



Article

Assessing the Effects of Free Fall Conditions on Damage to Corn Seeds: A Comprehensive Examination of Contributing Factors

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Abstract: Corn is a staple food crop grown in over 100 countries worldwide. To meet the growing demand for corn, losses in its quality and quantity should be minimized. One of the potential threats to the quality and viability of corn is mechanical damage during harvesting and handling. Despite extensive research on corn, there is a lack of reliable data on the damage its seeds undergo when they are subjected to mechanical impact against different surfaces during handling and transportation. This study is designed to investigate the effects of (a) drop height (5, 10, and 15 m) during free fall, (b) impact surface (concrete, metal, and seed to seed), seed moisture content (10, 15, 20, and 25% w.b), and ambient temperature (−10 and 20 °C) on the percentage of physical damage (PPD) and physiological damage to corn seeds. The PPD and the extent of physiological damage were determined as the percentage of seed breakage and the percentage of loss in germination (PLG), respectively. The latter parameter was specifically chosen to evaluate seeds that showed no visible external damage, thus enabling the assessment of purely internal damage that PPD did not capture. This approach enabled a comprehensive analysis of free fall's influence on the seeds' quality and viability, providing a complete picture of the overall impact. Total damage was then calculated as the sum of PPD and PLG. An evaluation and modeling process was undertaken to assess how corn seed damage depends on variables such as drop height, moisture content, impact surfaces, and temperatures. The results revealed that seeds dropped onto metal surfaces incurred a higher total damage (15.52%) compared to concrete (12.86%) and seed-to-seed abrasion (6.29%). Greater total damage to seeds was observed at an ambient temperature of −10 °C (13.66%) than at 20 °C (9.46%). Increased drop height increased seeds' mass flow velocity and correspondingly caused increases in both physical and physiological damage to seeds. On the other hand, increased moisture levels caused a decreasing trend in the physical damage but increased physiological damage to the seeds. The limitations of the developed models were thoroughly discussed, providing important insights for future studies. The results of this study promise to deliver substantial benefits to the seed/grain handling industry, especially in minimizing impact-induced damage.



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1. Introduction

With the ever-growing world population, minimizing food losses has become critical to ensuring food security in the world. Damage inflicted mechanically during harvesting and handling is one of the potential detriments to crops' overall quality and survival. In this regard, evaluating and modeling mechanical damage for grain and oilseeds have regained growing interest over the past few years [1–3]. Corn is one of the most important food crops worldwide, with a total world production of 1.2 billion tons in 2022 [4]. Indeed, due to the large mass and size of the corn seed, it is highly susceptible to mechanical damage [5–7]. Moreover, the absence of gluten, an innate internal adhesive found in other grains such as wheat and barley, contributes to the fragility of corn seeds [8]. One of the major causes of corn losses in its supply chain is the impact stress caused by factors such as free fall



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during different stages of harvesting, handling, and post-harvest processing. During these operations and based on the nature of the process, seeds may fall from various heights and hit different surfaces, inducing impact stress that causes quality and quantity losses.

Mechanical damage in seeds due to impact force can be broadly classified into external and internal damage [9]. External damage includes fissures, cracks, and fractures to the seed's exterior surface that are visible. On the other hand, internal damage (also known as 'stress cracking' or damage to the seed embryo) refers to fissures or small cracks caused by tensile or compressive stress through or following the processes of drying or rehydration, or as a result of force from impact loading [10]. Seeds depicting pronounced stress cracks tend to break more readily during subsequent handling and transportation are more susceptible to insect and mold infestation during storage, and usually have low viability [11,12]. Overall, mechanical damage to seeds can cause a decrease in their economic value, decreased storage potential [12] and viability [13–15], health concerns [16–18], and an increase in the downstream costs related to processing and product manufacturing [19].

During harvesting, handling, and transportation, seeds experience free fall and impact damage in combines, railcars/trucks, augers, and conveyors made from different materials. The severity of induced impact damage hinges on several parameters, including the height of the drop, the seed/grain's inherent features and prevailing conditions [density, size, moisture content (MC), and temperature], the ambient temperature, the type of surface that the impact occurs on, and the seeds' collision angle with the surface [1]. In this regard, researchers have conducted drop tests on various seeds, including corn, soybean, flaxseed, and wheat [2,8,10,13,20–24]. The results of these studies illustrate that impact damage to seeds increases with drop height but may decrease with MC and temperature [13,20].

Despite several studies on the impact of free fall on seed damage, to the best of our knowledge, no research has provided a comprehensive assessment considering varying drop heights, impact surface materials, seed MCs, and ambient temperatures simultaneously. This study bridges this gap, offering a comprehensive evaluation of physical damage to corn seeds under these multifaceted conditions, and assessing the physiological impact (expressed as percentage loss in germination (PLG)) on seeds that visually appear undamaged. In addition, this study provides measurements of mean seed velocities (both single kernel and mass flow) when dropped from different heights, introduces models for predicting the total induced damage, and identifies limitations within these models, pointing to potential areas for future research. This thorough approach and the inclusion of predictive damage modeling distinguish this study as it expands upon the existing research corpus. The insights garnered here are anticipated to foster more precise and in-depth studies in the future.

