Review article
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Factors influencing maize kernel breakage – a review

Čimbenici koji utječu na lom zrna kukuruza – pregled

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ABSTRACT

Maize (*Zea mays* L.) kernels are exposed to mechanical and physical impacts during harvest, transport, handling, and processing. Between harvest and processing, there are losses in grain weight and reduced physical quality often occurs. Cracked or broken kernels are quality factors that reduce the efficient use and sales value of maize grain. The adverse influence of mechanical impact on maize kernels ranges from the development of small and large cracks of the pericarp to completely broken kernels, and dust generation. Increasing the amounts of broken kernels results in potential problems during storage due to faster spoilage of grain, difficult and uneven aeration during handling and grain drying, increased risk of spontaneous heating and explosion, increased animal health issues due to reduced utilization rate, and increased respiratory infections of humans and animals, and inefficient processing due to unfavourable ratio of high-value products to low-value products in dry and wet milling. The maize kernel structure, the production system, and the climatic condition's during the maize growing season influence kernel hardness and brittleness or breakage susceptibility causing differences in the amount of breakage present. During artificial grain drying, high temperatures on the kernel surface lead to internal moisture gradients within grain kernels resulting in increased kernel crackage and breakage.

Keywords: climatic conditions, harvesting, kernel breakage, grain drying, grain storage

SAŽETAK

Zrna kukuruza (*Zea mays* L.) izložena su mehaničkim i fizičkim utjecajima tijekom žetve, transporta, i prerade. Između žetve i prerade pojavljuju se gubici u masi zrna, ali dolazi i do pogoršavanja fizičkih svojstava. Jedan od parametara kvalitete kukuruza je i udio polomljenih zrna koji može djelovati na prodajnu vrijednost kukuruza i na učinkovitost prerade. Uslijed mehaničkog utjecaja u perikarpu zrna kukuruza mogu se pojaviti manje ili veće pukotine, ali može doći i do dezintegracije zrna i nastanka prašine. Povećanje udjela loma u masi zrna može uzrokovati probleme tijekom skladištenja zbog bržeg kvarenja zrna, otežanog i neravnomjernog prozračivanja (ventiliranja) zrnene mase tijekom rukovanja i sušenja. Zatim, povećava se rizik od spontanog zagrijavanja (samozagrijavanja) i eksplozije, povećava se rizik od zdravstvenih problema kod životinja zbog lošijeg iskorištenja hrane, povećava se rizik od oboljenja rukovanja ljudi i životinja zbog respiratornih infekcija i na kraju ne postiže se ciljani (dobar) odnos visokovrijednih i manje vrijednih proizvoda u suhoj i vlažnoj meljavi. Struktura zrna, primijenjena agrotehnika i klimatske prilike tijekom vegetacijske sezone, utječu na tvrdoću i lomljivost zrna ili osjetljivost na lomljenje, čime se mogu objasniti razlike u sadržaju loma. Tijekom umjetnog sušenja, visoke temperature na površini zrna uzrokuju razlike u vlažnosti u unutrašnjosti zrna što ima za posljedicu nastanak pukotina i u konačnici lomljenje zrna. U ovom radu opisani su svi čimbenici koji posredno ili neposredno mogu uzrokovati oštećenja i lom zrna kukuruza kao i probleme koje navedeni čimbenici mogu prouzročiti tijekom dorade i skladištenja zrna kukuruza.

Ključne riječi: klimatski uvjeti, žetva, lom zrna, sušenje zrna, skladištenje zrna

INTRODUCTION

Based on production area and the quantity of grain production, maize (*Zea mays* L.) is the second most important crop in the world, and it is the most important crop produced in the Republic of Croatia (FAO STAT, 2023). Maize has an essential role in Croatian and world food security, and consequently, every preharvest and postharvest loss of grain quality affects the national and global grain supply chains (Mesterházy et al., 2020). Today, maize is an important feedstock for production of a large number of different products (Jukić et al., 2003; Ranum et al., 2014). Maize kernel quality attributes have been determined to facilitate marketing and end-use of grain. One of the primary quality attributes is the percent of broken kernels, that often reducing the quality of the harvested grain (Guo Ya-nan et al., 2022). The two basic methods for processing maize grain are dry milling for grits, meal, and flour, and wet milling for extraction of starch (Gwirtz and Garcia-Casal, 2014). For end-uses requiring dry milling, the most important grain properties are the absence of mycotoxins and a minimum of kernels invaded by mold, a low percent of broken kernels and a low level of stress cracks (Brekke, 1968); low brittleness as measured by kernel breakage susceptibility (Bauer and Carter, 1986; Kniep and Mason, 1989); high test weight and a high percentage of vitreous endosperm (Brekke, 1970., Paulsen and Hill, 1985); and a high yield of large particles of maize endosperm (i.e. grits) with a low concentration of oil (OTA, 1989; Paulsen et al., 1996 as cited by Kim, 2000a).

Thus, maize genotype and production practices, climate during the growing season, and harvest and handling processes that influence these desirable attributes are critical (Bilanski, 1963; Kneip and Mason, 1989; Duarte et al., 2005). Physical kernel damage can be classified as external and internal. External damage is caused mostly during harvest by combines/harvesters and handling equipment used to move maize grain from the field to the processing facility. Internal physical damage is caused by differential temperature and humidity of air surrounding versus inside kernels during field and artificial drying, or by physical impact or abrasion during harvest and handling and on rough concrete surfaces (Kalbasi-Ashtari, 1980). Damage caused by human activities or climatic conditions has both visible and invisible impacts with direct effects on grain quality or predisposing grain to further damage. The physical quality properties of a kernel are affected by the genotype, management practices, and environment during field production, by harvest timing and type of equipment during post-harvest handling, grain drying practices, storage structures, and transportation method (Maier and Bakker-Arkema, 2002; Mutungi et al., 2019). During threshing, grain cleaning, conveying, and handling grain loss can occur through both the sifting out of broken kernels and the lowering of the quality of the remaining kernels due to cracking, splitting, or breakage.

Namely, according to AACC method 55-20 (AACC, 1981), breakage susceptibility is defined as potential for corn kernel fragmentation when subjected to impact forces during (Martin et al., 1987). Between the field to the processing facility, the processes of harvesting, drying, storing, and handling maize physically stress the kernels by a combination of forces including compression, impact, shear, and abrasion (Watson and Herum, 1986). These physical stresses interact with kernel physical and chemical properties, temperature, moisture level and gradients (Fleurat-Lessard, 2016). Opinions differ to which force in commercial handling is the most important for kernel breakage, but most agree that cumulative impacts contributor to breakage. The purpose of this paper is to analyse the influence of various factors which cause the maize kernel breakage during vegetation as well as during the harvest, handling, storage and processing.

GRAIN YIELD AND GRAIN PROPERTIES

Grain yield and kernel breakage susceptibility

There are two basic principles that account for much of the difference in kernel breakage of maize grain. The first principle defines genetics, applied production practices, high soil or fertilizer nitrogen, irrigation and climate generally as the cause of higher grain yields and lower grain protein of softer kernels that are more sensitive to brittleness and more susceptible to kernel breakage (Figure 1, Mason and D'Croz-Mason, 2008). The second principle is based on the knowledge that conditions of lower nitrogen supply to maize plants lead to decreased total and zein protein concentrations in kernels, softer kernels that are usually more brittle and more likely to break (Figure 1). Often these two principles conflict with each other as high nitrogen availability is important to produce high grain yields, and producers must balance the economic needs for high grain yield versus minimizing potential kernel breakage. It is clear from the principles presented above that producers and processors cannot eliminate kernel breakage, but rather that management and handling grain must be used to minimize kernel breakage.

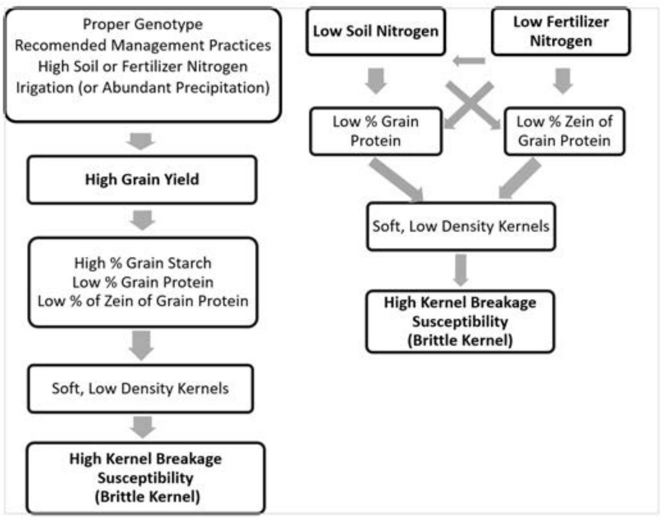

Figure 1. Flow charts of relationships between grain yield and nitrogen supply and maize kernel breakage susceptibility

Properties of maize genotypes and breakage susceptibility

Kernel characteristics and ear structure of maize genotypes are related to breakage susceptibility. Kernel properties includes that larger kernels are more susceptible to breakage than smaller kernels (Thompson and Foster, 1963; Miller et al., 1981; Le Ford and Russell, 1985; Moes and Vyn, 1988), round kernels are more susceptible to breakage than flat kernels (Thompson and Foster, 1963; Martin et al., 1987; Moes and Vyn, 1988; Balala et al., 2023), heavily kernels have lower susceptibility to breakage (Bauer and Carter, 1986), hard kernels have higher horny-flour ratios and are usually less susceptible to breakage than soft kernels (Le Ford and Russell, 1985; Szaniel et al., 1984; Li et al., 1996), and kernels with a thick pericarp have less kernel breakage than kernels with thin pericarps (Szaniel et al., 1984; Li et al., 1996). In addition to kernel properties, maize genetics is a major factor influencing kernel breakage often through regulation of kernel moisture concentration and rate of drydown between physiological maturity and harvest (thickness and properties of the pericarp and endosperm type and osmotic diffusion pressure of the kernels and morphological properties of ears, indirect effect on kernel breakage).

