

Methods for detecting and quantifying mechanical damage in fruits: Advances, challenges, and future perspectives

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ABSTRACT

Mechanical damage is a major factor affecting postharvest fruit quality, causing substantial economic losses throughout the supply chain. In addition to intrinsic factors such as species, cultivar, and growing conditions, fruit quality is strongly influenced by mechanical stresses during harvesting, handling, transport, and storage. Understanding the mechanisms and extent of such damage is essential for developing strategies to reduce losses and improve postharvest management. This review provides a comprehensive overview of current methods for detecting and quantifying mechanical damage in fruits, including finite element modelling for analysing stress distribution and deformation, pendulum impact tests for evaluating bruise susceptibility, penetrometers for assessing firmness, and non-destructive spectroscopic and imaging techniques for early damage detection. Particular attention is given to recent advances in non-destructive approaches and their potential for rapid and objective quality assessment. The current challenges, including standardisation of measurement protocols and scalability of advanced technologies, and outlines future perspectives for improving detection accuracy and reducing postharvest losses are highlighted.

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INTRODUCTION

Importance of fruit quality and mechanical damage

In addition to the type and quantity of fresh fruit in the diet, quality and healthiness of the fruit are also important, as governed by the relevant national regulations (*Ordinance on fruit quality*, 2008). Mechanical damage to fruit is research by agricultural scientists, the food industry, and technology experts. Peterson (2005) studied excessive damage to apples, peaches, and cherry fruit during separation and collection, finding that successful mechanical harvesting can be achieved if machine characteristics and construction are integrated into a compatible system, and if the cultivars have uniform fruit maturity. Uniform maturity allows the harvesting of firm fruits that are resistant to mechanical damage during separation, collection, and transport. Fenyvesi et al. (2013)

investigated stresses in apples and pears and concluded that during harvesting, transport, and handling, a certain percentage of damage occurs on the fruit surface with smaller loads, while more intense loads cause damage inside the fruit. They examined damage analysis for pears and apples using finite-element (FEM) and discrete-element (DEM) models, and found that maximum stress develops in the core, meaning the core accumulates stresses, while the load affecting the fruit varies depending on where it is applied (skin, flesh, core, or seed). FEM is a numerical method that has been used in the last 30 years to investigate the dynamic behaviour of objects. The use of machines and equipment in harvesting fruit, grapes, and vegetables requires an understanding of the dynamic behaviour of particles. Fruits, like other agricultural crops,

are exposed to various mechanical loads. Under such stress conditions, they behave as highly elastic materials, due to the complex integration of effects defined by geometry, shape, and surface roughness, and the movement of objects under stress results in deformation and fractures (Miyawaki et al., 2000). Opara and Pathare (2014) stated that understanding a product's susceptibility or resistance to damage is important for developing problem reduction strategies. Damage can be quantified using destructive manual measurements and subsequent analysis with technologies such as near-infrared spectroscopy, hyperspectral imaging, thermal imaging, and imaging nuclear magnetic resonance. However, there are also objective indices for quantifying the potential for product damage under mechanical load, but the most prominent is damage sensitivity, expressed as the amount of damage per unit of absorbed impactor compression energy. Fruits, like the woody tissue of plants, are sensitive to mechanical loads and are frequently damaged. For this reason, manufacturers of machines used in fruit production aim to make improvements to minimise damage to both the fruit and the tree. To ensure that machine construction meets agrotechnical requirements, designers must understand the physical and mechanical properties of fruits and plant tissues. Shirvani et al. (2014) investigated the mechanical properties of fruit and concluded that knowing the mechanical properties of fruit species enables assessment and predictions of deformations under external loads during transport, processing, and packaging. Abbott et al. (1984) conducted sensory and instrumental measurements of apple texture and stated that texture description can be achieved using mechanical properties such as hardness, elasticity, and deformation. Salarikia et al. (2017) evaluated patterns of stress distribution and deformations inside a pear resulting from the collision of the fruit with a flat surface made of different materials. They indicated that developing a strategy to reduce damage throughout the supply chain requires an understanding of the dynamic behaviour of fruit under different forced loads, and that FEM is one of the best techniques, in terms of accuracy and cost-effectiveness, for studying damage caused by impacts during harvesting, handling, packaging, and storage.