2. Materials and Methods

2.1. Sample

Corn seeds of the KSC709 hybrid were manually harvested at the optimum ripening stage for free fall tests. This hybrid exhibits broad adaptability to various regions in Iran and boasts a high potential yield of grain and silage. Harvested samples were stored at a temperature of 5 °C and relative humidity of around 90%, prior to the start of the experiments. These storage conditions were chosen to prevent seed germination before the tests [25]. The initial MC of seed samples was determined according to ASABE standard S352.2 [26] to be around 10%. Seed samples with higher MCs were prepared by spring pre-calculated amounts of distilled water and kept at 4 °C for 10 days.

2.2. Free Fall Test

Free fall conditions were simulated in laboratory trials to evaluate the effect of dropping corn samples onto various impact surfaces from different heights at diverse seed MCs and under different ambient temperatures. Three drop heights were selected: 5, 10, and 15 m, which typically reflect situations that could transpire on agricultural land, in

seed cleansing units, or at seed elevator sites [10]. The drop tests included three different surfaces: concrete, metal, and seeds on seeds. These tests were performed under two distinct ambient temperatures: 20 °C and −10 °C. To maintain a temperature of 20 °C, the experimental set-up was housed in a temperature-controlled environment. In the latter case, the set-up was placed outdoors when the temperature was −10 °C.

Each seed sample, weighing 500 g, was dropped from pre-determined varying heights through a polyvinyl chloride (PVC) pipe. Every observation set was replicated thrice. Prior to the free fall tests, seed samples were conditioned at the intended ambient temperature (either 20 °C or −10 °C) for a duration of 5 h. To achieve various drop heights, PVC pipes with a diameter of 100 mm were used. A hopper featuring a 40 mm opening was positioned at the apex of each pipe. The seed-drop rate was maintained at 0.25 kg/s. The pipe's lower end opened into a custom-built wooden compartment (Figure 1). To prevent the bouncing of seeds, a foam core was positioned at the front of this compartment. Test surfaces were arranged within this space. Impact surfaces were inclined at a 45° angle at the drop testing device's base to simulate seed drop in an empty hopper bin. These surfaces measured approximately 500 mm × 400 mm. Two wooden flaps were situated just above the impact surfaces, funneling seeds into a bucket positioned underneath. For seed-on-seed drop tests, a bucket filled with seeds of similar MC was used as a test surface. A very thin plastic wrap, constantly in contact with the seed surface, was laid on the test surface to facilitate easy separation of test samples.

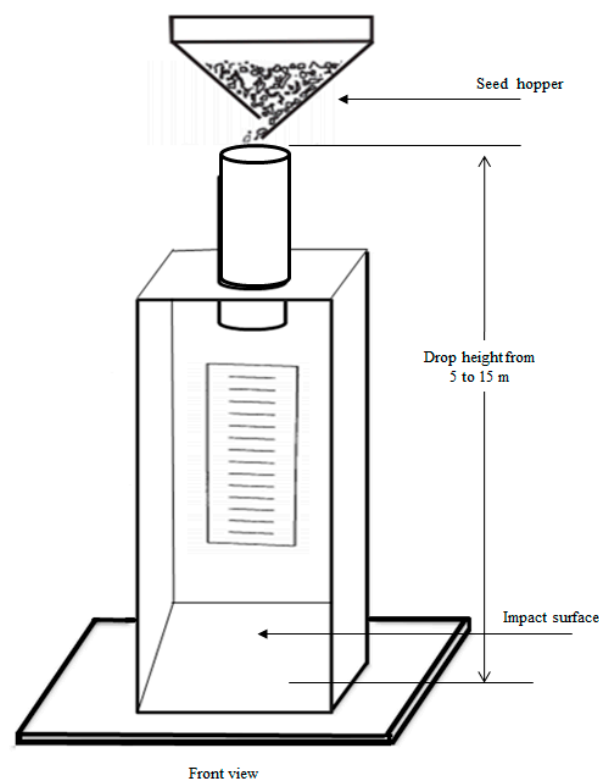


Figure 1. Schematic of wooden compartment used in drop tests.

2.3. Damage Assessment

After conducting the free fall tests, the tested seeds were manually sorted by a team of trained professionals. Through close visual inspection under a magnifying lens, seeds from each experimental group were categorized as either physically damaged or -undamaged [13,27]. Seeds with fissures and visible cracks were considered physically damaged. The percentage of physical damage (PPD) was computed by using the following equation [13]:

$$PPD = \frac{W_d}{W_t} \times 100 \quad (1)$$

where:

PPD: the percentage of physical damage (%).

W_d : mass of seeds with physical damage.

W_t : the original mass of the seed sample before the test.

An accelerated aging test was utilized to assess the internal damage to the impacted seeds with no sign of external damage. In this regard, seeds from each test group, which showed no external damage despite the impact, were further analyzed. This procedure was designed to reveal any internal damage caused by free fall and to assess the impact of free fall on the storage viability of the seeds. For executing the accelerated aging test, different seed samples (namely, free fall treated and control specimens) weighing forty grams each, were placed in a chamber at 42 °C and a humidity level of 100% for a duration of 72 h. Subsequently, these samples were subjected to a standard germination examination [28,29]. The loss in germination percentage (PLG) was calculated based on the difference between the germination percentage of free fall treated and control samples. Total damage was calculated as the sum of the physical damage and physiologic damages [30].

2.4. Measurement of Seed Velocity

The velocities of the seeds, both for mass flow and individual kernels, were recorded using a Nikon digital camera D53000 just prior to impacting the test surfaces. A 1 m distance was maintained between the bottom of the PVC pipe and the impact surface for recording velocities when the seeds exited the pipe (Figure 1). To assist in observing the distance the seeds traveled, horizontal lines were drawn at intervals of 5 cm and placed in the background. Videos capturing both scenarios—mass flow and single kernels—were recorded. As it was challenging to track seeds during mass flow, the speed of seeds was recorded at the commencement and termination of the mass flow.