FACTORS INFLUENCING THE KERNEL BREAKAGE

Pre-conditioning factors affecting maize kernel breakage

Scientists have been studying the factors that influence the occurrence of maize kernel breakage for many years. A summary of factors influencing maize kernel breakage are presented in Table 1 with related human management activities and climatic factors. Below are the factors that influence maize kernel breakage susceptibility.

Table 1. Influence of human activities and climatic conditions on maize kernel breakage

Production chain actions	Category of damage	Visibility of damage	Human activities			Climatic conditions	
			Impact on kernel breakage	Applied procedures	Factors affecting kernel breakage	Impact on kernel breakage	Factors affecting kernel breakage
Vegetation period	- External	Visible/ Invisible	Possible	Applied management practices	- Hybrid (kernel structure) - Planting date - Plant density - Fertilization (N) - European corn borer (Ostrinia nubilalis) - Birds and game	Possibly strong	- Precipitation - Air temperature - Air humidity - Hail
Harvest	Internal/ External	Visible/ Invisible	Predisposition/ Direct	Selection and adjustment of machinery	- Hybrid (kernel structure, diameter and shape of the ear and cob) - Grain moisture content - The speed of combine - Machine type and adjustment of combine header and threshing device	Predisposition	- Precipitation - Air temperature - Air humidity - Hail
Grain conditioning	Internal/ External	Visible/ Invisible	Direct	Selection and adjustment of equipment	- Internal conveying elements - Drying technology - Cooling the grains after drying	Strong	-Air temperature -Air humidity
Handling and transport	Internal/ External	Visible/ Invisible	Direct	Selection of means of transport and Adjustment of silo internal transportation system	- Grain moisture content - Unloading or reloading the buffer trailers with augers - Adjustment of transporters, bucket elevators and augers - Grain cleaning	Strong	-Air temperature -Air humidity
Grain Storage	Internal/ External	Visible/ Invisible	Direct	Selection of materials and constructions and adjustment of equipment	-Bin construction materials -Internal conveying elements -Unloading or reloading of bins	Strong	- Air temperature - Air humidity - Thermal conductivity of bin walls

Factors influencing maize kernel breakage susceptibility before physiological maturity

Kernel brittleness (i.e., kernel breakage susceptibility) is the most important kernel property related to breakage and is influenced by the applied management practices (Table 1, Figure 2). Among applied management practices, nitrogen fertilizer rate or soil nitrogen level has proved to be more important than other factors, because nitrogen increases the total and zein protein concentration of grain (Jellum et al., 1973; Bauer and Carter, 1986.; Sabata and Mason, 1992; Tsai et al., 1992; Zhang et al., 1993; Oikeh et al., 1998; Singh et al., 2005; Miao et al., 2006; Ruffo et al. al., 2007; Masoero et al., 2011; Holou and Kindomihou, 2011; Marković, 2014. Simić et al., 2020), and kernel hardness and decreases breakage susceptibility (Johnson and Russell, 1982; Kneip and Mason, 1989; Tsai et al., 1992; Ahmadi et al., 1995; Duarte et al., 2005; Tamagno et al., 2016). In production conditions with water deficits, the protein concentration of maize kernels usually increases as grain yield decreases (Ghassemi-Golezani et al., 2016). By increasing the amount of soil and/or fertilizer nitrogen, the proportion of zein protein increases and kernels become more resistant to mechanical damage (Rending and Broadbent, 1979; Tsai et al., 1992; Olckers et al., 2022). The total and zein protein concentration can be influenced by cultivation systems such as crop rotation, double-crop and other production practices that influence grain yield and nitrogen and zein protein concentrations of grain (Simić et al., 2020) and the related kernel hardness and breakage susceptibility. According to Fox and Manley (2009), both the content and composition of the zein fractions affected hardness. Kernel hardness is linked to specific zein proteins, especially alpha- and gamma-zein (Paiva et al., 1991; Lopes and Larkins, 1991; Dombrink-Kurtzman and Bietz, 1993). According to Dombrink-Kurtzman and Bietz (1993) more alpha-zein proteins occurred in hard than in soft endosperm fractions. In contrast, soft endosperm contained more 27-kDa gamma-zein on a percentage basis than did hard endosperm. With increasing hardness, the kernel is usually more resistant to mechanical damage (Cheetham et al., 2006).

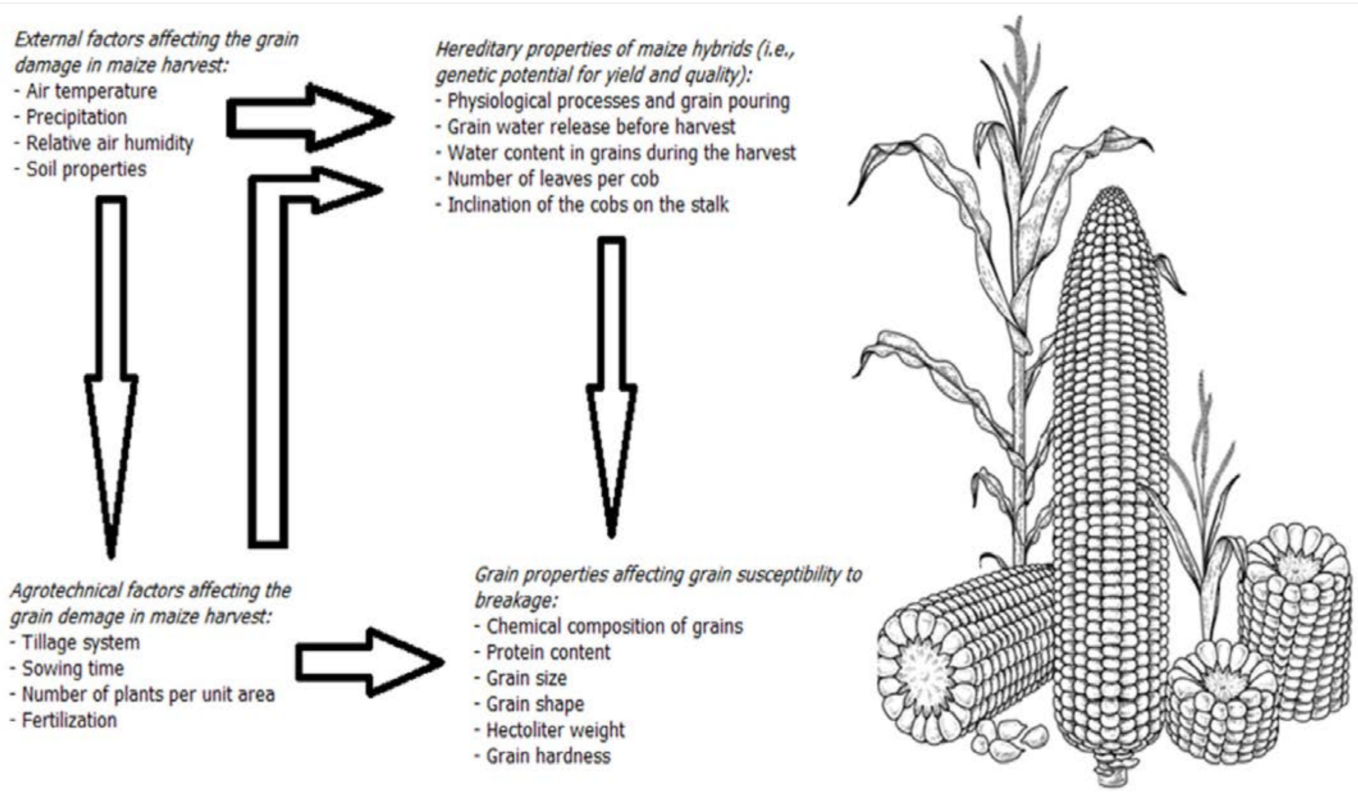

Figure 2. Factors affecting damage to corn kernels during growing season and harvest

By increasing the plant population grain yield is often increased, protein concentration decreases (Ahmadi et al., 1993; Ruffo et al., 2007), and susceptibility to kernel breakage increases (Bauer and Carter, 1986; Moes and Vyn, 1988; Vyn and Moes, 1988). Likewise, delayed planting of maize often decreases grain yield and increases susceptibility to kernel breakage (Cloninger et al., 1975; Moes and Vyn, 1988; Vyn and Moes, 1988; Kneip and Mason, 1989; Shumway et al., 1992). Irrigating maize during the growing season, or presence of abundant seasonal precipitation, decreases kernel density and increases the susceptibility to maize kernel breakage (Bauer and Carter, 1986; Kneip and Mason, 1989). Kernel brittleness and other properties are influenced by environmental factors during kernel development between grain fill (i.e., from R3 to R6 growth stages) such as soil water/moisture status, air temperature, and soil nitrogen availability (Kettlewell, 1996).

