design, and concave settings directly impact the intensity and type of damage inflicted. While diverse modeling approaches exist, from empirical relationships to sophisticated finite element analysis, continued development is needed for accurate prediction and optimization. These findings have significant implications for future research and practical applications. Future research should focus on:

Developing robust, universal models and bridging the gap between theoretical understanding and practical application requires accurate models across various grain types and threshing conditions. Another area of focus should be exploring alternative threshing technologies. Investigating and developing gentler threshing methods could minimize damage and improve grain quality. Finally, Integrating pre- and post-threshing treatments. Optimizing these practices can further mitigate damage susceptibility and preserve grain quality.

Advancing the theory and modeling of grain damage during threshing requires a multidisciplinary approach. Collaborative efforts between agricultural engineers, plant breeders, and food scientists are crucial for developing innovative solutions. Refining our understanding and predictive capabilities can minimize grain losses, enhance food security, and contribute to a more sustainable and efficient agricultural system.

References

Alotaibi, K.D., Al-Shamrani, M.A., Al-Dossary, M.A., 2020. An investigation on the effect of threshing parameters on barley grain quality. Int. J. Agr. Biol. 2:405–412.

Bao, J., 2019. Effects of grain breakage on the cooking quality of rice. J. Cereal Sci. 8:119–124.

Baryeh, E.A., 2003. A simple grain impact damage assessment device for developing countries. J. Food Eng. 56:37–42.

Batey, I.L., 2010. Maintaining grain quality during storage and transport. In: Wrigley, C.W., Batey, I.L. (eds.), Cereal grains. Cambridge, Woodhead Publishing. pp. 413–430.

Bian, Q., Ambrose, R.P.K., Subramanyam, B., 2015. Effects of insect-infested kernels on bulk flow properties of wheat. J. Stored Prod. Res. 63:51–56.

Bishaw, Z., Niane, A.A., Gan, Y., 2007. Quality seed production. In: Yadav, S.S., McNeil, D.L., Stevenson, P.C. (eds.), Lentil. Dordrecht, Springer. pp. 349–383.

Bramerdorfer, G., Tapia, J.A., Pyrhonen, J.J., Cavagnino, A., 2018. Modern electrical machine design optimization: techniques, trends, and best practices. IEEE Trans. Ind. Electron. 65:7672–7684.

Bramerdorfer, G., Zavoianu, A.-C., Silber, S., Lughofer, E., Amrhein, W., 2016. Possibilities for speeding up the FE-based optimization of electrical machines - A case study. IEEE Trans. Ind. Appl. 52:4668–4677.

Bucklin, R., Thompson, S., Montross, M., Abdel-Hadi, A., 2013. Grain storage systems design. In: Kutz, M. (ed.), Handbook of farm, dairy and food machinery engineering. Academic Press. pp. 123–175.

Callen, H.B., 1985. Thermodynamics and an introduction to Tthermostatistics. Hoboken, J. Wiley & Sons.

Chaturvedi, S., Shrivastava, A.K., Ramakrishnan, R.S., Koutu, G.K., Singh, S., 2020. Effect of moisture content on some physical properties of three varieties of Kodo (scrobiculatum L.) millet. Int. J. Curr. Microbiol. Appl. Sci. 9:3781–3788.

Chen, Y., 2020. Impact of microstructural characteristics on the mechanical properties of grains. Food Eng. Rev. 12:134–150.

Chen, Z., Wassgren, C., Ambrose, K., 2020. A review of grain kernel damage: mechanisms, modeling, and testing procedures. Trans. ASABE 63:455–475.

Christensen, R.M., 1982. Theory of viscoelasticity: An introduction. Amsterdam, Elsevier.

Cnossen, A.G., 2012. Effect of hulling and cracking on rice milling quality. J. Food Eng. 108:305–313.

Cole, M.B., Augustin, M.A., Robertson, M.J., Manners, J.M., 2018. The science of food security. Npj Sci. Food 2:14.