Modelling, simulation and experimental approaches

Kim et al. (2008) determined the modulus of elasticity and analysed the stress distribution of whole apples under parallel plate compression using FEM simulation based on the 3D geometry of real apple fruits, and compared the results with the application of the ASAE standard S368.4, for compression testing of agricultural materials of convex shape. They found that this standard was suitable for predicting both the maximum contact stress and the apparent modulus of elasticity.

In addition to FEM, other methods such as the Finite Difference Method, Boundary Element Method, and Meshless Method are also used to determine the physical properties and analyse the behaviour of fruits. Słupska et al. (2022) developed linear regression models to predict the volume of bruising based on fall height and surface type. They considered that numerical models are a practical tool for rapid damage volume estimation, with an accuracy of about 75% for collective models and 93% for individual models. Mechanical damage to cellular tissues is closely related to their microstructure. Therefore, the

behaviour of fruits under load depends on microstructural properties, such as cell size, cell wall thickness and stiffness, cell orientation, etc. (Stropek and Gołacki, 2020). According to Raji and Favier (2004), optimal design and control of primary production and harvesting operations require an understanding of the dynamic behaviour of agricultural products. The first step in FEM is to create objects with the appropriate shape and size in virtual space. The position of objects is determined by the coordinates of the centre of gravity for a spherical or other primitive shape (Fig. 1).

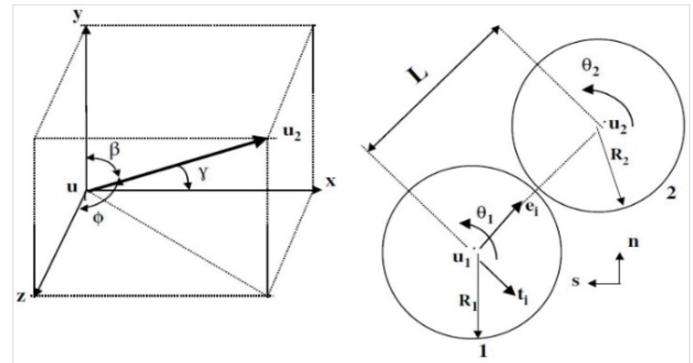


Figure 1. A pair of spherical objects in contact (Raji and Favier, 2004)

In order to model fruit behaviour using FEM, a suitable theoretical framework is required to describe the behaviour of deformable, highly elastic spherical particles under mechanical loading. The constitutive equation, which includes all forces (F) and moments acting on a moving particle in contact with neighbouring particles, can generally be expressed using Newton's second law of motion:

$$m\ddot{x} = \Sigma F \quad \text{and} \quad I\ddot{\theta} = \Sigma F_i R_c \quad (1)$$

where: m – mass of the particle; \ddot{x} – translational acceleration of particles; F – the sum of all forces acting on the body; θ – rotation acceleration; I – moment of inertia; F_i – tangential force; R_c – vertical distance from the line of action to the centre of the particle.

In fruit mechanics, this equation is practically applied to model how fruits move, collide, and distribute forces during processes such as handling, transport, and sorting, facilitating predictions and minimising mechanical damage.

Song et al. (2006) investigated the physical properties of pears using FEM. To obtain a non-symmetrical and non-spherical geometric model of the pear, they applied a new image processing technique. The pear was placed on a table, and the processing system consisted of a camera, a memory card, and software. The light values of the background object were used to separate the points. The 24-bit photos were processed with laboratory-made Visual Basic software, and the cross-section was obtained using the ANSYS 7.0 software (ANSYS Inc., Canonsburg, PA, USA). After pears were exposed to different vibrations (<100 Hz), the final quality of the pear was found to be influenced by shape, volume, and density. Fig. 2 shows the procedure for obtaining a cross-section of a pear.

Farkas et al. (2016) investigated the deformation of fruits under various mechanical influences, concluding that the occurrence of damage or deformation depends on several factors, including the height of the fall, the static load exerted on the fruit within the container, and the vibrational acceleration experienced during transport.

