Hindawi
Journal of Food Processing and Preservation
Volume 2023, Article ID 4828539, 8 pages
https://doi.org/10.1155/2023/4828539

*Research Article*

# Effect of Fruit Weight and Drop Height on Bruise Area and Contact Pressure Characteristics of Apple during Free Drop Test

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Received 18 April 2023; Revised 25 July 2023; Accepted 2 August 2023; Published 24 August 2023

Academic Editor: Fabiano A.N. Fernandes



Drop bruising is among the most common forms of mechanical damage to fruit during postharvest procedures. To minimize the damage inflicted on apples by free falling during harvesting, transportation and preservation processes and to better understand the mechanism of this damage, this paper investigates the area and contact pressure distribution of a drop bruise when an apple of a certain weight is dropped from a specific height onto a steel substrate. The characteristics of the contact pressure were measured using Prescale® pressure-sensitive film and subsequently analyzed to determine the relationship between the bruise area and the pressure distribution upon impact. Our findings indicate that the peak range of contact pressure stood between 0.5 and 0.6 MPa for an apple dropped from a height of 20-80 cm onto a steel substrate. The pressures displayed a fairly regular distribution with a relatively small pressure area, closely matching the bruised area. Additionally, the area with a pressure range of 0.2-0.4 MPa was found to be the largest, with an average pressure of 0.25-0.28 MPa. The pressure area showed a linear increase in correspondence with the increase in fruit weight and drop height, maintaining a consistent peak. The linear regression model, formulated using the product of the pressure area and average pressure, accurately predicts and assesses the bruised area of a dropped apple. This research could inform the design of mechanized and automated equipment aiming to reduce the frequency of bruising in apples.

## 1. Introduction

A substantial amount of fruit, including apples, sustains mechanical damage during various stages of the postharvest process such as transportation, harvesting, distribution, handling, and storing. This is substantiated by recent research [1–3]. In developing countries, mechanical damage to fruit ranges between 25 and 45%, a figure that is dramatically higher than that in developed nations [4]. Bruises, categorized as mechanical injuries, are not always immediately visible. They initiate a chain of detrimental events leading to fruit cell destruction, tissue browning, rotting, quality degradation, and consequential economic losses [5–7]. Therefore, it is paramount to investigate the traits of mechanical damage to control its occurrence, particularly in fruits like apples.

Free drop bruise is a prevalent type of mechanical damage. The bulk of fruit damage research gravitates towards the impact of such damage on fruit quality and the utilization of cushioning materials for bruise prevention. The underlying mechanism of bruising, however, has received inadequate attention. Research has been conducted on the correlation between the impact height and damage volume during picking and storage periods [8] and the efficacy of various packaging materials' cushioning performances [9–11].

A fruit drop impact model has been established using the drop bruising test of fruits including apples, pears, and melons [12–15]. Research has been done on the effect of cushion packing on the vibration bruising and dynamic features of boxed apples [16]. The study of contact pressure distribution, which bears a direct correlation with the fruit bruise region, is an essential primary step towards understanding the bruising process [17].

Presently, apple drop bruise mechanic research is predominantly focused on drop damage at various heights

Table 1: Characteristics of the apple samples (presented values described as mean ± standard deviation).

| Weight (g) | Mean diameter (mm) | Firmness (N) | Water content (%) |
|---|---|---|---|
| $168.56 \pm 20.17^d$ | $69.15 \pm 2.36^d$ | $67.4 \pm 4.6^a$ | $87.9 \pm 1.3^a$ |
| $226.11 \pm 13.36^c$ | $83.62 \pm 2.55^c$ | $67.6 \pm 4.3^a$ | $87.8 \pm 0.8^a$ |
| $277.44 \pm 12.41^b$ | $88.37 \pm 2.54^b$ | $67.4 \pm 4.9^a$ | $87.9 \pm 1.2^a$ |
| $324.96 \pm 14.46^a$ | $94.58 \pm 2.54^a$ | $66.9 \pm 4.6^a$ | $87.8 \pm 0.7^a$ |

Mean values are not significantly different ($p > 0.5$) for the same lower letter case letters within a column.

and contact materials, rarely correlating fruit quality with damage area and pressure distribution. To mitigate mechanical bruising, it is crucial to scrutinize the contact pressure distribution and damage process with regard to fruit weight and drop height.