Stressful conditions during grain-fill (stages R4 and R5) often decrease kernel size and weight due to inadequate carbohydrate supply (Abendroth et al., 2011). During grain-fill growth stages, grain yield, starch, protein and zein protein concentrations, and breakage susceptible are determined. Starch synthesis in maize kernel is more sensitive than protein synthesis to environmental conditions thus is a more important factor is stress production environments. Starch granules and proteins are more strongly bound in the hard endosperm than in the soft endosperm (Gooding and Davies, 1997). Martinez et al. (2022) stated that endosperm hardness depends on the degree of association between the protein matrix and amyloplasts inserted within it. Maize endosperm contains both amylose and amylopectin starch types, and the proportion of these starch types is dependent not only on genetics but also due to environmental conditions (Beckles and Thitisaksakul, 2014). Martinez et al. (2017) found that late sowing dates reduced the amylose percentage and the amylose/starch ratio. High temperatures during grain-fill growth stages cause a decrease in the proportion of amylose and an increase in the proportion of amylopectin in corn starch (Lu et al., 1996). Maize kernel endosperms with a high proportion of amylose starch are more compressible and harder than an endosperm with a high proportion of amylopectin starch (Dombrink-Kurtzman and Knutson, 1997). On the one hand, increasing the starch content decreases kernel hardness (Robutti et al., 2000), and on the other hand, as mentioned before, increasing the amylose content increases maize kernel hardness (Sandhu et al., 2007). Thus, it can be concluded that in addition to total and zein protein concentrations, starch properties also affect kernel breakage. It is important that the appropriate genotype be planted (Duarte et al., 2005; Novacek et al., 2013) in a desirable climate with recommended production practices (Eyhérabide et al., 2004; Cirilo et al., 2011; Martinez et al., 2022) and that the duration of grain fill lasts as long as possible to attain high grain yields (Novacek et al., 2013) with hard/dense kernels with desirable shape, size and low kernel breakage susceptibility is produced.

Factors influencing maize kernel breakage susceptibility between physiological maturity and harvest

After physiological maturity, kernel and ear structure affect the kernel moisture content at harvest, altering breakage susceptibility. Kernel moisture is related to the thickness and properties of the pericarp (Purdy and Crane, 1967b; Wolf et al., 1969; Helm and Zuber, 1969), and endosperm type and osmotic diffusion pressure of the kernels (Crane et al., 1959; Purdy and Crane, 1967a; Nass and Crane, 1970; Georgiev and Mohutanov, 1980). Kernel moisture is also related to the morphological properties of ears (Fig 2). These include husk leaf number (Troyer and Ambrose, 1971; Georgiev and Mohutanov, 1980; Cavalieri and Smith, 1985; Jukić, 2004; Nielsen, 2018), husk leaf thickness (Nielsen, 2018), husk leaf senescence (Snelling and Hoener, 1940; Baron and Daynard, 1984; Cavalieri and Smith, 1985; Sweeney et al., 1994; Nielsen, 2018), husk coverage of the ear (Jukić, 2004; Nielsen, 2018), husk tightness (Troyer and Ambrose, 1971; Nielsen, 2018), and ear inclination/ear angle (Cavalieri and Smith, 1985; Jukić, 2004; Nielsen, 2018). The rate of water release from kernels from physiological maturity to harvest is influenced by weather/climate conditions

(Dodds and Pelton, 1967; Jukić et al., 2007) and applied management practices such as sowing time, plant population, and fertilizer application (Olson and Sander, 1988; Pejić et al., 1997; Jukić, 2004, Figure 2).

Factors influencing maize kernel breakage during grain harvest

With the development of modern combines (harvesters) and grain carts, grain harvest is faster and easier, but the problem of kernel breakage has increased, especially when poor environmental conditions are present at harvest or when improper harvester settings are used. Since the 1970s, attention has increasingly focused on mechanical damage of maize kernels during harvest (Mahmoud and Buchele, 1975). W. Baader (1964 as cited by Volkovas et al., 2006) indicated that kernel damage is higher for maize than other crops due to these morphological characteristics and to the fact that most maize is mechanically harvested. The factors influencing the amount of kernel damage may be divided into plant and machine parameters (Table 1; Waelty, 1967). Plant parameters include kernel hardness or strength as measured by compressive strength, tensile strength, shear strength, modulus of elasticity of the kernel, kernel detachment resistance as measured by rachilla strength, glume-kernel bond strength, and cob characteristics of compressive strength and deformation (Waelti, 1967). These plant parameters are largely controlled by genetics but can be somewhat modified by production environment and practices. The primary cause of mechanical kernel damage during harvest is shelling the grain (i.e., separation of maize kernels and cob; Chen et al., 2020).

One factor which leads to increasing the percentage of broken maize kernels is high-impact shelling action during combining (Kline, 1973; Chowdhury and Buchele, 1978; Nguyen, 1982). When maize grain is being shelled by a concave combine cylinder, the ears are subjected to low and high impacts and compressive loading between the rasp bar and the filler plates of the cylinder and the steel bars of the concave (Chowdhury and Buchele, 1978). Maize ears with different diameter, shape and length are genotype properties that influence the cylinder-concave clearance which is an important machine parameter (Waelti, 1967; Petkevičius et al., 2008; Zimmer et al., 2009). Li et al. (2023) report that Huang et al. (2018) found that the concave clearance was the main factor affecting the maize threshing rate and kernel damage rate. Mechanical damage increases with increases in cylinder speed (Waelty, 1967; Chowdhury and Buchele, 1978). Differences between axial and tangential threshing mechanisms in maize kernel damage have been found with the fact that axial threshing mechanisms was better than tangential in most of the studied properties (Poničan et al., 2009). Other important machine parameters are type and number of cylinder bars (Waelti, 1967), settings of threshing devices (Baader, 1964, as cited Volkovas et al., 2006), and different threshing component types (Ma et al., 2020). Wang et al. (2021) reported that harvest losses are mainly caused by incomplete threshing and the breakage of kernels. Mechanical breakage at harvest has been shown to be influenced more by kernel size, shape, and structure than by kernel hardness (Martin et al., 1987). Besides ear and kernel morphology, kernel moisture concentration greatly influences maize kernel breakage (Kline, 1973; Johnson, 1982; Dutta, 1986; Cheetham et al., 2006; Zimmer et al., 2009; Shahbazi and Shahbazi, 2018; Ma et al., 2020; Gou et al., 2022) with least damage occurring at optimal harvest kernel moisture concentration of 18 to 24% (Johnson, 1982; Cheetham et al., 2006; Zimmer et al., 2009).

Factors influencing maize kernel breakage during the grain drying

Modern maize production practices to optimize grain yields usually results in grain harvest at 25 to 40% moisture concentration, thus requiring artificial drying (Pliestić, 1997; Vitazek, 2011). Grain drying is a very complex thermophysical process causing temperature and moisture gradients within kernels and within the grain storage bin. Wetter and warmer grain swells, drier and colder grain shrinks thereby forming physical gradients that lead to tissue rupture causing stress crackage and kernel breakage (Abasi and Minaei, 2014).

The first indication of stress from drying is a single crack usually extending from the tip toward the crown of the kernel and visible on the side of the kernel opposite to the germ (Gunasekaran et al., 1985). The grain drying method influences the amount of maize damage (Table 1). Brown et al. (1979) found that kernel stress cracking was prevalent in all batch-dried grain, regardless of the drying temperature. Breakage susceptibility and stress cracking increases with length of high drying temperatures and long drying time (Wetchacama et al., 2001). When the drier air temperature rises from 25 °C to 60 °C, it has no apparent effect on kernel chemical makeup or test weight while increasing kernel breakage susceptibility, stress-cracked kernels and percentage of broken kernels (Paulsen et al., 1983; Peplinski et al., 1989; Gürsoy et al., 2013). As drying temperature increases from 50 °C to 80 °C, the percentage of kernels with multiple and checked stress cracking increase (Kim et al., 2000b). Slow cooling after drying at high temperatures significantly reduces stress cracking.