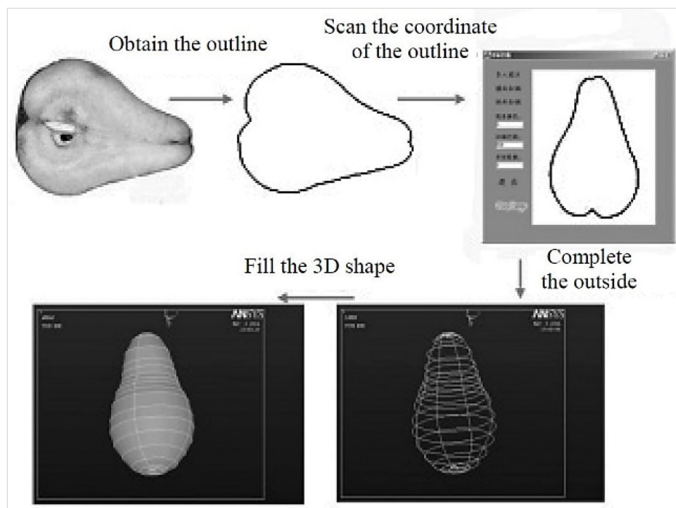


Figure 2. Geometric modelling of pear fruit (Song et al., 2006)

If mechanical injuries are undetected, the fruit spoils, affecting other fruits and ultimately reducing the quality of the final product. Once detected, a defective product can be removed from the process. For this purpose, several methods of image and heat processing can be used to distinguish bruised fruit from non-bruised fruit. Visual and infrared spectroscopy, as well as early damage detection using hyperspectral data and thermal imaging, are most commonly used. These methods can detect damaged fruits, thus preventing further mechanical injuries. The authors used an instrument with computer-controlled compression, called the DyMa Test. The deformation in this test is measured with a laser sensor using load wedges of \varnothing 4 mm, \varnothing 5 mm, and \varnothing 6 mm, and the results indicate that this method can determine the sensitivity of individual fruits under different load forces. The measuring circuit and settings are shown in Fig. 3.

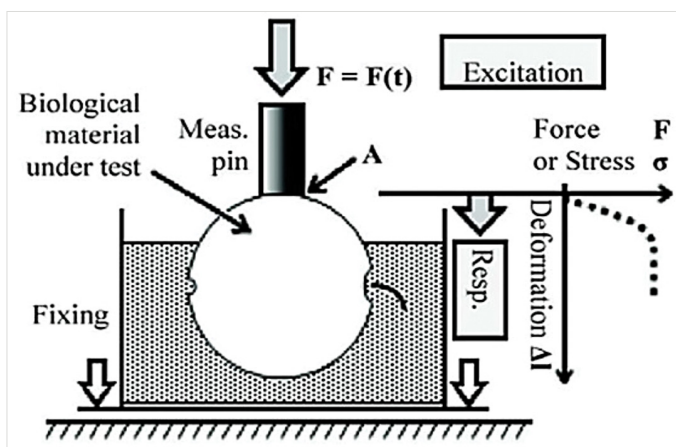


Figure 3. Diagram of the application of mechanical load in the DyMa Test (Farkas et al. 2016)

Li et al. (2017) reviewed 25 mechanical models related to compressive and impact loads on fresh fruits to examine the influence of impacts and other mechanical contacts between fruits or between fruits and a surface. They stated that it is crucial to develop accurate mathematical models that relate the mechanical properties of fresh fruit at different stages of ripening, and to characterise the microscopic behaviour of fruit materials, especially internal properties such as tissue

damage and microcracks, and then to develop appropriate damage criteria for such materials.

Fu et al. (2023) presented a method for measuring damage to fresh apples caused by repeated impacts using a pendulum with an arm length of 0.15 m, a rotating angle sensor, and a piezoelectric impact force sensor, and found that repeated shocks can significantly affect both the extent of damage and susceptibility to damage. To assess the amount of damage, they use three indices (BA, BV, and BS) that significantly affect the occurrence of damage. BA is an index of the amount of damage with respect to the size of the damage and is useful for rapid visual grading and sorting decisions. BV is the damage index for the size of internal damage and is particularly relevant for evaluating hidden defects that affect storage life and marketability. BS is the index that examines the ratio of BV to impact energy (E_{td}) and is most commonly used to quantify the potential for fruit damage due to mechanical stress, making it especially important for optimising handling, packaging, and transport conditions to reduce postharvest losses. The BA and BV indices are determined using the following equations:

$$BA = \frac{\pi w_1 w_2}{4} \quad \text{and} \quad BV = \frac{\pi d_b}{24} (3w_1 w_2 + 4d_b^2), \quad (2)$$

where: w_1 – greater width of damage; w_2 – smaller width of damage, d_b – depth of damage, as shown in Fig. 4.