In this experiment, a pressure-sensitive film is employed to measure the contact pressure distribution area of apples falling from varying heights. The objective is to elucidate the mechanism of fruit drop damage and to design and optimize equipment for apple picking, sorting, packaging, processing, transportation, and sales.

## 2. Materials and Methods

*2.1. Materials.* The "Fuji" apple cultivars utilized for drop tests were procured directly from a local producer in Luochuan County, Shaanxi Province, China. The samples were carefully selected, ensuring damaged fruits were omitted, and the remaining apples were chosen on the basis of their average weight. Subsequently, these samples were stored in a controlled atmosphere at a temperature of $0 \pm 2$°C, with relative humidity at 95%, carbon dioxide concentration at 0.7%, and oxygen at 2%.

Prior to the testing, the mass of the fruits was measured, generating 120 samples per mass group. Referencing the apple mass classification criteria, the apple mass was further segregated into four groups, as illustrated in Table 1.

Sixty apple samples were randomly selected from each weight group, and then a Fruit Hardness Tester (FT-327, Breuzzi, Italy) with a probe diameter of 3.5 mm was chosen to measure fruit hardness. In addition, the fruit water content was determined using the weight-dryer method.

*2.2. Free Drop Test and Contact Pressure Distribution Measurement.* The free drop test was carried out utilizing a device developed by the author, as delineated in Figure 1. This testing apparatus, built with a rigid steel frame, was engineered to drop apple samples from a predetermined height varying from 10 to 100 cm. As depicted in Figure 1, fruit samples were secured by a holder using the Venturi effect generated by an air compressor. Once the test height was set, the test was initiated by switching off the control.

The drop test was conducted over a substrate positioned at the bottom of the instrument. A 5 mm-thick steel plate, bearing a density of 7.85 g.cm$^3$, and a modulus of elasticity of 210 GPa served as the dropping substrate. An ultrathin pressure film from Prescale® (LLLW, FUJIFILM Prescale,

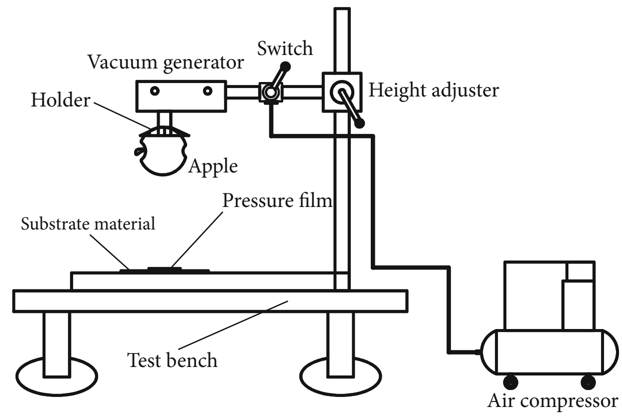



Figure 1: Free drop test device.

Japan) with a testing range from 0.2 to 0.6 MPa was placed on the dropping substrate.

As the common falling distance, the free drop height $h$ ranged from 20 to 80 cm, graduated every 20 cm. The apple samples were placed in the holder in the lateral position with the test height adjusted. After each collision of fruit with the steel substrate, the tested fruit was stopped by hand to avoid another impact, which ensure that there is only one bruise for every sample. Measurements were made with one hit per apple, at four impact heights and thirty repetitions.

*2.3. Bruise Area Measurement.* After removal of the fruit skin, the bruised surface area was calculated as surface of the ellipse described with the following formula [18]:

$$BA = \frac{\pi \bullet w_1 \bullet w_2}{4}, \quad (1)$$

where $w_1$ and $w_2$ were the larger and smaller axes of the ellipse (cm) and BA was the bruised surface area (cm$^2$).

*2.4. Statistical Analysis.* Mean values and standard deviations (SD) were calculated from the data using SPSS 16.0 version (SPSS inc., Chicago, IL, USA). Statistically significant differences ($p < 0.05$) among various dropping treatments were conducted by analysis of variance (ANOVA) and Duncan's test using SAS 9.0 (SAS Institute Inc., USA).