2.5. Statistical Analysis

The experiment was set up as a factorial design. The factors included drop height (H) and impact surface (S) with three levels each, moisture content (MC) with four levels, and ambient temperature (T) with two levels. Three replicates were used to measure PPD, PLG, and total damages. Thus, there were 216 ($3 \times 3 \times 4 \times 2 \times 3$) observations. Duncan's multiple range tests were used to compare the means.

3. Results and Discussion

Table 1 shows the results of the analysis of variance (ANOVA) for the PPD, PLG, and total damage (PPD+PLG) to corn seeds for different independent variables. The impact surface, drop height, MC, and temperature significantly affected the percentage of various types of damage in corn seeds ($p < 0.01$). Moreover, the interaction between impact surface $\times$ drop height, impact surface $\times$ MC, impact surface $\times$ temperature, drop height $\times$ temperature, MC $\times$ temperature, and drop height $\times$ MC had significant effects ($p < 0.01$) on the percentage of various types of damage in corn seeds. Overall, the results indicate that corn seeds' PPD (seed breakage) and PLG (physiological deterioration) were affected by impact surface, drop height, MC, and ambient temperature.

The mean values of the PPD, PLG, and total damage of corn seeds at various impact surfaces, drop heights, MC, and temperatures are shown in Table 2 (the mean values were calculated from triplicated data). At the temperature of 20 °C and MC of 10%, seeds were dropped from a height of 15 m, resulting in an average PPD of 17.33% on metal, 10.31% on concrete, and 5.69% on seeds. At −10 °C, 10% MC, and a drop height of 15 m, the average PPD was as high as 22.18% on metal, 16.14% on concrete, and 9.81% on seeds. From the data for the average PLG of corn seeds in Table 2, one can conclude that seeds' physiological quality (germination loss) was influenced by impact surface, drop height, MC, and temperature. At −10 °C and 25% MC, for seeds dropped from a height of 15 m, germination loss was as high as 10.77% on metal, 9.97% on concrete, and 6.97% on seeds.

At 20 °C and MC of 25%, seeds dropped from a height of 15 m, resulting in an average germination loss of 9.53% on metal, 8.73% on concrete, and 5.73% on seeds.

At 20 °C and an MC of 10%, seeds dropped from a height of 15 m, resulted in an average total damage of 23.53% on metal, 15.71% on concrete, and 8.09% on seeds. While at −10 °C and 10% MC, and a drop height of 15 m, the total damage was as high as 29.21% on metal, 22.37% on concrete, and 13.04% on seeds.

Table 1. Variance analysis results (mean square) for the percentage of physical damage (PPD), physiological damage (PLG), and total damage to corn seeds, influenced by impact surface, drop height, moisture content (MC), and temperature.

Source	DF	Types of Damage		Total Damage
		PPD	PLG	
Impact surface (S)	2	579.54 **	266.93 **	1626.95 **
Drop height (H)	2	347.30 **	189.57 **	1012.77 **
S × H	4	36.64 **	0.46 **	42.45 **
Moisture content (MC)	3	562.39 **	110.27 **	186.76 **
S × MC	6	16.18 **	0.26 *	13.55 **
H × MC	6	13.18 **	0.26 *	10.95 **
S × H × MC	12	4.07 **	0.26 *	4.531 **
Temperature (T)	1	582.20 **	46.07 **	955.84 **
S × T	2	19.30 **	0.07 ^{ns}	21.59 **
H × T	2	13.99 **	0.06 ^{ns}	15.50 **
MC × T	3	11.26 **	1.14 **	9.915 **
S × H × T	6	0.98 ^{ns}	0.06 ^{ns}	0.86 ^{ns}
S × MC × T	6	0.12 ^{ns}	0.02 ^{ns}	0.05 ^{ns}
H × MC × T	6	0.41 ^{ns}	0.02 ^{ns}	0.30 ^{ns}
S × H × MC × T	12	0.84 ^{ns}	0.02 ^{ns}	0.88 ^{ns}
Error	144	0.65	0.10	0.77

**— $p < 0.01$, *— $p < 0.05$ and ^{ns}—not significant, DF = degree of freedom, PPD = percentage of physical and PLG = percentage loss in germination.

Table 2. Mean percentages of physical, physiological, and total damages to corn seeds under different independent variables.

Drop Height (m)	Moisture Content (%)	PPD (%)			PLG (%)			Total Damage (PPD + PLG) (%)		
		Concrete	Metal	Seed/Seed	Concrete	Metal	Seed/Seed	Concrete	Metal	Seed/Seed
T = 20 °C										
5	10	6.17	6.49	2.77	2.20	3.00	0.80	8.37	9.49	3.57
	15	4.20	4.48	0.95	3.23	4.03	0.91	7.43	8.51	1.86
	20	1.54	2.43	0.31	4.40	5.20	1.40	5.94	7.63	1.71
	25	0.73	0.82	0.30	5.53	6.33	2.53	6.26	7.15	2.83
10	10	8.38	9.50	4.60	4.80	5.60	1.80	13.18	15.1	6.4
	15	5.56	9.04	1.58	5.83	6.63	2.83	11.39	15.67	4.41
	20	3.50	5.39	0.88	7.00	7.80	4.00	10.5	13.19	4.88
	25	0.69	2.34	0.47	8.13	8.93	5.13	8.82	11.27	5.6
15	10	10.31	17.33	5.69	5.40	6.20	2.40	15.71	23.53	8.09
	15	7.31	8.70	3.59	6.43	7.23	3.43	13.74	15.93	7.02
	20	4.69	6.71	0.55	7.60	8.40	4.60	12.29	15.11	5.15
	25	3.43	4.61	0.52	8.73	9.53	5.73	12.16	14.14	6.25

Table 2. Cont.