Stress crack development was also increased by higher drying temperature and higher harvest moisture (Kim et al., 2000b; Weller et al., 1990). Rapid high temperature drying increased stress cracking of kernel, increase breakage susceptibility pre-disposing grain to breakage during subsequent handling (Nguyen, 1982; Vitázek and Jurík, 2015). There are new technologies for drying maize grain that aim to reduce energy consumption and at the same time preserve the quality of the grain (Babić and Babić, 2020; Babić et al., 2007). Certain quality parameters of maize grain are influenced by the temperature of the air used to dry the grain. The laboratory quality characteristics of test weight, viability, amount of kernel stress cracking and steeping performance were determined by Peplinski et al. (1994). Increasing drying temperature decreased test weight, germination, nitrogen solubility index, and increased kernel breakage susceptibility. High drying temperatures differentially reduce grain quality of dried kernels dependent on genotype (Shoughy et al., 2009). High-temperature drying maize grain reduces the wet milling starch recovery and quality (Vojnovich et al., 1975; Weller et al., 1988; Haros and Suarez, 1997) and dry milling yield and number of high-value products (Brekke et al., 1973; Peplinski et al., 1982; Kirleis and Stroshine, 1990).

Factors influencing maize kernel breakage during grain handling

Maize kernels may be handled 20 to 40 times between harvest and final processing (Hall, 1974, as cited by Dutta, 1986). There are two basic types of mechanical damage – abrasion and impact. Abrasion is caused by friction of the maize kernel sliding over a surface like concrete or metal. For the most part, abrasion results in very little kernel damage. Impact is the major cause of mechanical damage. Kernel is a fragile commodity that we are continually impinging against hard, immovable objects (Beckham, 1988). The various handling operations may include free fall and conveying equipment such as screw conveyors, vertical bucket elevators, drop spouts and kernel throwers (Table 1).

Repeated handling of maize kernels in a grain elevator reduces physical quality, including increased kernel breakage (Boac, 2010). Kernel damage or breakage occurs during grain transfer from the unloading pit to the silo storage cell. These are due to loading and unloading of vehicles, trampling of grain, passing kernels through screw augers and bucket elevators while filling silo cells. The bucket elevator produces breakage through impact when buckets collect maize grain from the elevator boot (Boumans, 1985; Pliestić and Šutalo, 2001). Sands and Hall (1971) studied shelled maize grain damage during transport in a screw conveyor. They found that the conveyor caused a small amount of damage to dry maize when operated at full capacity, but the level of damage increased greatly when the conveyor was operated at 1/4 capacity. Maize kernel breakage during pneumatic conveyance is mostly due to turbulent interchange in the flow pattern, impact of kernel with each other and with pipe wall, impact at elbows (i.e., change in direction and crushing at airlock feeder) (Mwaro et al., 2012), and increasing velocity (Hellevang, 1985). Similarly, Chung (1969) concluded that greater air velocity, higher conveying length, lower grain moisture concentration, and larger size and/or round of maize kernels increased the amount of broken kernels and stress cracks, dockage, and total physical damage caused by pneumatic conveying. The most important factor was the air velocity, followed by the conveying length.

Kernel velocity, moisture content, impact surface, angle of impact, size and shape all have been shown to influence impact damage to maize kernels, with the kernel velocity at impact being the most important, and kernel size and shape (large round, small flat and large medium flat) the least important factors (Keller et al., 1972). Drop height was the most important variable in the free-fall and spouting tests (Foster and Holman, 1973) and reducing drop height shows the greatest potential for breakage reduction in commercial grain handling (Fiscus et al., 1971). Kernel breakage caused by grain falling on top other grain is consistently less than that caused by grain falling onto concrete at all grain temperatures and moisture concentrations (Fiscus et al., 1971). Mechanical damage has a negative impact on the storage of maize grain (Table 2).

During the handling of grain bulks, segregation is a natural tendency of the grain mixture components differing in some properties such as size, shape, density, particle surface roughness, electrostatic charge, chemical affinities, and stability, and/or thermal stability (Jian et al., 2019). According to the authors segregation causes many grain storage problems such as non-uniform distribution of airflow during drying and aeration, insect and mold multiplication spots, hot spot development (a pocket of grain with significantly higher temperatures and moisture contents than its peripheries), incorrect grade

Table 2. The relationship between maize kernel breakage and some factors during handling and storage

Factor	Cause	Consequences	Losses	
			Quality	Quantity
Respiration (aerobic)	Mechanically damaged kernels have higher respiration rates	Spontaneous heating (self-heating), hot spots, bin-burning, possible degrading.		+
Insects and mites	Mechanically damaged kernels are suitable for insects and mites feeding	Spontaneous heating, bin-burning, degrading, contamination, food safety, rejection for processing, impact on human health (allergens, bronchial asthma, farmer's lung, mycotoxins).	+	+
Microorganisms (Bacteria, fungi)	Fusarium spp. and Aspergilus spp. infection during the vegetation	Spontaneous heating, bin-burning, contamination by mycotoxins, degrading, food safety, rejection for processing, impact on human health (allergens, bronchial asthma, farmer's lung, mycotoxins).	+	+
Stratification and aggregation of grain mass	Broken kernels accumulate at or near the center of core in the bin	Appearance of rat holes and bridges in bins, sticking to bin walls, clogging of silo cells openings, interruption of operations, impact on general safety.	+	+
Ventilation	Broken kernels reduce the efficiency of ventilation in bin	Increasing consumption of electrical power and consequently costs of energy increase.	+	
Dust formation	Maize is one of the dustiest grain crop products; the harvesting of wet maize and forced drying - higher kernel breakage and amount of dust; smaller particle size – higher explosiveness; drier particles are easily ignited; reduced particle size via breakage decreases the economic value of maize	Impact on safety - Human safety (allergens, respiratory problems) - Explosion - Fire Costs of cleaning labour force and maintenance costs of equipment for dust control Lower proportion of high value products and product loss as dust (considerable importance for dry milling)	+	+

evaluation, and dust explosion. Mills (1989) states that cleaning harvested material to remove high-risk debris, broken seeds, immature weed seeds, chaff, dust, and other fines can improve the efficiency of aerators and bin driers by increased airflow. Damaged maize grain does not only reduce the market value, but also increases the respiration of damaged grain, which easily causes fever fermentation and infection by disease mold (Yang et al., 2022). According to Mills (1989), mold activity in binned seed products can result in clumping and aggregation of grains in localized areas, formation of bridges of material across the top or within the bin contents, or adherence of material to bin walls (hang-ups). Heat, which is produced by both seed and mold respiration, is manifested as an increase in grain temperature. Hot spots are areas within a bulk commodity that have a higher temperature than the surrounding material (Mills, 1989). As a result of the increase in temperature in the grain mass, self-ignition can occur. With each handling operation in grain facilities, dust is also generated (Martin and Sauer, 1976; Hurst and Dosman, 1990; Table 2). Thiam and Dyck (2020) found that 80 to 90% of the dust is generated during the grain transportation and reception in grain facility, and the other 10% during drying. Dust emitted during handling is a safety and health hazard as well as an air pollutant (Boac et al., 2009). The dust fraction smaller than 8 µm includes the respirable fraction that negatively influences health of workers and livestock animals (Martin and Sauer, 1976). Handling shelled maize grain generates more than twice as much total dust than handling wheat (*Triticum aestivum* L.). Dust may include particles of grain kernels, small amounts of spores of smuts and molds, insect debris, pollens, and field dust. Dusts have a high organic content and a substantial suspensible fraction, and concentrations above the minimum explosive concentration (MEC) pose an explosion hazard (US EPA, 2003). The cumulative amount of broken maize and dust produced by repeated handling is linearly related to the amount of grain transfers within grain elevators (Converse and Eckhoff, 1989). The rate of broken maize generation and dust emissions increases with high temperature heated-air drying. Considering all of the above, a lot of knowledge and experience is needed to preserve stored grain.

CONCLUSION

Maize kernel breakage has an important influence on price as broken corn and foreign material (BCFM) is a grading factor. In addition, there is lower production of high-value end products during wet and dry milling. Grain drying is negatively influenced by breakage due to segregation of broken kernels during grain bin filling leading to pockets wit reduced air flow in the stored grain. Without adequate air movement to control formation of temperature and moisture gradients, the segregated material increases moisture and temperature spots in the gain bin leading to development of molds and increasing storage insect infestation.

Kernel breakage leads to increased dust generation with consequent human and livestock health issues and possible grain combustion. Therefore, the evaluation of breakage susceptibility is critical for assessing maize pricing and determining best handling and transport methods. We further investigated the relationship production and climatic factors that precondition maize grain for kernel breakage and some ear morphology and kernel factors that influence grain breakage during harvest, handling, and storage. Maize kernel breakage cannot be avoided in modern production, but can be reduced by genotype selection, production management, and use of gentle harvesting and handling methods.

REFERENCES

Abasi, S., Minaei, S. (2014) Effect of drying temperature on mechanical properties of dried corn. Drying Technology, 32, 774–780. DOI: https://doi.org/10.1080/07373937.2013.845203

Abendroth, L. J., Elmore, R. W., Boyer, M. J., Marlay, S. K. (2011) Corn growth and development. PMR 1009. Ames: Iowa State University Extension.

Ahmadi, M., Wiebold, W. J., Beuerlein, J. E., Eckert, D. S., Schoper, J. (1993) Agronomic practices that affect kernel characteristics. Agronomy Journal, 85, 615-619. DOI: https://doi.org/10.2134/agronj1993.00021962008500030018x

Ahmadi, M., Wiebold, W. J., Beuerlein, J. E. (1995) Physical characteristics of corn kernels as influenced by nitrogen fertilization. Communications in soil science and plant analysis, 26, 145-153. DOI: https://doi.org/10.1080/00103629509369286

Babić M., Babić, Lj., Minute, G. (2007) Technical characteristics of new generation grain dryer. Journal on Processing and Energy in Agriculture, 4(11), 203-207.