## 3. Results and Discussion

*3.1. Effect of Weight and Drop Height on Bruise Area of Apple during Free Drop Test.* Figures 2(a) and 2(b) illustrate the

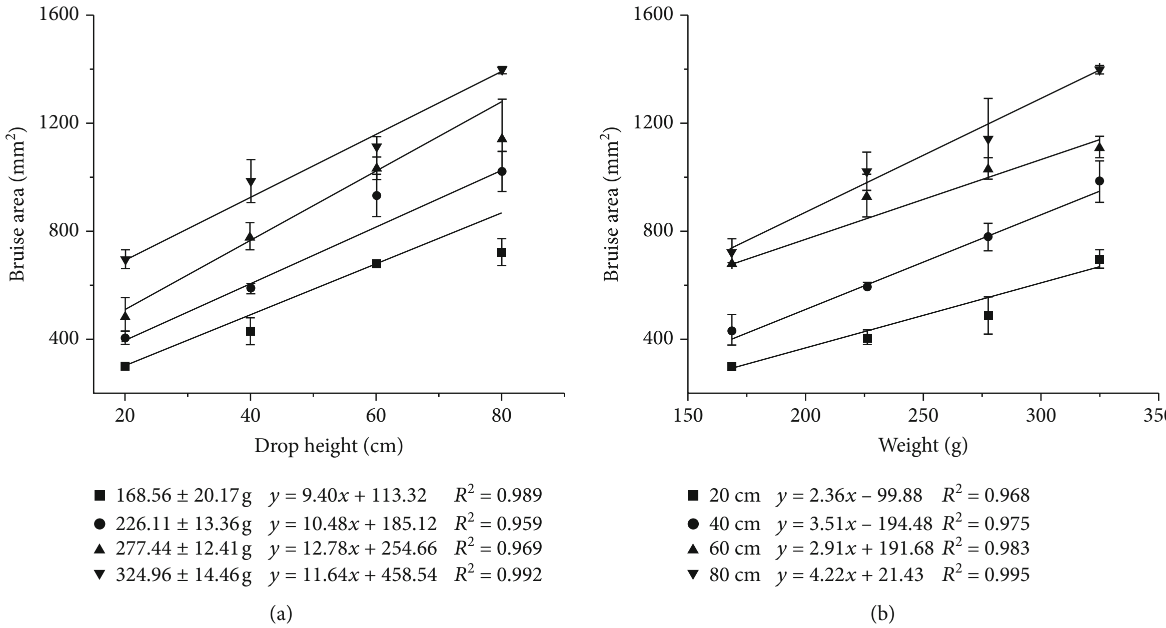



Figure 2: Effect of weight and drop height on bruise area of apple.

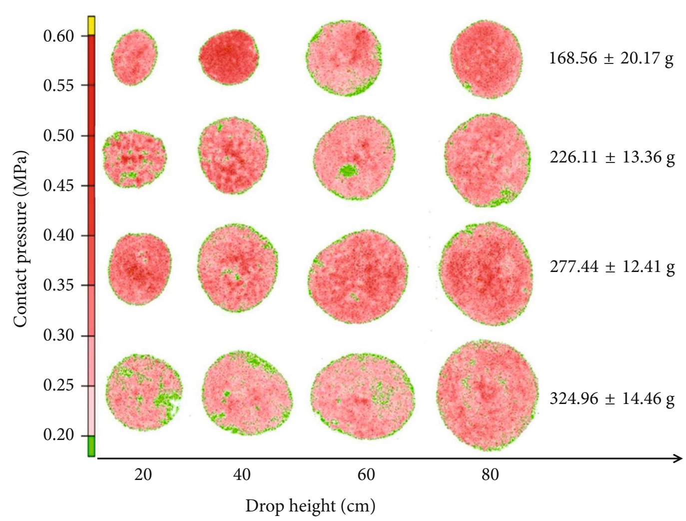



Figure 3: Effect of weight and drop height on contact pressure of apple.

fluctuations in bruise areas caused by drops, contingent on the drop height, and weight of the apple. As observed in Figure 2(a), when apples of uniform weight were dropped onto the steel substrate, there was a linear increase in the bruise area corresponding to the drop height. The correlation coefficients for the linear fitting equations for apples weighing 168.56 ± 20.17 g, 226.11 ± 13.36 g, 277.44 ± 12.41 g, and 324.96 ± 14.46 g were 0.989, 0.959, 0.969, and 0.992, respectively. As shown in Figure 2(b), for any given height, the bruise area of the dropped apples increased linearly in proportion to the weight of the apples, exhibiting coefficients of determination at 0.968, 0.975, 0.983, and 0.995, respectively. As the weight and drop height increased, so did the impact energy, and, being a rigid material, the steel substrate absorbed minimal energy, leading to an increased bruise area in the apples due to absorption of the remaining energy.