Drop Height (m)	Moisture Content (%)	PPD (%)			PLG (%)			Total Damage (PPD + PLG) (%)		
		Concrete	Metal	Seed/Seed	Concrete	Metal	Seed/Seed	Concrete	Metal	Seed/Seed
T = −10 °C										
5	10	9.84	10.87	5.57	3.03	3.83	1.07	12.87	14.70	6.64
	15	7.84	8.33	3.30	4.40	5.20	1.40	12.24	13.53	4.7
	20	4.17	4.27	1.04	5.00	5.80	2.00	9.17	10.07	3.04
	25	3.28	2.37	0.47	6.77	7.57	3.77	10.05	9.94	4.24
10	10	12.88	14.97	7.38	5.63	6.43	2.63	18.51	21.41	10.01
	15	9.90	12.04	4.30	7.00	7.80	4.00	16.9	19.84	8.3
	20	7.04	9.18	2.26	7.60	8.40	4.60	14.64	17.58	6.86
	25	3.63	4.27	1.20	9.37	10.17	6.37	13	14.44	7.57
15	10	16.14	22.18	9.81	6.23	7.03	3.23	22.37	29.21	13.04
	15	11.77	15.21	6.63	7.60	8.40	4.60	19.37	23.61	11.23
	20	8.96	12.08	3.04	8.20	9.00	5.20	17.16	21.08	8.24
	25	6.60	9.68	2.31	9.97	10.77	6.97	16.57	20.45	9.28

PPD = Percentage physical damage and PLG = percentage loss in germination.

Table 3 outlines a comparative analysis of PPD, PLG, and total damage averages from the drop tests. All four independent variables exerted a significant impact ($p = 0.05$) on the values measured. The mean values of PPD, PLG, and total damage to corn seeds were highest on the metal surface, followed by concrete. Under various test conditions, seeds dropped on metal incurred the highest total damage of 15.52% (8.47% physical damage and 7.04% loss in germination). In the case of the concrete surface, the total damage was 12.86% (6.61% physical damage and 6.25% loss in germination). When seeds were dropped on the seeds' surface, a significantly lower average total damage of 6.29% (2.90% physical damage and 3.39% loss in germination) was obtained. It is apparent that the contact surface drastically affects seed damage. Therefore, it is recommended that corn handlers avoid dropping seeds directly on hard surfaces such as metal and concrete. If such an arrangement is impossible, alternative strategies, such as covering the hard surface with softer material, may decrease the extent of impact damage.

In terms of drop height, damage (both PPD and PLG) to corn seeds remarkably increased with increasing drop height (Table 3). Dropping seeds at 15 m resulted in the highest total damage of 15.03% (8.24% physical damage and 6.79% loss in germination) in comparison with 12.07% (5.88% physical damage and 6.19% loss in germination) and 7.59% (3.86% physical damage and 3.73% loss in germination) in drop heights of 10 m and 5 m, respectively. The obtained PLG data may be interpreted as a significant reduction in the storage potential of corn seed with increasing dropping heights. Moreover, significant disparities were observed between the mean total damage to seeds at varied drop heights ($p < 0.05$). This detrimental effect of amplified impact stress/drop height aligns with the findings of Nadimi et al. [13] on flaxseeds. Based on the potential energy equation ($E = mgh$), it is expected that an increase in drop height would correspondingly increase the impact energy applied to the seeds. Additionally, the increase in kernel velocity with drop height can result in a higher impact force on seeds [10,23].

Lower ambient temperatures resulted in increased physical and physiological damage to corn seeds (Table 3). The low temperature, i.e., −10 °C, caused a higher total damage of 13.66% (7.63% physical damage and 6.03% loss in germination) than 9.46% (4.35% physical damage and 5.11% loss in germination) at 20 °C. This may be caused by the crystallization of available free water. Therefore, it is recommended that the free fall of seeds be avoided in lower ambient temperature conditions, such as late night to early morning in cold regions. Tang et al. [31] observed the same damage trend in lentils. Overall, it is well known that

grain becomes increasingly brittle at lower temperatures, so handling could induce more damage in winter than in summer [32,33].

Table 3. Comparison of mean values for various dependent variables using Duncan’s multiple range tests.

Independent Variable	Dependent Variable		
	PPD (%)	PLG (%)	Total Damage (%)
Impact surface			
Concrete	6.61 b*	6.25 b	12.86 b
Metal	8.47 a	7.05 a	15.52 a
Seed/seed	2.90 c	3.39 c	6.29 c
Drop height			
5 m	3.86 c	3.73 c	7.59 c
10 m	5.88 b	6.19 b	12.07 b
15 m	8.24 a	6.79 a	15.03 a
Temperature			
−10 °C	7.63 a	6.03 a	13.66 a
20 °C	4.35 b	5.11 b	9.46 b
Moisture content			
10%	10.05 a	3.96 d	14.01 a
15%	6.93 b	5.05 c	11.98 b
20%	4.34 c	5.90 b	10.24 c
25%	2.65 d	7.35 a	10.00 c

PPD = percentage physical damage and PLG = percentage loss in germination. * a–d: Mean values in the columns with the same letter are not significantly different ($p < 0.05$).