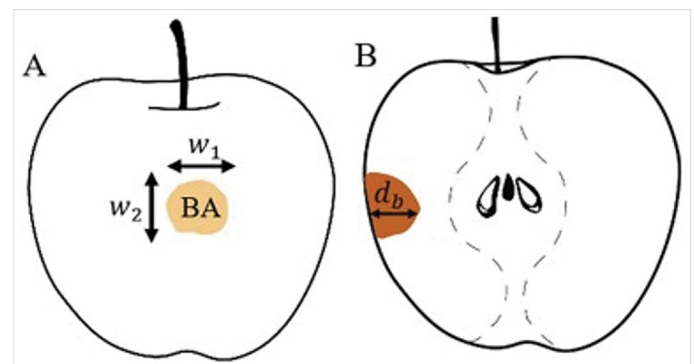


Figure 4. Diagram of damage measurements on an apple (Fu et al., 2023)

The BS index is determined by the equation:

$$BS = BV / E_{td}. \quad (3)$$

Non-destructive sensing and artificial intelligence approaches

When determining the quality of agricultural products, non-destructive methods are preferable as they are both faster and more economical than conventional methods, and cause no damage to the fruits. These include common sensor techniques such as imaging, spectroscopic, acoustic, mechanical methods, as well as E-nose and E-tongue techniques. Aboonajmi and Faridi (2016) stated that qualitative and quantitative measurements of agricultural products that cause no physical, chemical, thermal or mechanical damage can be considered non-destructive tests, and their advantages should play a more significant role in the fruit and vegetable industry. Mohd and Hashim (2022) also studied these methods and concluded that non-destructive techniques represent future trends in agricultural products quality assessment. Fathizadeh et al. (2021) stated that these methods are accurate, fast and suitable for online applications, and that the use of artificial intelligence and data fusion techniques could further increase the accuracy of product quality measurements.

Optical sensing approaches have become central to modern bruise detection, enabling fast, non-contact inspection. Visible/NIR and SWIR (Short-Wave Infrared) hyperspectral imaging can detect biochemical and structural changes associated with bruised tissue before symptoms become visible. Okere et al. (2023) demonstrated that Vis-NIR and SWIR hyperspectral imaging classified pomegranate bruise severity with high accuracy, while also reducing data dimensionality through informative wavelength selection. Similar progress has been reported for apples, pears, blueberries, strawberries, kiwifruit, and peaches, where spectral imaging has been combined with machine learning or deep learning to detect early bruises and hidden defects (Liu et al., 2023, 2026; Zhang et al., 2024; Locatelli et al., 2026; Sun et al., 2026).

Recent research has shifted towards rapid, non-destructive, data-driven methods capable of detecting visible, subsurface, and latent mechanical damage. These approaches integrate optical, spectroscopic, acoustic, and imaging techniques with artificial intelligence to enable objective, high-throughput quality assessment. The review by Nicolai et al. (2007) remains a cornerstone, establishing near-infrared spectroscopy as a fundamental tool for non-destructive quality assessment of fruits and vegetables, and providing the methodological basis for subsequent spectroscopic and imaging applications.

Deep learning has further improved the detection of subtle or irregular damage patterns. Convolutional neural networks (CNN), YOLO (You Only Look Once) based detectors, faster R-CNN (Region-based Convolutional Neural Networks) models, and hybrid spectral-spatial architectures can detect damaged regions, classify bruise severity, and support automated grading. Recent studies have reported effective early bruise detection in apples using hyperspectral imaging and YOLO-based models, in strawberries using hyperspectral imaging and deep learning, and in blueberries using hyperspectral feature fusion with machine-learning classifiers (Zhang et al., 2024; Sun et al., 2026). These methods are promising for industrial applications as they reduce subjectivity and enable rapid inspection, although model robustness across cultivars, lighting conditions, maturity stages, and acquisition systems remains a significant limitation.

X-ray imaging, computed tomography, and thermal imaging provide complementary information for internal or subsurface defects that may not be detectable using surface-based optical methods. X-ray imaging has recently been applied for internal quality inspection of pears, while active infrared and thermal imaging have shown potential for detecting subsurface bruises based on thermal contrast and heat-transfer differences between healthy and damaged tissue (Bharadwaj et al., 2025; Yang et al., 2025). Although these technologies offer strong diagnostic potential, their cost, processing requirements, radiation safety considerations, and integration into high-throughput sorting lines must be considered.