Babić, M., Babić, Lj. (2020) Advantages and disadvantages of direct and indirect drying of mercantile grain and seeds. Journal on Processing and Energy in Agriculture 24 (2), 81-84.

Balala, M., Kovačev, I., Čoga, L., Slunjski, S., Cella, F., Sito, S., Jukić, Ž. (2023) Influence of nitrogen fertilization on the rupture force of maize kernels. In: Proceedings of the 49th Symposium "Actual Tasks on Agricultural Engineering". Opatija, Croatia, 28 February-2 March 2023, 303-313.

Baron, V. S., Daynard, T. B. (1984) Factors affecting grain drying in early-maturing European and Canadian corn hybrids. Canadian Journal of Plant Science, 64, 465-474. DOI: https://doi.org/10.4141/cjps84-069

Bauer, P. J., Carter, P. R. (1986) Effect of seeding date, plant density, moisture availability, and soil nitrogen fertility on maize kernel breakage susceptibility. Crop Science, 26 (6), 1220-1226. DOI: https://doi.org/10.2135/cropsci1986.0011183X002600060030x

Beckham, S. (1988) Mechanical damage - causes and solutions. In: Proceedings of the Short Course for Seedsmen. 59-89. Available at: https://ir.library.msstate.edu/bitstream/handle/11668/14108/1988-05-Beckham [Accessed 26 October 2023].

Beckles, D. M., Thitisaksakul, M. (2014) How environmental stress affects starch composition and functionality in cereal endosperm. Starch, 66 (1-2), 58-71. DOI: https://doi.org/10.1002/star.201300212

Bilanski, W. K. (1963) Breaking strenght of seed grains. Canadian Agricultural Engineering, 5 (1), 21-24. Available at: https://library.csbe-scgab.ca/docs/journal/5/5_1_21_ocr.pdf [Accessed 16 October 2023].

Boac, J. M. (2010) Quality changes, dust generation, and commingling during grain elevator handling. Doctoral dissertation. Manhattan: Kansas State University.

Boac, J. M., Maghirang, R. G., Casada, M. E., Wilson, J. D., Jung, Y. S. (2009) Size distribution and rate of dust generated during grain elevator handling. Applied Engineering in Agriculture, 25 (4), 533-541. DOI: https://doi.org/10.13031/2013.27456

Boumans, G. (1985) Grain Handling and Storage. Amsterdam: Elsevier Science Publishers B.V.

Brekke, O. L. (1968) Corn dry milling: Stress crack formation in tempering of low moisture corn and effect on degerminator performance. Cereal Chemistry, 45, 291-303. Available at: https://www.cerealsgrains.org/publications/cc/backissues/1968/Documents/chem45_291.pdf [Accessed 26 October 2023].

Brekke,O.L. (1970) Corn dry milling industry. In: Inglett, G. E., ed. Corn: culture, processing, products. Westport, CT: AVI, 262-291.

Brekke, O. L., Griffin, E. L., Shove, G. C. (1973) Dry milling of corn artificially dried at various temperatures. Transactions of the American Society of Agricultural and Biological Engineers, 16 (4), 761-765. DOI: https://doi.org/10.13031/2013.37620

Brown, R. B., Fulford, G. N., Daynard, T. B., Meiering, A. G., Otten, L. (1979) Effect of drying method on grain corn quality. Cereal Chemistry, 56 (6), 529-932. Available at: https://www.cerealsgrains.org/publications/cc/backissues/1979/Documents/chem56_529.pdf [Accessed 7 September 2023].

Cavalieri, A. J., Smith, O. S. (1985) Grain filling and field drying of a set of maize hybrids released from 1930 to 1982. Crop Science, 25 (5), 856-860. DOI: https://doi.org/10.2135/cropsci1985.0011183X002500050031x

Cheetham, H., Millner, J., Hardacre, A. (2006) The effect of nitrogen fertilization on maize grain quality and yield. In: Proceedings of the Thirty-sixth Annual Conference. Agronomy Society of New Zealand, 71-84.

Chen, Z., Wassgren, C., Ambrose, K. (2020) A review of grain kernel damage: mechanisms, modeling and testing procedures. Transactions of the American Society of Agricultural and Biological Engineers, 63 (2), 455-475 DOI: https://doi.org/10.13031/trans.13643

Chowdhury, M. H., Buchele, W. F. (1978) The nature of corn kernel damage inflicted in the shelling crescent of grain combines. Transactions of the American Society of Agricultural and Biological Engineers, 21, 610-614. Available at: https://core.ac.uk/download/pdf/38932934.pdf [Accessed 7 September 2023].

Cirilo, A. G., Actis, M., Borrás, F. S., Robutti, J. L., Andrade, F. H., Valentinuz, O. R. (2011) Crop management affects dry milling quality of flint maize kernels. Field Crops Research, 122 (2) 140-150. DOI: https://doi.org/10.1016/j.fcr.2011.03.007

Cloninger, F. D., Horrocks, R. D., Zuber, M. (1975) Effects of harvest date, plant density, and hybrid on corn grain quality. Agronomy Journal, 67 (5), 693-695. DOI: https://doi.org/10.2134/agronj1975.00021962006700050028x

Converse, H. H., Eckhoff, S. R. (1989) Corn dust emissions with repeated elevator transfers after selected drying treatments. Transactions of the American Society of Agricultural and Biological Engineers, 32(6), 2103-2107. Available at: https://www.ars.usda.gov/ARSUserFiles/30200525/Corn%20Dust%20Emissions%20with%20Repeated%20Elevator%20Transfers%20After%20Selected%20Drying%20Treatments.pdf [Accessed 7 September 2023].

Crane, P. L., Miles, S. R., Newman, J. E. (1959) Factors associated with varietial differences in rate of field drying in corn. Agronomy Journal, 51 (6), 318-320. DOI: https://doi.org/10.2134/agronj1959.00021962005100060003x

Chung, C. J. (1969) Mechanical damage to corn in a pneumatic conveying system. A Masters' thesis. Manhattan: Kansas State University.

Dombrink-Kurtzman, M. A., Bietz, J. A. (1993) Zein composition in hard and soft endosperm of maize. Cereal Chemistry, 70 (1), 105-108. Available at: https://www.cerealsgrains.org/publications/cc/backissues/1993/Documents/70_105.pdf [Accessed 24 October 2023].

Dombrink-Kurtzman, M. A., Knutson, C. A. (1997) A study of maize endosperm hardness in relation to amylose content and susceptibility to damage. Cereal Chemistry, 74 (6), 776-780. DOI: http://dx.doi.org/10.1094/CCHEM.1997.74.6.776

Dodds, M. E., Pelton, W. L. (1967) Effect of weather factors on the kernel moisture of a standing crop wheat. Agronomy Journal, 59 (2), 181-184. DOI: https://doi.org/10.2134/agronj1967.00021962005900020018x

Duarte, A. P., Mason, S. C., Jackson, D. S., Kiehl, J. C. (2005) Grain quality of Brazilian maize genotypes as influenced by nitrogen level. Crop Science, 45 (5), 1958-1964. DOI: https://doi.org/10.2135/cropsci2004.0587

Dutta, P. (1986) Effects of grain moisture, drying methods, and variety on breakage susceptibility of shelled corn as measured by the Wisconsin Breakage Tester. Doctoral dissertation. Iowa State University.

Eyherabide, G. H., Robuti, J. L., Percibaldi, N. M., Presello, D. A, Alvarez, M. D. (2004) Association between grain yield and endosperm hardness in maize cultivars. Maydica, 49 (4), 319-326.

Food and Agriculture Organization (2023) FAOSTAT Database. Food and Agriculture Organization of the United Nations. Available at: https://www.fao.org/faostat/en/#data/QC [Accessed 4 September 2023].

Fleurat-Lessard, F. (2016) Stored-grain pest management. Reference Module in Food Science. DOI: https://doi.org/10.1016/B978-0-08-100596-5.00190-6

Fiscus, D. E., Foster, G. H., Kaufman, H. H. (1971) Physical damage of grain caused by various handling techniques. Transactions of the American Society of Agricultural and Biological Engineers, 14 (3), 480-485. DOI: https://doi.org/10.13031/2013.38319

Foster, G. H. Holman, L. E. (1973) Grain Breakage Caused by Commercial Handling Method. USDA, Research Services. Marketing Research Report. No. 968. Available at: https://archive.org/details/grainbreakagecau968fost [Accessed 17 October 2023].

Fox, G., Manley, M. (2009) Hardness methods for testing maize kernels. Journal of Agricultural and Food Chemistry, 57 (13), 5647-5657. DOI: https://doi.org/10.1021/jf900623w

Ghassemi-Golezani, K., Heydari, S., Dalil, B. (2016) Changes in seed oil and protein contents of maize cultivars at different positions on the ear in response to water limitation. Acta agriculturae Slovenica, 107 (2), 311-319. DOI: https://doi.org/10.14720/aas.2016.107.2.05

Georgiev, T., Mohutanov, I. (1980) Correlations between kernel moisture content at harvest time and some maize characters. Journal of Genetics and Plant Breeding, 13, 180-190.