Dobrzaski, B., Stpniewski, A., 2013. Physical properties of seeds in technological processes. Sn: Grundas, S. (ed.), Advances in agrophysical research. InTech.

Eshelby, J.D., 1951. The force on an elastic singularity. Philos. T. R. Soc. S-A. 244:87–112.

Eyshi Rezaei, E., Webber, H., Gaiser, T., Naab, J., Ewert, F., 2015. Heat stress in cereals: Mechanisms and modelling. Eur. J. Agron. 64:98–113.

Fleurat-Lessard, F., 2016. Postharvest operations for quality preservation of stored grain. In: C. Wrigley, H. Corke, K. Seetharaman, J. Faubion (eds.), Encyclopedia of food grains. Academic Press, pp. 117–125.

Gan, C., Zhu, X., Xu, J., Guan, X., Xie, Y., 2021. Comparative study of threshing mechanisms on the quality of wheat and rice grains. Trans. ASABE 64:75–83.

Ghasemi-Varnamkhasti, M., Khalili, H., Aghbashlo, M., 2020. Effect of moisture content and pre-drying treatment on barley grain damage during the threshing process. Agric. Eng. Int. 22:29–36.

Greffeuille, V., Abecassis, J., Barouh, N., Villeneuve, P., Mabille, F., Bar L'Helgouac'h, C., Lullien-Pellerin, V., 2007. Analysis of the milling reduction of bread wheat farina: Physical and biochemical characterisation. J. Cereal Sci. 45:97–105.

Griffith, A.A. 1921. VI. The phenomena of rupture and flow in solids. Philos. T. R. Soc. Lond. 221:163–198.

Han, T., Petukhov, Y., Levy, A., Kalman, H. 2006. Theoretical and experimental study of multi-impact breakage of particles. Adv. Powder Technol. 17:135–157.

Han, Y., Li, G., Jia, F., Meng, X., Chu, Y., Chen, P., et al. 2021. Analysis of breakage behavior of rice under impact. Powder Technol. 394:533–546.

Jindal, V.K., Herum, F.L., Hamdy, M.Y.1979. Selected breakage characteristics of corn. Trans. ASAE 22:1193-1196.

Kaur, C., Solanki, D., Choudhary, L.R. 2019. Constraints in adoption of post harvest technologies in maize crop faced by farm families of Udaipur and Chittorgarh District of Rajasthan, India. Int. J. Curr. Microbiol. Appl. Sci. 8:429–432.

Keller, D.L., Converse, H.H., Hodges, T.O., Chung, D.S. 1972. Corn kernel damage due to high velocity impact. Trans. ASAE 15:0330–0332.

Khan, K., Moses, S.C., Kumar, A., Kumar, D. 2017. Design a seed metering wheel for sowing pigeon pea seeds. Int. J. Curr. Microbiol. Appl. Sci. 6:4291–4299.

Kroupa, P. 2003. The outer quality loss during grain post-harvest treatment and handling. Res. Agric. Eng. 49:91–102.

Kumar, D., Kalita, P. 2017. Reducing postharvest losses during storage of grain crops to strengthen food security in developing countries. Foods 6:8.

Kumar Korram, A., Jogdand, S.V., Victor, V.M., Chandravanshi, A., Mandal, S. 2018. Feasibility testing of mini rice mill operation in animal driven rotary mode system. Int. J. Curr. Microbiol. Appl. Sci. 7:2433–2440.

Langer, J.S. 2008. Shear-transformation-zone theory of plastic deformation near the glass transition. Phys. Rev. E 77:021502.

Lemaitre, J., Chaboche, J.-L. 1990. Mechanics of solid materials. Cambridge, Cambridge University Press.

Li, Z., Thomas, C. 2014. Quantitative evaluation of mechanical damage to fresh fruits. Trends Food Sci. Technol. 35:138-150.

Liu, M., Shi, X. 2019. Brief introduction of engineering property for coarse grained soil. IOP Conf. Ser. Earth Environ. Sci. 267:032047.

Liu, X., Yang, J. 2003. Effects of vehicle impact velocity and front-end structure on dynamic responses of child pedestrians. Traffic Inj. Prev. 4:337–344.