Comparable trends were found in other studies by researchers conducting drop damage tests on apples, loquat fruit, and muskmelons (refer to [19–21]). They observed positive correlations between fruit weight and drop height to the bruise area of the dropped fruit. This significant variation in bruise areas, caused by differences in weight and drop height, is likely to be closely related to the varying distribution of contact pressure in the apples.

*3.2. Effect of Weight and Drop Height on Contact Pressure Distribution of Apple during Free Drop Test.* Figure 3 illustrates the influence of fruit weight and drop height on the

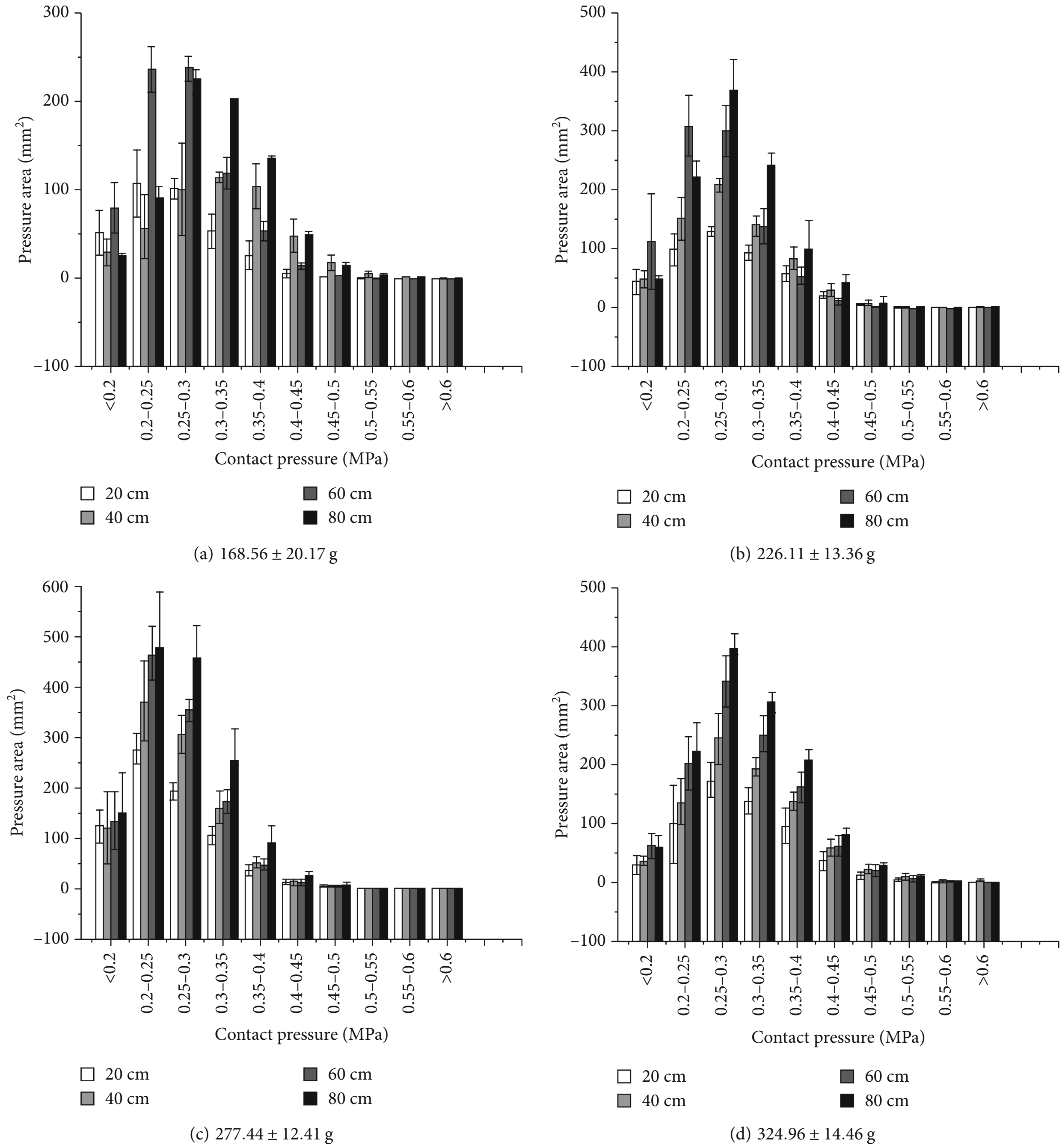
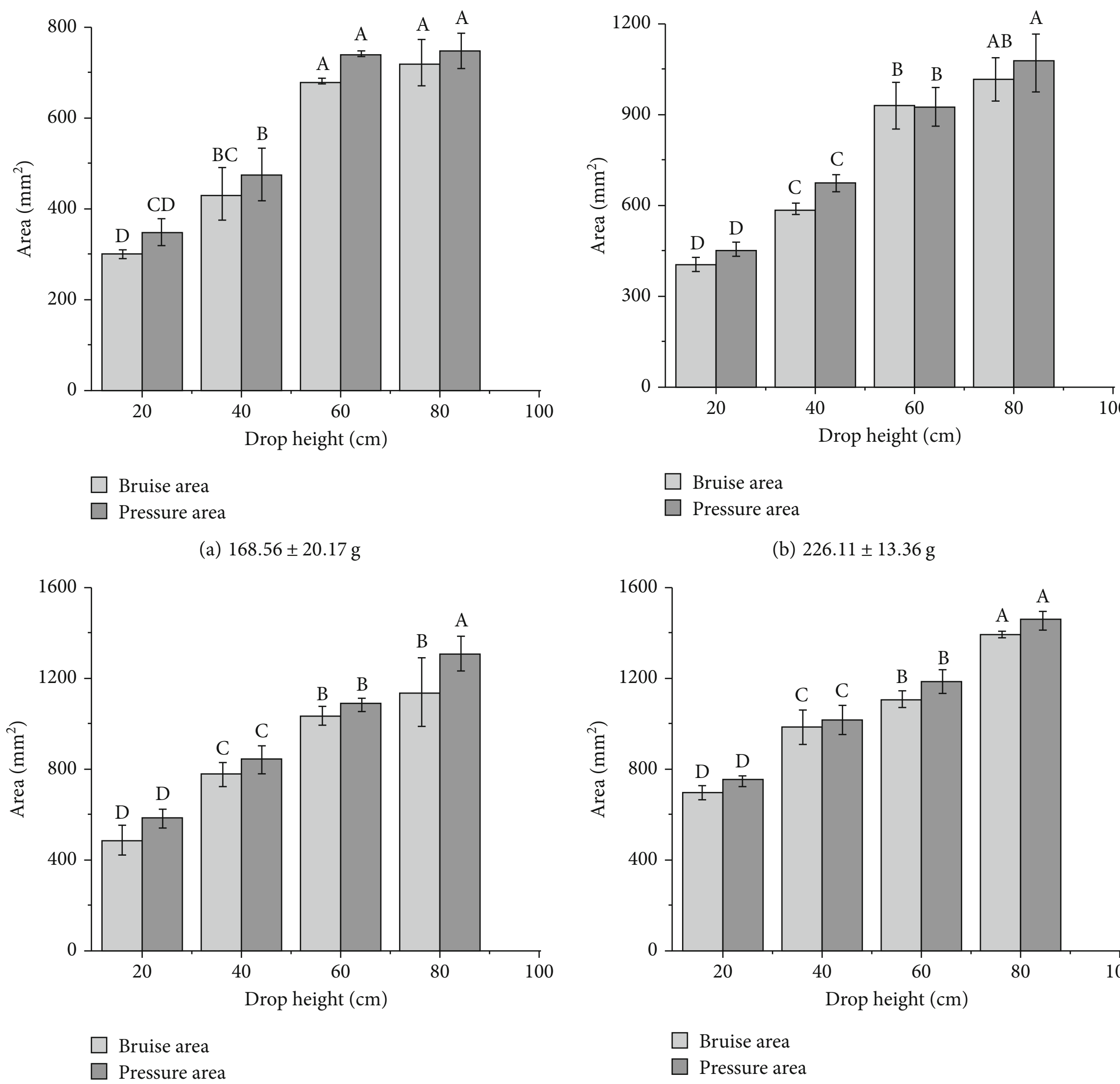