Overall, recent advances indicate that the future of mechanical-damage detection lies in multimodal sensing, sensor fusion, and artificial intelligence. Combining mechanical measurements with spectral, thermal, X-ray, and image-based data can provide a more comprehensive description of fruit damage, while machine learning can transform large sensor datasets into objective quality decisions. However, wider adoption will require standardised protocols, open datasets, validation under commercial conditions, and cost-effective

hardware suitable for integration into industrial grading and supply-chain systems (Mei and Li, 2023; Chamorro-Padial et al., 2024).

DISCUSSION

The mechanical properties depend on fruit structure, as well as on other factors. Fig. 5 shows the structure of a pear, apple and peach, highlighting the basic elements that primarily determine their mechanical properties.

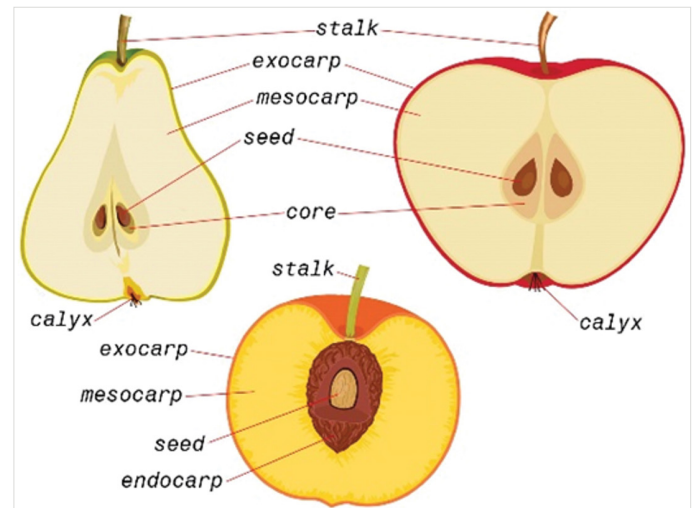


Figure 5. Illustration of the structure of a pear, apple and peach

The textural properties of fruits can be determined by precise indicators obtained through measurement or by descriptive terms based on visual inspection. Along with nutritional properties, taste and appearance, texture is one of the main indicators in the quality assessment of agricultural products. According to Jašić (2007), the mechanical attributes of texture are divided into five basic characteristics: hardness, cohesiveness, viscosity, elasticity and adhesiveness. The hardness or degree of damage to fruits and vegetables is determined by measuring the force required to cause damage or by measuring the area of the damage. Fig. 6 shows the procedure for determining the hardness of pear fruit.

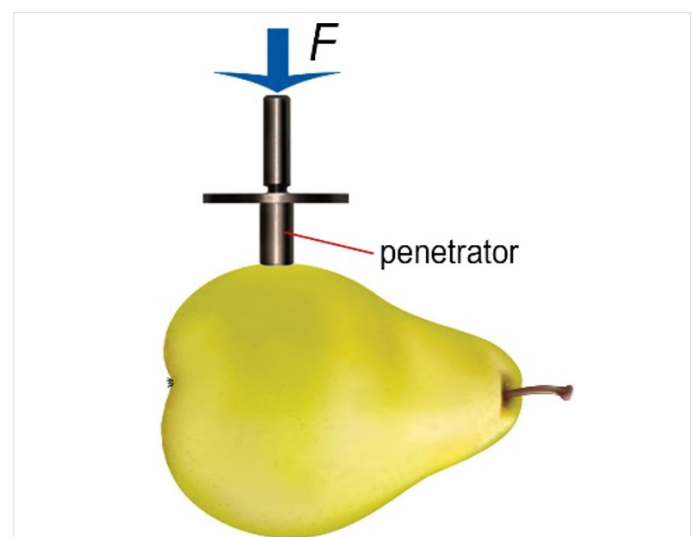


Figure 6. Illustration of hardness determination of fruit

Hardness H can be defined as a property of a material that resists the penetration of a foreign body (penetrator) into its structure. The hardness of a material is determined by the equation:

$$H = F / A, \quad (4)$$

where: H – hardness; F – the force with which the probe acts on the fruit (N); A – penetrator surface area (mm^2).