The results presented in Table 3 also indicate that as seeds’ MC increased from 10% to 25%, the PPD decreased from 10.05% to 2.65%. The observed trend seems reasonable because low MC makes seeds more brittle making them prone to physical damage. Similar trends were previously reported by Nadimi et al. [13], Gu et al. [34], and Su et al. [35–37]. However, a higher MC also led to a greater reduction in seed germination. This result indicates that corn seeds with lower MCs could better tolerate physiological damage than those with higher MCs, which agrees with previous reports [27]. Higher MCs may have caused the flexibility of the seed tissues, transferring the impact energy to the embryo to further reduce the germination percentage. The PLG of corn seeds increased from 3.96% to 7.35% as MC increased from 10% to 25%. Similar trends have been previously reported for wheat [27], soybean [30], and corn seeds [38]. At 10% MC, seeds had a higher mean total damage of 14.01% compared with 11.98%, 10.24%, and 10.00%, at MCs of 15, 20, and 25%, respectively. The results confirm that the MC of corn seed plays a crucial role in the severity of induced mechanical damage. With the increase in MC, the percentage of physiological and physical damage increased and decreased, respectively. These findings will allow the corn handlers to make informed decisions on the MC of corn seeds during handling and transportation to minimize the risk of mechanical damage. It is recommended that future studies perform a more in-depth analysis to identify the optimum MC to minimize both physical and physiological damage to corn seeds.

Figure 2 illustrates the interplay between the impact surface and drop height on the total damage to corn seeds. When seeds fell onto metal or concrete surfaces, the total damage to the seeds was significantly higher. This difference was larger at 15 m compared with 10 m and 5 m heights. The relationship between total damage to seeds (TD, %) and drop height (DH, m) was captured by the following best-fit equations for various impact surfaces:

$$TD = 3.19 + 1.67DH - 0.03DH^2 \quad R^2 = 0.999 \quad \text{for concrete} \quad (2)$$

$$TD = 2.58 + 1.67DH - 0.03DH^2 \quad R^2 = 0.999 \quad \text{for metal} \quad (3)$$

$$TD = -1.01 + 1.06DH - 0.03DH^2 \quad R^2 = 0.999 \quad \text{for seeds-on-seeds} \quad (4)$$

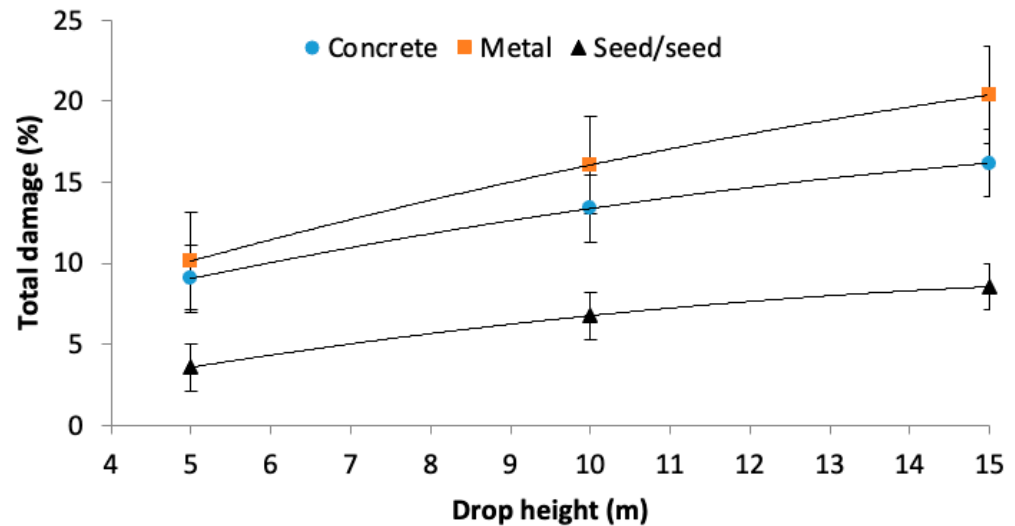


Figure 2. Total induced damage to corn seeds under synergistic effects of impact surface and drop height.

Figure 3 shows the effect of the interaction of impact surface and ambient temperature on the total damage to corn seeds. The difference in total damage was lower when seeds were dropped on seeds, compared to seeds dropped on either metal or concrete at a higher temperature (20 °C) as opposed to a lower temperature (−10 °C).