Figure 4: Contact pressure area distribution of apples.

distribution of contact pressure in an apple. The distribution profile of contact pressure was almost elliptical, as presented in Figure 3. When an apple was dropped onto a steel substrate with limited cushioning capability, the contact pressure area within the apple increased proportionally with the rise in drop height and fruit weight. The peak contact pressure lacked consistency and was mostly scattered near the central point of contact. Moreover, decreased pressure (≤0.2 MPa) was mainly concentrated towards the edge and across a relatively smaller region. With increasing drop height and fruit weight, the distribution area for low pressure (≤0.2 MPa) markedly decreased and progressively concentrated towards the edge distribution. Interestingly, the pressure reading of 0.2 MPa was lower than the critical bruising pressure threshold of apple flesh tissue. In accordance with this, the average pressure was calculated to be between 0.25 and 0.28 MPa.

The distribution of contact pressure areas within apples is depicted in Figure 4. As indicated in Figure 4, upon dropping apples of varying weights from different heights, the resulting contact pressure displayed a normal distribution. The majority of the area was subjected to contact pressure within the range of 0.2-0.4 MPa, which significantly contributed to the apple's bruise. The pressure area peaked within




(a) 168.56 ± 20.17 g (b) 226.11 ± 13.36 g (c) 277.44 ± 12.41 g (d) 227.44 ± 12.41 g

Figure 5: The relationship between the drop bruise area and the contact pressure area.

the range of 0.2-0.35 MPa. However, a minimal contact area experienced pressure within the 0.4-0.6 MPa range, thus contributing insignificantly to the bruise zone in apples.

Variations in the contact pressure area for different weights and drop height impacts were not significant when the contact pressure was less than 0.2 MPa. For drop heights of 20 and 40 cm, minimal differences in contact pressure area were observed when contact pressure was below 0.2 MPa, but larger discrepancies were noted for drop heights of 60 and 80 cm compared to 20 and 40 cm. Importantly, the bruise area was found to be in relation to the free drop height.

Post dropping the apple, the pressure area signifies the distribution and magnitude of the contact pressure. The contact pressure area of the apple expanded as both the fruit weight and drop height increased, and it exhibited a normal distribution pattern, in agreement with the findings of Feng and Wu [22] and Wu et al. [23]. The fruit drop damage test can also predict the bruise area of the fruit, thereby allowing successful control of potential fruit damage (refer to [24, 25], and [26]). The uneven distribution of pressure areas is primarily due to the irregular surface of the apple as reported by Feng [22]. Additionally, the unequal distribution of contact pressure might be associated with the angle at which the fruit falls. This conjecture warrants further exploration.

*3.3. The Relationship between the Drop Bruise Area and the Contact Pressure Area.* Figure 5 represents the correlation between the drop bruise area and the contact pressure area within the apples. As indicated in Figure 5, the difference between the drop bruise area and the contact pressure area within apples was not statistically significant ($p > 0.05$). However, the contact pressure area was consistently larger than the drop bruise area. The green region was primarily

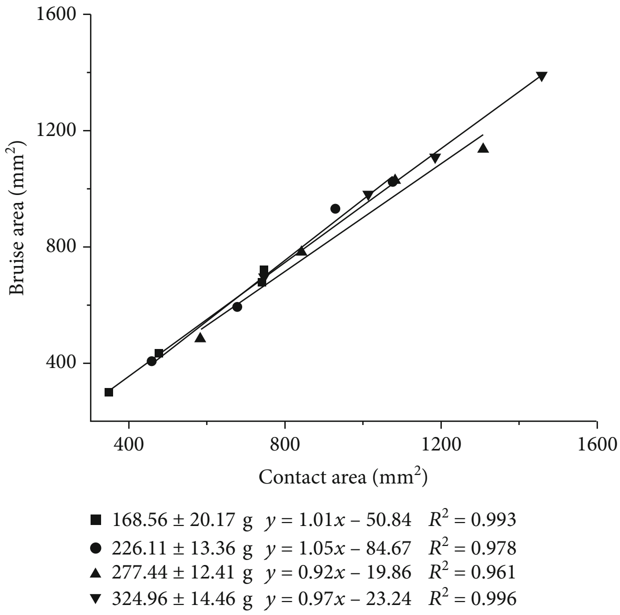



Figure 6: The fitting curves of the drop bruise area and the contact pressure area.

comprised of low pressure (<0.2 MPa) which gradually shifted towards the edge, while the apple maintained a certain amount of contact area without resulting in bruises. When the pressure was raised to ≥0.2 MPa, it became close to the compressive yield strength of the pulp, thereby inducing bruising.