Skendrović Babojević and Fruk (2016) stated that monitoring the hardness of fruit is important when deciding its intended use and storage period. Hardness is mainly influenced by the nature and size of the fruit, calcium content, maturity at harvest, temperature, light, time, storage conditions, and other factors, and can be determined by various devices, including a penetrometer designed for materials such as fruit or vegetables. Fig. 7 shows the analogue, digital, and digital penetrometers on a stand.



Figure 7. Analogue, digital, and digital penetrometer on a stand

Not all fruits have the same characteristics, and for each fruit type, specific penetrators are used that differ in the surface area they penetrate into the fruit. Fig. 8 shows several penetrators with varying diameters (d).

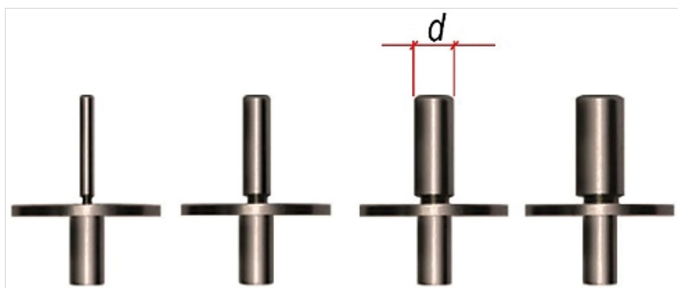


Figure 8. Penetrators with different diameters (Skendrović Babojević and Fruk, 2016)

Fathzadeh et al. (2021) found that the hardness of apples is related to juiciness and freshness, and that these are more important quality indicators than sugar and acid content. Based on information about hardness values, the nano-mechanical properties of fruit can be inferred during the ripening period, facilitating decisions on the optimal time for harvesting.

Table 1. Penetrator diameter values for different fruit types (Skendrović Babojević and Fruk, 2016)

Fruit type	Penetrator diameter (roller probe) (mm)
Berries, grapes and other small fruits	3
Avocados, berries, etc.	6
Pears, stone fruit, avocados, etc.	8
Apples	11

During harvesting, fruits and vegetables are subjected to various static and dynamic loads. When a fruit strikes a working element or collides with another fruit, deformation occurs, consuming energy. The impact strength of fruit is most commonly assessed using the coefficient of specific energy loss (k), as the energy required to destroy 1 mm^3 of apple fruit (Lukač and Pandurović, 2011), according to the equation:

$$k = E_k / V, \quad (5)$$

where: k – energy loss coefficient (J/mm^3); E_k – kinetic energy of the impact (J); V – volume of fruit deformation (mm^3).

The fruit elasticity factor (k_e) is determined by the ratio of the velocity after impact (V_2) to the velocity at the start of impact (V_1), according to the equation:

$$k_e = V_2 / V_1, \quad (6)$$

where: k_e – elasticity factor; V_1 – velocity at the start of impact (m/s); V_2 – velocity after impact (m/s).

The elasticity factor (k_e) is determined by dropping a fruit from a certain height (h_1) and measuring the height of its bounce from the substrate (h_2). Fig. 9 illustrates the procedure for determining the elasticity factor (k_e).

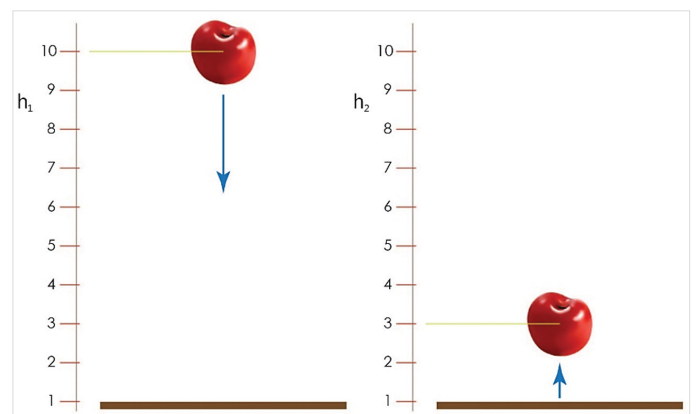


Figure 9. Procedure for determining the elasticity factor (h_1 represents the initial drop height of the fruit, and h_2 represents the rebound height after impact with the substrate; heights are expressed in centimetres (cm)).