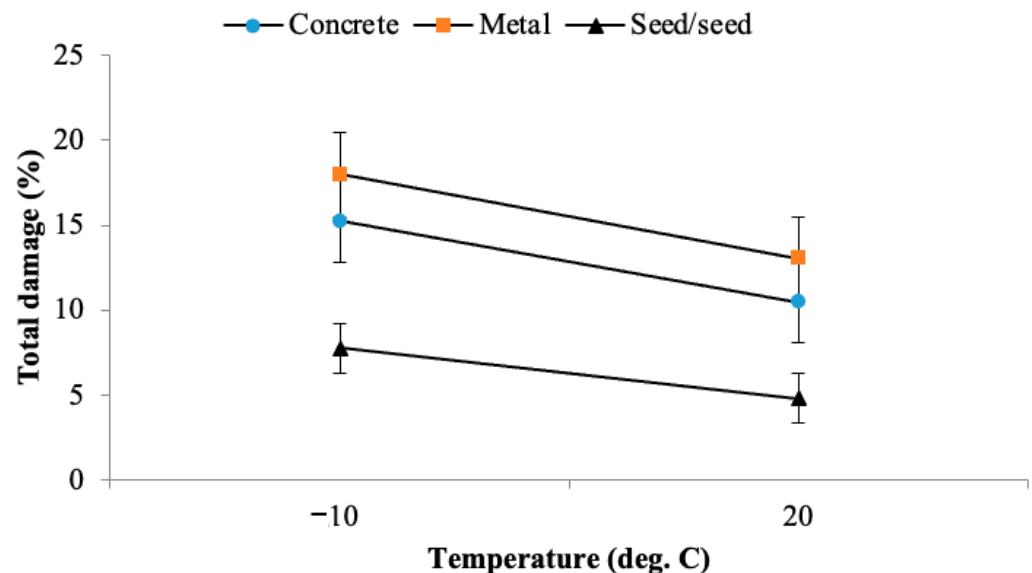


Figure 3. Total induced damage to corn seeds under synergistic effects of impact surface and temperature.

The interaction of drop height and ambient temperature on the total damage to corn seeds is shown in Figure 4. The low temperature caused a higher total seed damage at higher drop heights than at lower ones. There was a steady increase in damage between temperatures at each drop height level. The relationship between the total damage to seeds

(TD, %) and the drop height (DH, m) at different ambient temperatures was articulated through the following best-fit equations:

$$TD = 3.08 + 0.64DH \quad R^2 = 0.999 \quad \text{at } 20^\circ\text{C} \quad (5)$$

$$TD = 5.29 + 0.84DH \quad R^2 = 0.989 \quad \text{at } -10^\circ\text{C} \quad (6)$$

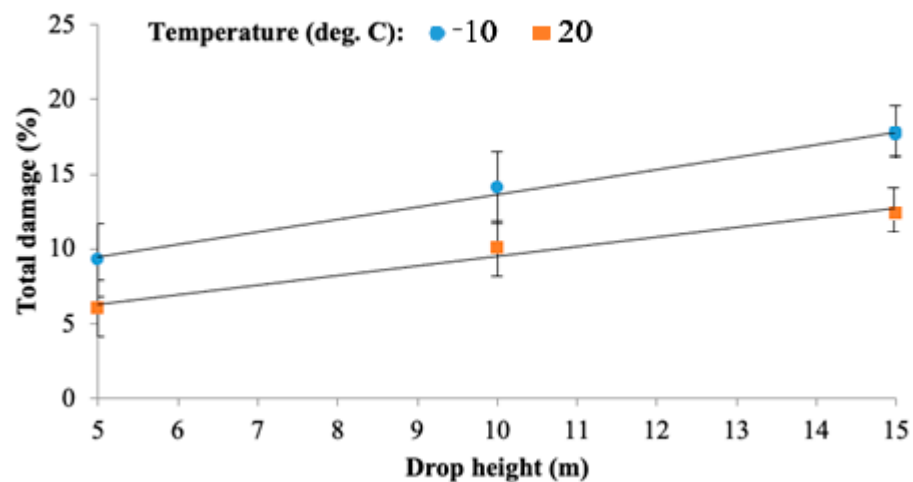


Figure 4. Total induced damage to corn seeds under synergistic effects of drop height and temperature.

The interactive effect of impact surface and MC on the total damage inflicted on corn seeds is depicted in Figure 5. There was a notably smaller difference in total damage among the four MCs when seeds landed on other seeds, as opposed to metal or concrete. The role of MC was less prominent when seeds fell onto seeds. The relationship between total damage to seeds (TD, %) and MC (%) was captured using the following best-fit equations for the three impact surfaces:

$$TD = 26.71 - 0.93MC + 0.02MC^2 \quad R^2 = 0.999 \quad \text{for concrete} \quad (7)$$

$$TD = 26.02 - 0.93MC - 0.02MC^2 \quad R^2 = 0.986 \quad \text{for metal} \quad (8)$$

$$TD = 16.21 - 1.08MC - 0.27MC^2 \quad R^2 = 0.968 \quad \text{for seeds-on-seeds} \quad (9)$$

Figure 6 illustrates the interaction between drop height and MC, and how it affects total damage to corn seeds. The reduction in seed MC led to a sharper increase in total damage as drop height increased.

Figure 7 displays the interaction between temperature and MC on total corn seed damage. Generally, the total damage incurred by corn seeds was less at 20 °C than at −10 °C. The relationship between total damage to seeds (TD, %) and MC (%) was denoted by the subsequent best-fit equations for temperatures of 20 °C and −10 °C, respectively:

$$TD = 17.96 - 0.82MC + 0.02MC^2 \quad R^2 = 0.999 \quad \text{at } 20^\circ\text{C} \quad (10)$$

$$TD = 24.68 - 0.99MC + 0.02MC^2 \quad R^2 = 0.989 \quad \text{at } -10^\circ\text{C} \quad (11)$$