Gooding, M. J., Davies, W. P. (1997) Wheat production and utilization. Wallingford, UK: CAB International.

Gunasekaran, S., Deshpande, S. S., Paulsen, M. R., Shove, G. C. (1985) Size characterization of stress cracks in corn kernels. Transactions of the American Society of Agricultural and Biological Engineers, 28 (5), 1668-1672. DOI: https://doi.org/10.13031/2013.32496

Ya-nan, G., Liang-yu, H., Lu-lu, L., Shang, G., Jun-feng, H., Bo, M., Rui-zhi, X., Jun, X., Peng, H., Ke-ru, W., Shao-kun, L. (2022) Study of corn kernel breakage susceptibility as a function of its moisture content by using a laboratory grinding method. Journal of Integrative Agriculture, 21(1), 70-77.
DOI: https://doi.org/10.1016/S2095-3119(20)63250-6

Gürsoy, S., Choudhary, R., Watson, D. G. (2013) Microwave drying kinetics and quality characteristics of corn. International Journal of Agricultural and Biological Engineering, 6 (1), 90-99. Available at: https://www.ijabe.org/index.php/ijabe/article/view/751/557 [Accessed 5 September 2023].

Gwirtz, J. A., Garcia-Casal, M. N. (2014) Processing maize flour and corn meal food products. Annals of the New York Academy of Sciences, 1312 (1), 66-75. DOI: https://doi.org/10.1111/nyas.12299

Haros, M., Suarez, C. (1997) Effect of drying, initial moisture and variety in corn wet milling. Journal of Food Engineering, 34 (4), 473-481. DOI: https://doi.org/10.1016/S0260-8774(97)00099-X

Helm, J. L., Zuber, M. S. (1969) Pericarp thickness of dent corn inbred lines. Crop Science, 9 (6), 803-804. DOI: https://doi.org/10.2135/cropsci1969.0011183X000900060040x

Hellevang, K. J. (1985) Pneumatic Grain Conveyors. Journal of ASAE-850 No.58 (13), Available at: https://library.ndsu.edu/ir/bitstream/handle/10365/17333/AE-850-1985.pdf [Accessed 6 October 2023].

Holou, R. A. Y., Kindomihou, V. (2011) Impact of nitrogen fertilization on the oil, protein, starch, and ethanol yield of corn (*Zea mays* L.) grown for biofuel production. Journal of Life Sciences, 5, 1013-1021. Available at: https://www.researchgate.net/profile/Kindomihou-Valentin/publication/259502524_Impact_of_Nitrogen_Fertilization_on_the_Oil_Protein_Starch_and_Ethanol_Yield_of_Corn_Zea_mays_L_Grown_for_Biofuel_Production/links/00b4952c565eced616000000/Impact-of-Nitrogen-Fertilization-on-the-Oil-Protein-Starch-and-Ethanol-Yield-of-Corn-Zea-mays-L-Grown-for-Biofuel-Production.pdf [Accessed 6 October 2023].

Hurst, T. S.; Dosman, J. A. (1990) Characterization of health effects of grain dust exposures. American Journal of Industrial Medicine, 17 (1), 27-32. DOI: https://doi.org/10.1002/ajim.4700170106

Jian, F., Narendran, R. B., Jayas, D. S. (2019) Segregation in stored grain bulks: Kinematics, dynamics, mechanisms, and minimization – A review. Journal of Stored Products Research, 81, 11-21.
DOI: https://doi.org/10.1016/j.jspr.2018.12.004

Jellum, M. D., Boswell, F. C., Young, C. T. (1973) Nitrogen and boron effects on protein and oil of corn grain. Agronomy Journal, 65 (2), 330-331. DOI: https://doi.org/10.2134/agronj1973.00021962006500020043x

Johnson, R. S. (1982) Damage to shelled corn during transport in drag conveyors. A Master's thesis. Manhattan: Kansas State University.

Johnson, D. Q., Russell, W. A. (1982) Genetic variability and relationships of physical grain quality traits in the BSSS population of maize. Crop Science, 22 (4), 805-80. DOI: https://doi.org/10.2135/cropsci1982.0011183X002200040025x

Jukić, Ž., Krička, T., Ćurić, D., Voća, N., Koražija, M. (2003) Velocity of drying of corn kernel grown on different levels of agrotechnology for bioetanol production. Industrial Heat Engineering, 25 (4), 232-233.

Jukić, Ž. (2004) Water release rates of maize grain in the field and dryer in a convection drying process. Doctoral dissertation. Zagreb: University of Zagreb Faculty of Agriculture (in Croatian).

Jukić, Ž., Janušić, V., Matin, A., Tomić, F. (2007) Water release rate from corn kernel affected by cropping intensity. Cereal Research Communications, 35 (2), 569-572.
DOI: https://doi.org/10.1556/CRC.35.2007.2.101

Kalbasi-Ashtari, A. (1980) Effect of internal and external damage on deterioration rate of shelled corn. Retrospective Theses and Dissertations. Paper 7337. http://lib.dr.iastate.edu/rtd

Keller, D.L., Converse, H.H., Hodges, T.O., Chung, D.S. (1972) Corn kernel damage due to high velocity impact. Transactions of American Society of Agricultural Engineers 15: 330.

Kettlewell, P.S. (1996) Agronomy and cereal quality. In: Herny, R.J., Kettlewell, P.S., eds. Cereal grain quality. Chapman&Hall, London, Cambridge, pp. 407-437.

Kim, T.H., Hampton, J.G., Opara, L., Hardcare, A.K., Hill, M.J., Mackay, B. (2000a) Effects of pre-harvest and post-harvest factors on grain hardness and stress cracking in three maize hybrids. Proceedings of the Agronomy Society of New Zealand, 30:83-91.

Kim, T.H. (2000b) Physical changes in maize (*Zea mays* L.) grains during postharvest drying. Doctoral dissertation. Massey University of New Zealand.

Kirleis, A.W., Stroshine, R.L. (1990): Effects of hardness and drying air temperature on breakage susceptibility and dry-milling characteristics of yellow dent corn. Cereal Chem. 67(6):523-528.

Kneip, K.R., Mason, S.C. (1989) Kernel breakage and density of normal and opaque-2 maize grain as influenced by irrigation and nitrogen. Crop Sci. 29:158-163.

LeFord, D. R., Russell, W. A. (1985) Evaluation of physical quality in BS17 and BS1 (HS)C1. Crop Science, 25 (3), 421-425. DOI: https://doi.org/10.2135/cropsci1985.0011183X002500030010x

Li, P. X. P., Hardacre, A. K., Campanella, O. H., Kirkpatrick, K. J. (1996) Determination of endosperm characteristics of 38 corn hybrids using the Stenvert Hardness Test. Cereal Chemistry, 73 (4), 466-471.

Li, X., Zhang, W., Xu, S., Du, Z., Ma, Y., Ma, F., Liu, J. (2023) Low-damage corn threshing technology and corn threshing devices: a review of recent developments. Agriculture, 13 (5), 1006.
DOI: https://doi.org/10.3390/agriculture13051006

Lopes, M. A., Larkins, B. A. (1991) γ-Zein content is related to endosperm modification in quality protein. Crop Science, 31 (6), 1655-1662. DOI: https://doi.org/10.2135/cropsci1991.0011183X003100060055x

Lu, T., Jane, J., Keeling, P., Singletary, G. (1996) Maize starch fine structures affected by ear developmental temperature. Carbohydrate Research, 282 (1), 157-170.
DOI: https://doi.org/10.1016/0008-6215(95)00370-3

Ma, Z., Han, M., Li, Y. M., Yu, S. C., Chandio, F. A. (2020) Comparing kernel damage of different threshing components using high-speed cameras. International Journal of Agricultural and Biological Engineering, 13(6), 215-219. DOI: https://doi.org/10.25165/j.ijabe.20201306.5395

Mahmoud, A., Buchele, W. (1975) Distribution of shelled corn throughput and mechanical damage in a combine cylinder. Transactions of the American Society of Agricultural and Biological Engineers, 18 (3), 448–452. Available at: https://core.ac.uk/download/pdf/38933008.pdf [Accessed 5 October 2023].

Maier, D. E., Bakker-Arkema, F. W. (2002) Grain drying systems. Faculty Design Conference of the Grain Elevator and Processing Society. St. Charles, Illinois, 28-31 July 2002. Available at: https://fyi.extension.wisc.edu/energy/files/2016/09/Grain-drying-Systems-GEAPS-2002-secured.pdf [Accessed 14 September 2023].

Marković, M. (2014) Influence of irrigation and nitrogen fertilization on yield and quality of (*Zea mays* L.) maize grain. Poljoprivreda, 20 (1), 54-56. Available at: https://hrcak.srce.hr/index.php?show=clanak&id_clanak_jezik=182290 [Accessed 5 September 2023].