Lizhang, X., Yaoming, L., Zheng, M., Zhan, Z., Chenghong, W. 2013. Theoretical analysis and finite element simulation of a rice kernel obliquely impacted by a threshing tooth. Biosyst. Eng. 114:146–156.

Looh, G.A., Xie, F., Mangeh (III), F.C., Wang, X., Wang, X. 2020. Performance assessment of a self-propelled paddy grain thresher under different threshing functional parameters. Appl. Eng. Agric. 36:141–149.

Maindarkar, S., Dubbelboer, A., Meuldijk, J., Hoogland, H., Henson, M. 2014. Prediction of emulsion drop size distributions in colloid mills. Chem. Eng. Sci. 118:114–125.

Mima, G., Oka, T. 1967. Grain-boundary sliding in high-purity aluminium (99.999%) bicrystals during the high-temperature (isothermal) shear test. Trans. Jpn. Inst. Met. 8:40–44.

Mohammadi Shad, Z., Atungulu, G.G. 2019. Post-harvest kernel discoloration and fungi activity in long-grain hybrid, pureline and medium-grain rice cultivars as influenced by storage environment and antifungal treatment. J. Stored Prod. Res. 81:91–99.

Nuttall, J.G., O'Leary, G.J., Panozzo, J.F., Walker, C.K., Barlow, K.M., Fitzgerald, G.J. 2017. Models of grain quality in wheat - A review. Field Crops Res. 202:136–145.

Oli, P., Ward, R., Adhikari, B., Torley, P. 2016. Colour change in rice during hydration: Effect of hull and bran layers. J. Food Eng. 173:49–58.

Onwe, D.N., Umani, K.C., Olosunde, W.A., Ossom, I.S. 2020. Comparative analysis of moisture-dependent physical and mechanical properties of two varieties of African star apple (Chrysophyllum albidum) seeds relevant in engineering design. Sci. Afr. 8:e00303.

Panasiewicz, M., Grochowicz, J., Sobczak, P. 2009. Influence of hydrothermal processes on selected physical properties of oat grain. J. Food Eng. 90:81–89.

Paulsen, M.R., Singh, M., Singh, V. 2019. Measurement and maintenance of corn quality. In: S.O. Serna-Saldivar (ed.), Corn (Third Edition). AACC International Press. pp. 165–211.

Polikarpova, E.P., Mizikovskiy, I.E. 2020. Objectification of losses in accounting of agricultural organizations. Proceedings of the International Conference on Policies and Economics Measures for Agricultural Development (AgroDevEco 2020). Atlantis Press. pp. 283-289.

Rao, R.V., Pawar, R.B. 2020. Constrained design optimization of selected mechanical system components using Rao algorithms. Appl. Soft Comput. 89:106141.

Rice, J.R. 1968. A path independent integral and the approximate analysis of strain concentration by notches and cracks. J. Appl. Mech. 35:379-386.

Roberts, A.W., Arnold, P.C. 1966. Grain damage due to agricultural machinery part 1 - Harvesting Machines (survey only) and auger conveyors. Wollongong University College Bulletin. Available from: https://archivesonline.uow.edu.au/nodes/view/18013#idx198509

Schmidt, M., Zannini, E., Arendt, E. 2018. Recent advances in physical post-harvest treatments for shelf-life extension of cereal crops. Foods 7:45.

Shirmohammadi, M., Charrault, E. 2018. Determining properties of almond kernel under various moisture content levels. Acta Hortic. 199-206.

Sreenivasulu, N., Butardo, V.M., Misra, G., Cuevas, R.P., Anacleto, R., Kavi Kishor, P.B. 2015. Designing climate-resilient rice with ideal grain quality suited for high-temperature stress. J. Exp. Bot. 66:1737–1748.

Srivastava, A.K. 2006. Engineering principles of agricultural machines. St. Joseph American Society of Agricultural and Biological Engineers.

Tavares, L.M., Carvalho, R.M. 2007. Impact work index predic-