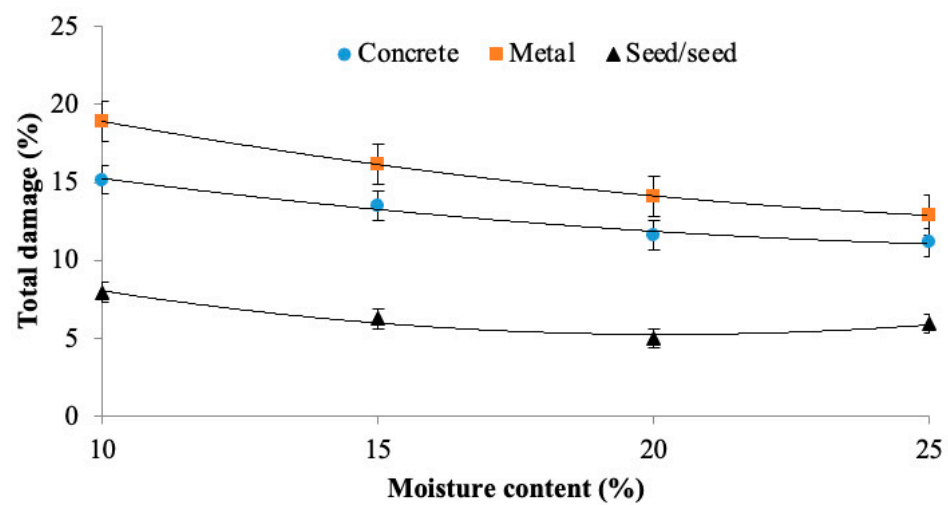


Figure 5. Synergistic effect of impact surface and moisture content on the total damage to corn seeds.

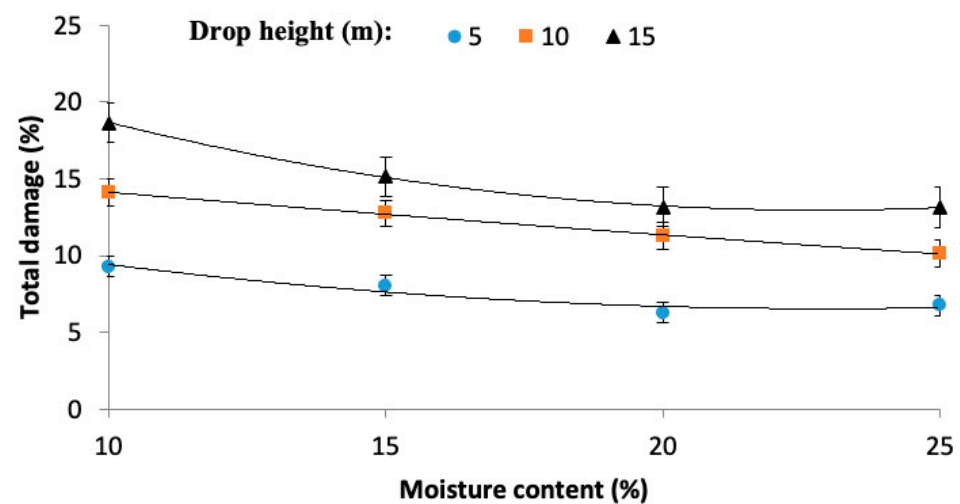


Figure 6. Total induced damage to corn seeds under synergistic effects of drop height and moisture content.

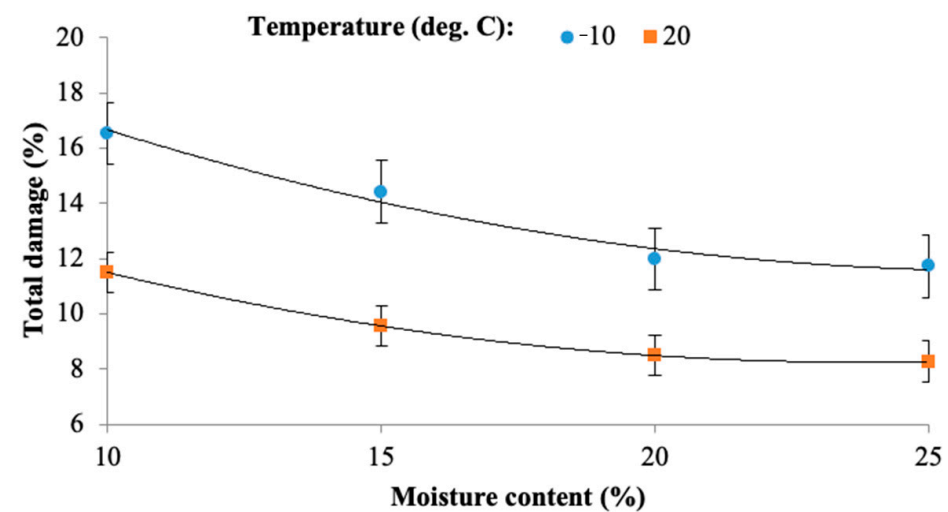


Figure 7. Total induced damage to corn seeds under synergistic effects of temperature and moisture content.

Table 4 shows the average velocity (single seed and mass flow) for corn seeds dropped from different heights. Table 4 reveals that the mass velocities recorded at various drop heights were higher compared to the velocities of individually dropped seeds. This disparity can potentially be attributed to the presence of air resistance within the drop tubes, influencing the overall mass velocity of the seeds. A notable increase in mass velocity of corn seeds with ascending drop heights is also apparent in Table 4. The average mass flow velocity for seeds dropped from a height of 5 m was recorded at 7.85 m/s, while for seeds dropped from 10 m, the average mass flow velocity reached 10.12 m/s. Seeds dropped from the highest height of 15 m exhibited the highest average mass flow velocity of 13.90 m/s. At these speeds, the average total damage to corn seeds was 7.59%, 12.07%, and 15.03%, respectively (Table 3). Increased drop height increased seeds' mass flow velocity and correspondingly caused increases in both physical and physiological damage to seeds. These data indicate that impact velocities below 8 m/s limit the total damage to seeds to less than 8%. The observed trend of increasing seed damage with impact speed has been previously reported for broad bean beetle [39].