The fitted curves demonstrating the relationship between the contact pressure area and the drop bruising area of apples are displayed in Figure 6. Across different apple weights, a strong correlation was evident between the drop bruise area and the contact pressure area, with fitted correlation coefficients of 0.993, 0.978, 0.961, and 0.996. This indicates that the contact pressure area of apples can accurately predict the bruise area.

Figure 6 features the fitting curves of drop bruise area and the contact pressure area. Notably, no significant differences were found between the damage area and the contact pressure area of apples ($p > 0.05$). Yet, a strong linear relationship existed between the contact pressure area and bruised area, with the former being larger than the latter. The critical value for damage to the apple pulp tissue is 0.203 MPa. When contact pressure is less than 0.2 MPa, the apple exhibits a contact area but no damage. This could be attributed to the apple pulp's robust recovery ability, when the contact pressure does not reach the critical damage threshold for the flesh tissue. This results in a concave fruit surface that reduces damage and protects the fruit, demonstrating the elastic deformation of the apple's pulp. There is no enzymatic release of phenolics to brown stressed spots, as the pulp is not degraded.

When contact pressure is equal to or greater than 0.2 MPa, the apple reaches the damage yield strength, leading to cell rupture and the release of phenolic compounds, which induce browning [22]. Consequently, it can be inferred that visible damage occurs when apple contact stress exceeds 0.2 MPa. Gao et al. [24] carried out a sweet potato drop impact damage test and established a pressure model to compute the damage force value and critical drop damage height of sweet potatoes within a certain mass range. For the harvesting, transportation, grading, processing, and other equipment involved in fruit and vegetable handling, the crucial value of mechanical damage can provide more holistic data support.

*3.4. Effect of Weight and Drop Height on the Average Contact Pressure of Apple during Free Drop Test.* Table 2 presents the impact of fruit weight and drop height on the average contact pressure of apples. As depicted in Table 2, the average contact pressure demonstrated dynamic fluctuations in response to changes in fruit weight and drop height, with a variation range of 0.25-0.36 MPa. The reasons for such fluctuations might be linked to the maturity of the fruit's collision contact surface, the location of collision, and the angle at which the collision occurs. The mean contact pressure of apples weighing 168.56 ± 20.17 g and 226.11 ± 13.36 g did not differ significantly ($p > 0.05$), insinuating that the impact of the apple's shape pertaining to the mean contact pressure was within the range of 0.25-0.36 MPa, manifesting a noticeable difference. The mean contact pressure in apples weighed 168.56 ± 20.17 g and 226.11 ± 13.36 g showed a significant variation. An increase in weight led to a significant rise in the average contact pressure of apples ($p < 0.05$), although the difference remained insignificant, suggesting a correlation between the average contact pressure and apple weight, rather than the drop height.

The average contact pressure within apples was found to be related to the weight of the fruit rather than the drop height, revealing that the drop bruise area was unaffected by the mean contact pressure. This conclusion aligns with the findings given by Feng and Wu [22].

*3.5. The Relationship between the Drop Bruise Area and the Drop Impact Force.* Figure 7 illustrates the relationship between the drop bruise area and the drop impact force for apples of various weights. It is evident from Figure 7 that apples weighing 324.96 ± 14.46 g and 277.44 ± 12.41 g exhibited a strong linear correlation between the drop bruise area and the drop impact force on the steel substrate, boasting a coefficient of $R^2 \geq 0.962$. The apple groups weighing 226.11 ± 13.36 g and 168.56 ± 20.17 g had a coefficient nearing 0.9. Fitted correlation coefficients for differing apple weights falling on the steel substrate can achieve $R^2$ values exceeding 0.9, enabling prediction of the drop bruise area for varying apple weights.

The bruise area and average contact pressure appear to coincide with the apple's impact force [27]. The impact force of varying weights consistently correlates well with the drop bruise area, facilitating both the prediction and evaluation of apple impact bruising on the steel substrate. A finite element model has been engineered using the relationship between the impact force and drop bruise area of apples to enhance investigation into the mechanical properties of apple drops and collision bruises.