Factors such as specimen conditioning prior to testing, geometry, and loading rate can affect test results, so standardisation of testing and reporting procedures is required to ensure the comparability of data from different sources. Factors such as variety, drying temperature, storage technique, maturity, and processing technique should also be taken into account (ASABE, 2008). Chen and Opara (2013) stated

that texture profile analysis establishes a "bridge" between objective measurement and subjective sensation, making food characteristics predictable. Khodabakhshian and Hassani (2021) reported that determining the elastic properties of agricultural products at the macro level results in very different values for certain samples. When researching the elasticity of fruits and vegetables, a practical test is Young's modulus, as the ratio of tensile stress to elongation and also a measure of material stiffness (Shirvani et al. 2014). For most materials, Young's modulus of elasticity is used when calculating the change in volume that occurs under the action of an external force (impact, compression).

Opara et al. (2007) described the application of a newly designed device for determining damage from the mechanical impact on fruits. They stated that a major limitation of existing devices is the lack of an objective measurement of the height of the bounce, which is necessary when determining the actual impact energy. This new device was assessed to be superior to devices using a subjective assessment of bounce height, and it provides a simple and cost-effective tool for researching damage to fruits and vegetables. Fig. 10 shows their device design.

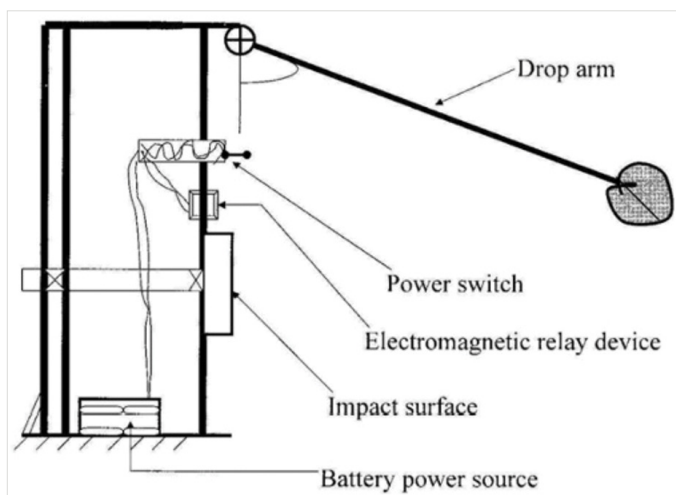


Figure 10. Diagram of the impact testing device (Opara et al., 2007)

An additional problem in direct strain measurement is the need to eliminate oscillations during impact that affect the measuring device (Abedi and Ahmadi, 2013). This issue can be addressed by using a high-speed camera that is not rigidly attached to the research device (Horabik et al., 2017; Liang et al., 2018; Surdilović et al., 2018). Nassiri and Jafari (2013) conducted research with the main objective of introducing an analytical method for predicting the allowable static load applicable to apple fruits. To predict the deformation energy absorbed by the fruit, a point load is applied to a solid spherical object, and the test is carried out at two different temperatures, 0 and 25°C. To simplify the problem, the shape of an apple is approximated as a sphere, and a point load P is applied to the contact surface, as shown in Fig. 11.

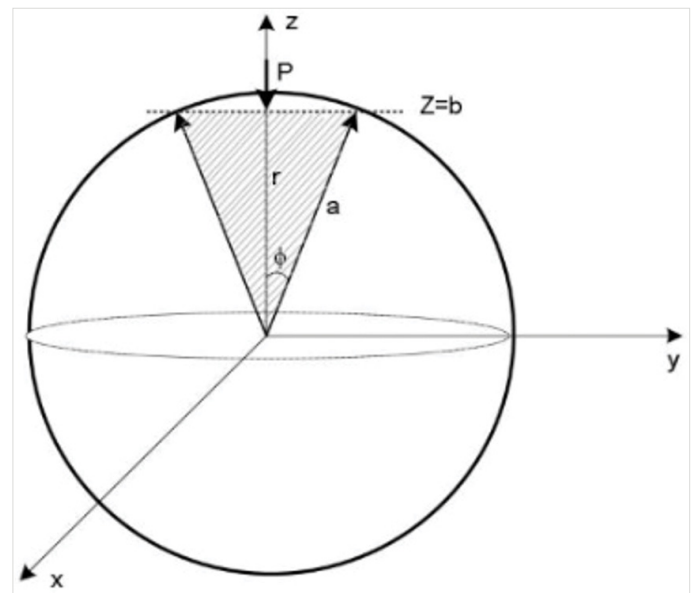


Figure 11. A spherical object subjected to an external point load (Nassiri and Jafari, 2013)

The same authors stated that the transient strain energy in the domain $(0, t_0)$ was calculated using the method of variables (where t_0 is the duration of the load during the stress relaxation test), and that strain energy can therefore be calculated as a function of time and the geometry of the apple.