Martin, C. R., Converse, H. H., Czuchajowska, Z., Lai, F. S., Pomeranz, Y. (1987) Breakage susceptibility and hardness of corn kernels of various sizes and shapes. Applied engineering in agriculture, 3(1), 104-113. DOI: https://doi.org/10.13031/2013.26655

Martínez, R. D., Cirilo, A. G., Cerrudo, A. A., Andrade, F. H., Reinoso, L., Valentinuz, O. R., Balbi, C. N., Izquierdo, N. G. (2017) Changes of starch composition by postflowering environmental conditions in kernels of maize hybrids with different endosperm hardness. European Journal of Agronomy 86, 71-77. DOI: https://doi.org/10.1016/j.eja.2017.04.001

Martínez, R. D., Cirilo, A. G., Cerrudo, A. A., Andrade, F. H., Izquierdo, N. G. (2022) Environment affects starch composition and kernel hardness in temperate maize. Journal of the Science of Food and Agriculture, 102 (12), 5488-5494. DOI: https://doi.org/10.1002/jsfa.11903

Masoero, F., Gallo, A., Giuberti, G., Zanfi, C., Spanghero, M. (2011) Effect of nitrogen fertilization on chemical composition and rumen fermentation of different parts of plants of three corn hybrids. Animal Feed Science and Technology, 164 (3-4), 207-216. DOI: https://doi.org/10.1016/j.anifeedsci.2011.02.001

Mason, S. C., D´Croz-Mason, N. E. (2008) Agronomic practices influence maize grain quality. Journal of Crop Production, 5 (1-2), 75-91. DOI: https://doi.org/10.1300/J144v05n01_04

Martin, C. R., Sauer., D. B. (1976) Physical and biological characteristics of grain dust. Transactions of the American Society of Agricultural and Biological Engineers, 19 (4), 720-723. Available at: https://www.ars.usda.gov/ARSUserFiles/30200525/Physical%20and%20Biological%20Characteristics%20of%20Grain%20Dust.PDF [Accessed 9 September 2023].

Mesterházy, A., Oláh, J., Popp, J. (2020) Losses in the grain supply chain: causes and solutions. Sustainability, 12(6), 2342. DOI: https://doi.org/10.3390/su12062342

Miao,Y., Mulla, J. D., Pierre, C. R., Hernandez, A. J. (2006) Within-field variation in corn yield and grain quality responses to nitrogen fertilization and hybrid selection. Agronomy Journal, 98 (1), 129-140. DOI: https://doi.org/10.2134/agronj2005.0120

Miller, B. S., Hughes, J. W., Rousser, R., Poneranz, Y. (1981) Measuring the breakage susceptibility of shelled corn. Cereal Foods World, 26, 75-80.

Mills, J. T. (1989) Spoilage and heating of stored agricultural product, Prevention, detection, and control. Ottawa: Minister of Supply and Services.

Moes, J., Vyn, T. J. (1988) Management effects on kernel breakage susceptibility of early maturing corn hybrids. Agronomy Journal, 80 (4), 699-704. DOI: https://doi.org/10.2134/agronj1988.00021962008000040029x

Mutungi, C., Muthoni, F., Bekunda, M., Gaspar, A., Kabula, E., Abass, A. (2019) Physical quality of maize grain harvested and stored by smallholder farmers in the Northern highlands of Tanzania: Effects of harvesting and pre-storage handling practices in two marginally contrasting agro-locations. Journal of Stored Products Research, 84, 101517. DOI: https://doi.org/10.1016/j.jspr.2019.101517

Mwaro, W. B., Maranga, S. M., Ikua, B., Kanali, C. L. (2012) Establishing the amount of grain breakage taking place in bulk maize during conveyance through the drag chain conveyor. In: Proceedings of the 2012 Mechanical Engineering Conference on Sustainable Research and Innovation, 3-4 May 2012, 166-172.

Nass, H. G., Crane, P. L. (1970) Effects of endosperm mutants on drying rate in corn (*Zea mays* L.). Crop Science, 10 (2), 141-144. DOI: https://doi.org/10.2135/cropsci1970.0011183X001000020005x

Nguyen, V.T. (1982) Breakage susceptibility of blended corn. Doctoral dissertation. Ames: Iowa State University.

Nielsen, R. L. (2018) Field drydown of mature corn grain. Available at: https://www.agry.purdue.edu/ext/corn/news/timeless/graindrying.html [Accessed 17 October 2023].

Novacek, M. J., Mason, S. C., Galusha, T. D., Yaseen, M. (2013) Twin rows minimally impact irrigated maize yield, morphology, and lodging. Agronomy Journal, 105 (1), 268-276. DOI: https://doi.org/10.2134/agronj2012.0301

Olckers, S. L., Osthof, G., Perry, K. W. N., van Biljon, A., Labuschagne, M. (2022) The impact of low nitrogen conditions on the chemical composition and four pasting properties of quality protein maize. Cereal Research Communications, 50, 1117-1125. DOI: https://doi.org/10.1007/s42976-022-00253-6

Oikeh, S. O., Kling, J. G., Okoruwa, A. E. (1998) Nitrogen management effests on maize grain quality in the West Africa moist savanna. Crop Science, 38 (4), 1056-1061. DOI: https://doi.org/10.2135/cropsci1998.0011183X003800040029x

Olson, R. A., Sander, D. H. (1988) Corn production. In: Spraque, G.F., Dudley, J.W., eds. Corn and corn improvement (3rd edition). 639-686.

Paiva, E., Kriz, A. L., Maria, J. V., Peixoto, V. D., Wallace, J. C., Larkins, B. A. (1991) Quantitation and distribution of γ-zein in the endosperm of maize kernels. Cereal Chemistry, 68(3), 276-279.

Paulsen, M. R., Hill, L. D., White, D. G., Sprague G. F. (1983) Breakage susceptibility of corn-belt genotypes. Transactions of the American Society of Agricultural and Biological Engineers, 26 (6), 1830-1836. DOI: https://doi.org/10.13031/2013.33851

Paulsen, M. R., Hill.,L. D. (1985) Corn quality factors affecting dry milling performance. Journal of Agricultural Engineering Research, 31 (3), 255-263. DOI: https://doi.org/10.1016/0021-8634(85)90092-7

Pejić, I., Čoga, L., Puntar, I., Bolarić, S., Pecina, M. (1997) Sadržaj i intenzitet otpuštanja vlage iz zrna hibrida kukuruza kod različite gnojidbe dušikom. Poljoprivredna znanstvena smotra. 62, 3-4 (in Croatian).

Peplinski, A. J., Anderson, R. A., Brekke, O. L. (1982) Corn dry milling as influenced by harvest and drying conditions. Transactions of the American Society of Agricultural and Biological Engineers, 25(4), 1114-1117. DOI: https://doi.org/10.13031/2013.33680

Peplinski, A. J., Paulsen, M. R., Anderson, R. A., Kwolek, W. F. (1989) Physical, chemical, and dry-milling characteristics of corn hybrids from various genotypes. Cereal Chemistry, 66, 117-120.

Peplinski, A. J., Paulis, J. W., Bietz, J. A., Pratt, R. C. (1994) Drying of high-moisture corn: changes in properties and physical quality. Cereal Chemistry, 71 (2), 129-133. Available at: https://www.cerealsgrains.org/publications/cc/backissues/1994/Documents/71_129.pdf [Accessed 17 September 2023].

Petkevičius, S., Špokas, L., Steponavičius, D. (2008) Substantion of technological parameters of wet maize ear threshing. Agronomy Research, 6, 271-280. Available at: https://agronomy.emu.ee/vol06Spec/p6S12.pdf [Accessed 17 September 2023].

Pliestić, S. (1997) Expanding the Bc 492 hybrid corn corn kernel depending on the airflow in the crossflow dryer. In: Proceedings of XIII International Symposium of Technologists for Drying and Storing, Stubičke Toplice, pp. 17-43. (in Croatian).

Pliestić, S., Šutalo, M. (2001) Breakage of Corn Kernel on an Vertical Elevator Transportation. Agriculturae Conspectus Scientificus, 66 (4), 203-215. Available at: https://hrcak.srce.hr/12492 [Accessed 5 October 2023].

Poničan, J., Angelovič, M., Jech, J., Žitňák, M., Galambošová J., Findura, P. (2009) The effect of the design concept of combine harvester threshing mechanism on the maize crop threshing quality. Savremena poljoprivredna tehnika (4), 219-280, 2009. Available at: https://scindeks-clanci.ceon.rs/data/pdf/0350-2953/2009/0350-29530904268P.pdf [Accessed 16 September 2023].