Table 4. The average velocities (mass flow and single seed velocities) of seeds dropped from different heights.

Drop Height (m)	Velocity (Single Seed) (m/s)	Velocity (Mass Flow) (m/s)
5	7.25	7.85
10	9.45	10.12
15	11.02	13.90

It is worth mentioning that the experimental study on modeling damage to corn seeds under free fall has certain limitations that are worth exploring in future research. One of the limitations is the effect of PVC pipes on the landing of seeds. Herein, the authors assumed that such an effect was negligible and did not explicitly account for it. However, dedicated research is required to confirm such a hypothesis and to quantify the potential impact of PVC pipes on seed landing.

Another limitation is a replication of the exact conditions of free fall in the air. While the authors attempted to reduce disparities in the speed and vertical fall heights of the seeds, there could be differences between the controlled lab conditions and unconstrained free fall scenarios. Hence, investigating the differences in seed behavior between free fall in the air and a confined tube is another interesting topic for future research.

Moreover, our experimental design, while allowing for a controlled study by employing isolated drops of 500 g corn seeds, may not fully mirror the complexities of actual harvesting and transportation conditions. In real-world scenarios, harvested corn is often placed in bags or containers. During bulk flow, kernels form a fluidized bed where they are cushioned by intergranular air and surrounding kernels, possibly leading to modified collisions. Therefore, future research should address this limitation by using larger volumes of grains and simulating the transportation conditions in bags or containers. Incorporating these real-world conditions would enable a more comprehensive understanding of grain behavior and the associated damage.

It is also worth mentioning that our study calculated total damage as the sum of physical and physiological damages, adopting a methodology prevalent in previous seed damage investigations [30]. This process encompassed a visual inspection for physical damage, a practice routinely used in grain elevator quality assessments [19], complemented by an accelerated aging test to discern physiological damage. This approach provides a wide-ranging evaluation of overall seed damage without a specific focus on the intersection between physical and physiological damage. While some seeds may sustain both types of damage, the objective of this study was not to unravel this overlap, but to provide a holistic view of the overall seed damage. Future research, specifically focused on identifying the

simultaneous presence of both types of damage in the same seeds, could adopt a more targeted methodology.

In addition, this study only investigated the effects of two temperatures. Although the choice of -10°C may not be typical for harvesting corn, it was appropriate for evaluating the impact of low temperatures on seed damage during free fall, which is important for simulating the loading and unloading of grain silos at various environmental temperatures. However, future research should explore the impact of additional temperatures, such as $+10^{\circ}\text{C}$ or $+30^{\circ}\text{C}$, to better understand how different temperatures can affect seed damage.

A potential topic to consider in future studies is to evaluate the effect of other contributing factors such as dust on corn damage during grain handling. Correlating PLG results with X-ray-based microstructural data is another potential topic for future research [2,13,40–43]. Moreover, the implementation of state-of-the-art machine vision tools, such as imaging or spectroscopy, can automate mechanical damage assessments in grains [2,13,19,24,44–47]. Ultimately, the present work only considered damage to corn seeds. To better understand the generalizability of these findings, it would be valuable to extend the research to other grains and oilseeds.

4. Conclusions

The present research comprehensively investigated the impact of free fall on the physical and physiological qualities of corn seeds under various conditions including drop heights, impact surface materials, seed moisture content, and ambient temperatures. The following key findings and novel contributions can be summarized as:

1. The study affirms that mechanical damage due to free fall significantly affects both physical and physiological attributes of corn seeds. This highlights the importance of evaluating both physical and physiological damage, as focusing solely on physical damage may not provide a comprehensive representation of the overall damage inflicted on the seeds.
2. The findings emphasize the crucial role of drop heights and mass flow velocities in determining the extent of seed damage. Higher values of these parameters were associated with increased seed damage, whereas limiting the impact velocities to approximately 8 m/s at a 5-m drop height resulted in minimal damage among the tested treatments.
3. The impact surfaces played a crucial role, where seeds dropping on hard surfaces such as metal or concrete incurred more damage than those dropping on seeds. This highlights the importance of careful selection of surface materials during handling.
4. Ambient temperature demonstrated a significant inverse relationship with the total damage to corn seeds, suggesting that handling seeds at lower ambient temperatures should be minimized.
5. The increase in seed moisture content resulted in a corresponding increase in physiological damage and a decrease in physical damage, highlighting the importance of managing moisture content to minimize overall seed damage. Determining the optimal moisture content for preserving corn seed quality requires more targeted studies.

These findings not only expand the current understanding of mechanical damage in corn seeds but also offer practical recommendations for handling practices to reduce seed damage. Notwithstanding the findings, the study recognizes certain limitations, such as the need to investigate the differences between free fall in the air and in a confined tube, and the behavior of a larger volume of grains during handling. Future studies should consider these limitations and extend the investigation to other grains and oilseeds and additional factors such as dust and varying temperatures. By addressing these gaps, this study contributes to the broader goal of improving agricultural product handling and storage practices. Furthermore, it lays the groundwork for future studies in this area, thereby driving the ongoing endeavor to minimize food losses and enhance food security.

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