Table 2: Effect of weight and drop height on the average contact pressure of apple.

| Weight (g) | Height (cm) | | | |
|---|---|---|---|---|
| | 20 | 40 | 60 | 80 |
| 168.56 ± 20.17 | 0.263 ± 0.026$^{Ba}$ | 0.330 ± 0.030$^{Aa}$ | 0.270 ± 0.010$^{ABb}$ | 0.315 ± 0.005$^{Aa}$ |
| 226.11 ± 13.36 | 0.290 ± 0.014$^{Aab}$ | 0.290 ± 0.012$^{Abc}$ | 0.265 ± 0.015$^{Bb}$ | 0.295 ± 0.015$^{Aab}$ |
| 277.44 ± 12.41 | 0.308 ± 0.023$^{Aa}$ | 0.313 ± 0.015$^{Aab}$ | 0.300 ± 0.016$^{Aa}$ | 0.308 ± 0.011$^{Aa}$ |
| 324.96 ± 14.46 | 0.258 ± 0.008$^{Aa}$ | 0.265 ± 0.011$^{Ac}$ | 0.263 ± 0.08$^{Aab}$ | 0.270 ± 0.014$^{Ab}$ |

Mean values are not significantly different ($p > 0.05$) for the same lower letter case letters within a column among the fruit weight, and for the same capital letters within a row among the drop height.

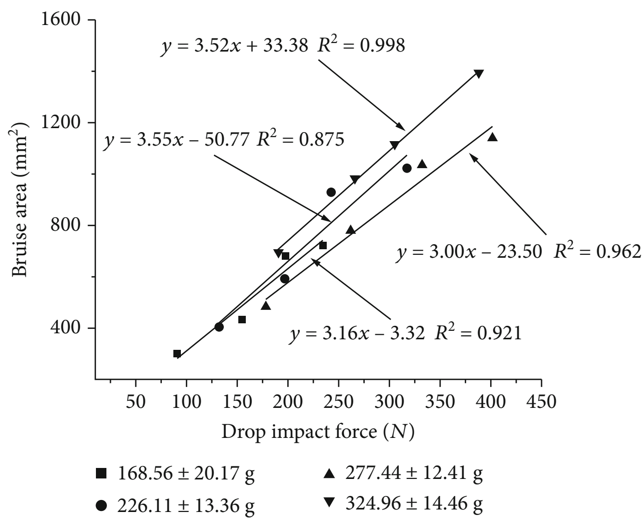



Figure 7: The relationship between the drop bruise area and the drop impact force.

Additionally, rubber sheets, corrugated cardboard, and foam boards are common contact materials used in practical apple production systems. Leveraging the robust linear association between the damage area and impact force during steel plate collisions, the impact force-damage relationship during apple collisions with these three contact materials and novel packaging materials can be further probed. This paves the way to a theoretical foundation for the optimization of mechanical equipment design during apple transportation, processing, and packaging, presenting a more inclusive reference for damage prediction and packaging design. Celik et al. [27] employed a finite element simulation method to accurately forecast apple fruit drop damage.

## 4. Conclusions

This study analyzes the area of bruising and the distribution of contact pressure when an apple of a given weight is dropped from a certain height onto a steel substrate. The contact pressure attributes were measured using a Prescale® pressure-sensitive film, and its distribution was evaluated to determine the relationship between the bruise area of the apple and contact pressure distributions. The findings show that the peak of contact pressure for an apple, dropped from a height of 20-80 cm onto the steel substrate, was between 0.5 and 0.6 MPa. This pressure distribution appeared to follow a normal curve concentrated around a smaller pressure area that closely matched the bruise area. Moreover, a pressure range of 0.2-0.4 MPa impacted the largest area, with an average pressure of 0.25-0.28 MPa. As the weight increased and the height of the drop grew, the pressure area expanded linearly with a constant peak. The average pressure showed negligible changes for apples dropped onto rigid material. A linear regression model, fitted with the product of the pressure area and average pressure, can accurately predict and assess the bruise area of an apple. This model can be a pertinent reference in the design of mechanized and automated equipment aimed at minimizing the probability of apple bruising.

## Data Availability

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

## Conflicts of Interest

All authors disclosed no relevant relationships.

## Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 32102026) and the Key Research Development Program of Shaanxi Province, China (No. 2023-YBNY-159).

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