Purdy, J. L., Crane, P. L. (1967a) Inheritance of drying rate in ¨mature¨ corn (*Zea mays* L.). Crop Science, 7 (4), 294-297. DOI: https://doi.org/10.2135/cropsci1967.0011183X000700040003x

Purdy, J. L., Crane, P. L. (1967b) Influence of pericarp on differential drying rate in "mature" corn (*Zea mays* L.). Crop Science, 7 (4), 379-381. DOI: https://doi.org/10.2135/cropsci1967.0011183X000700040031x

Ranum, P., Pena-Rosas, J. P., Garcia-Casal, M. N. (2014) Global maize production, utilization, and consumption. Annals of the New York Academy of Sciences, 1312 (1), 105–112. DOI: https://doi.org/10.1111/nyas.12396

Rending, V. V., Broadbent, F. E. (1979) Proteins and amino acids in grain of maize grown with various levels of applied N1. Agronomy Journal, 71 (3), 509-512. DOI: https://doi.org/10.2134/agronj1979.00021962007100030032x

Robutti, J. L., Borrás, F. S., Ferrer, M. E., Percibaldi, N. M., Knuston. C. E. (2000) Evaluation of quality factors in Argentine maize races. Cereal Chemistry, 77 (1), 24-26. DOI: https://doi.org/10.1094/CCHEM.2000.77.1.24

Ruffo, M. L., Henninger, A. S., Below, F. E. (2007) Proc. Illinois Fert. Conf., Peoria, IL. 26-28 January 2007. Illinois Dept. of Ag. Fert. Res. and Educ. Counc.

Sabata, R. J., Mason, S. C. (1992) Corn hybrid interactions with soil nitrogen level and water regime. Journal of Production Agriculture, 5 (1), 137-142. DOI: https://doi.org/10.2134/jpa1992.0137

Sandhu, K. S., Singh, N., Malhi, N. (2007) Some properties of corn grains and their flours i: physicochemical,functional and chapati-making properties of flours. Food Chemistry, 101(3), 938–946. DOI: https://doi.org/10.1016/j.foodchem.2006.02.040

Sands, L. D., Hall, G. E. (1971) Damage to shelled corn during transport in a screw conveyor. Transactions of the American Society of Agricultural and Biological Engineers, 14 (3), 584-585. DOI: https://doi.org/10.13031/2013.38344

Shahbazi, F., Shahbazi, R. (2018) Mechanical damage to corn seeds. Cercetări Agronomice în Moldova, 6 (3), 1-12. DOI: https://doi.org/10.2478/cerce-2018-0021

Shoughy, M. I., Marey, S. A., El-Shenawy, A. A. (2009) Effect of drying temperatures on stress cracks and breakage suseptibility of corn grains. Misr Journal of Agricultural Engineering, 26(1), 453- 468. DOI: https://doi.org/10.21608/mjae.2020.110163

Shumway, C. R., Cothren, J. T., Serna-Saldivar, S. O., Rooney, L. W. (1992) Planting date and moisture effects on yield, quality and alkaline-processing characteristics of food-grade maize. Agronomy Journal, 32 (5), 1265-1269. DOI: https://doi.org/10.2135/cropsci1992.0011183X003200050040x

Simić, M., Dragičević, V., Mladenović Drinić, S., Vukadinović, J., Kresović, B., Tabaković, M., Brankov, M. (2020) The contribution of soil tillage and nitrogen rate to the quality of maize grain. Agronomy, 10 (7), 976; DOI: https://doi.org/10.3390/agronomy10070976

Singh, M., Paulsen, M. R., Tian, L., Yao, H. (2005) Site–specific study of corn protein, oil, and extractable starch variability using nit spectroscopy. Applied Engineering in Agriculture, 21 (2), 239-251. DOI: https://doi.org/10.13031/2013.18138

Snelling, R. O., Hoener, I. R. (1940) Relationships between some measures of maturity in maize. Journal of the American Society of Agronomy, 32 (6), 451-454.

Szaniel, J., Sagi, F., Palvolgyi, I. (1984) Hardness determination and quality prediction of maize kernel by new instrument, the monograph (*Zea mays*, technological properties). Maydica 29, 9-20.

Sweeney, P. M., St. Martin, S. K., Clucas, C. P. (1994) Indirect inbred selection to reduce grain moisture in maize hybrids. Crop Science, 34 (2), 391-396. DOI: https://doi.org/10.2135/cropsci1994.0011183X003400020016x

Tamagno, S., Greco, I. A., Almeida, H., Di Paola, J. C., Ribes, F. M., Borrás, L. (2016) Crop management options for maximizing maize kernel hardness. Agronomy Journal, 108 (4), 1561–1570. DOI: https://doi.org/10.2134/agronj2015.0590

Thiam, A. P., Dyck, J. P. (2020) Managing dust emissions from on-farm grain handling systems. #20-045 | AGDEX 110/735 | JUNE 2020. Available at: Managing dust emissions from on-farm grain handling systems|ontario.ca [Accessed 7 August 2023].

Thompson, R. A., Foster, G. H. (1963) Stress cracks and breakage in artificially dried corn. Marketing Research Report No. 631. Agricultural Marketing Service, United States Department of Agriculture, Washington, DC.

Tsai, C. Y., Dweikat, I., Huber, D. M., Warren, H. L. (1992) Interrelationship of nitrogen nutrition with maize (*Zea mays*) grain yield, nitrogen use efficiency and grain quality. Journal of the Science of Food and Agriculture, 58 (1), 1-8. DOI: https://doi.org/10.1002/jsfa.2740580102

Troyer, A. F., Ambrose, W. B. (1971) Plant characteristics affecting field drying rate of ear corn. Crop Science, 11 (4), 529-531. DOI: https://doi.org/10.2135/cropsci1971.0011183X001100040019x

Vitázek, I. (2011) Technika sušenia v teórii a v praxi – Obilniny (Drying technique in theory and in practise - Cereals). Nitra: SPU v Nitre, 2011, 100p. ISBN 978-80-552-0641-7.

Vitázek, I., Jurík, I. (2015) Technika pre sušenie a skladovanie zrnín (Technique for drying and storing grains). Nitra: SPU v Nitre, 135. ISBN 978-80-552-1419-1.

Vojnovich, C., Anderson, R. A., Griffin, J. E. L. (1975) Wet-milling properties of corn after field shelling and artificial drying. Cereal Foods World, 20 (7), 333-335.

Volkovas, V., Petkevičius, S., Špokas, L. (2006) Establishment of maize grain elasticity on the basis of impact load. ISSN 1392 - 1207. MECHANIKA. 2006. Nr.6(62).

Yang, L.; Lü, Q.; Zhang, H. (2022) Experimental study on direct harvesting of corn kernels. Agriculture, 12 (7), 919. DOI: https://doi.org/10.3390/agriculture12070919

Vyn, T. J., Moes, J. (1988) Breakage susceptibility of corn kernels in relation to crop management under long growing season conditions. Agronomy Journal, 80 (6), 915-920. DOI: https://doi.org/10.2134/agronj1988.00021962008000060015x

US EPA. (2003) Food and Agricultural Industries. In Emission Factors/ AP-42. 5th ed. Vol. I. Research Triangle Park, N.C.: U.S. Environmental Protection Agency.

Waelti, H. (1967) Physical properties and morphological characteristics of maize and their influence on threshing injury of kernels. Doctoral dissertation. Ames: Iowa State University.

Wang, K., Xie, R., Ming, B., Hou, P., Xue, J., Shaokun Li, S. (2021) Review of combine harvester losses for maize and influencing factors. International Journal of Agricultural and Biological Engineering, 14 (1), 1-10. Available at: https://www.ijabe.org/index.php/ijabe/article/view/6034 [Accessed 11 October 2023].

Watson, S. A., Herum, F. L. (1986) Comparison of eight devices for measuring breakage susceptibility of shelled corn. Cereal Chemistry, 63(2), 139-142. Available at: https://www.cerealsgrains.org/publications/cc/backissues/1986/Documents/Chem63_139.pdf [Accessed 17 September 2023].

Weller, C. L., Paulsen, M. R., Steinberg, M. P. (1988) Correlation of starch recovery with assorted quality factors of four corn hybrids. Cereal Chemistry 65 (5), 392-397. Available at: https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1097&context=biosysengfacpub [Accessed 18 September 2023].

Weller, C. L., Paulsen, M. R., Steinberg, M. P. (1990) Stress cracking and breakage susceptibility as affected by moisture content at harvest for four yellow dent corn hybrids. Transactions of the American Society of Agricultural and Biological Engineers, 33 (3), 863-869. DOI: https://doi.org/10.13031/2013.31411

Wetchacama, S, Soponronnarit, S., Prachayawarakorn, S., Pongpullponsak, A., Tuntiwetsa, W., Kositcharoeankul, S. (2001) Study of parameters affecting drying kinetics and quality of corns. Kasetsart Journal, 35 (2), 195-204.

Wolf, M. J., Cull, I. M., Helm, J. L., Zuber, M. S. (1969) Measuring thickness of excised mature corn pericarp. Agronomy Journal, 61 (5), 777-779. DOI: https://doi.org/10.2134/agronj1969.00021962006100050037x

Zimmer, R., Košutić, S., Zimmer, D. (2009) Poljoprivredna tehnika u ratarstvu (Agricultural technology in farming). Osijek: Sveučilište J. J. Strosmayera Poljoprivredni fakultet Osijek (in Croatian).

Zhang, F., Mackenzie, A. F., Smith, D. L. (1993) Corn yield and shifts among corn quality constituents following applications of different nitrogen fertilizer sources at several times during corn development. Journal of Plant Nutrition, 16 (7), 1317-1337. DOI: https://doi.org/10.1080/01904169309364615