Emadi et al. (2011) investigated the physical and mechanical properties of peaches, such as mass, volume, arithmetic mean diameter, density, sphericity, and stiffness, and found that determining the stiffness value non-destructively is feasible using the arithmetic mean diameter. Zhang et al. (2017) aimed to develop quadratic polynomial regression models using near-infrared spectroscopy to determine differences in skin colour, fruit hardness, soluble dry matter content, and their relationships with chlorophyll absorbance (absorption difference index, IAD) in nectarines. They stated that the quadratic polynomial regression method can be used to examine the relationship between fruit quality indicators and the degree of maturity, and that the regression relationship between hardness and IAD can be applied to predict the maturity of other varieties of peaches and nectarines.

CONCLUSIONS

Mechanical damage remains a major cause of postharvest losses in fruit production and supply chains, significantly affecting quality and economic value. Conventional methods such as compression tests, penetrometers, and impact devices provide useful information on fruit mechanical resistance, but are often destructive and limited in detecting hidden damage. Modern non-destructive approaches, including acoustic sensing, spectroscopy, hyperspectral imaging, X-ray/CT, thermal imaging, and machine vision, offer strong potential for rapid and objective quality assessment. The integration of artificial intelligence and machine learning further enhances bruise detection, classification, and prediction of damage severity.

However, key challenges remain, including the standardisation of measurement protocols, variability among fruit types, scalability of advanced technologies, and high implementation costs. Future research should focus on cost-effective sensors, multimodal data fusion, and robust AI models suitable for real-world applications. These developments could significantly improve detection accuracy and reduce postharvest losses.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Vlado Kušec: Conceptualisation, Methodology, Investigation, Writing – original draft, Visualisation. **Igor Kovačev:** Methodology, Investigation, Writing. **Martina Skendrović Babojelić:** Investigation, Resources. **Ante Galić:** Conceptualisation, Supervision, Writing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ETHICS AND PERMIT APPROVALS

Not applicable.

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AI USE STATEMENT

The authors used InstaText and Grammarly solely for language editing purposes, including grammar correction and language translation. No AI tools were used for generating scientific content, data analysis, interpretation of results, or drawing conclusions. All scientific content, analysis, and conclusions remain the sole responsibility of the authors.

SAŽETAK

Metode za otkrivanje i kvantificiranje mehaničkih oštećenja voća: napredak, izazovi i buduće perspektive

Mehanička oštećenja glavni su čimbenik koji utječe na kvalitetu voća nakon berbe, uzrokujući značajne ekonomske gubitke u cijelom lancu opskrbe. Osim unutarnjih čimbenika kao što su vrsta, sorta i uvjeti uzgoja, na kvalitetu plodova snažno utječu mehanička naprezanja tijekom berbe, rukovanja, transporta i skladištenja. Razumijevanje mehanizama i opsega takvih oštećenja ključno je za razvoj strategija smanjenja gubitaka i unapređenje postupaka nakon berbe. Ovaj pregledni rad daje sveobuhvatan prikaz suvremenih metoda za otkrivanje i kvantificiranje mehaničkih oštećenja plodova, uključujući modeliranje metodom konačnih elemenata (FEM) za analizu raspodjele naprezanja i deformacija, testove udara njihovom za procjenu osjetljivosti na modrice, penetrometre za procjenu čvrstoće te različite nedestruktivne spektroskopske i slikovne tehnike za rano otkrivanje oštećenja. Posebna je pozornost posvećena najnovijim dostignućima u području

nedestruktivnih metoda i njihovu potencijalu za brzo i objektivno ocjenjivanje kvalitete. Rad ističe aktualne izazove, uključujući standardizaciju mjernih protokola i primjenu naprednih tehnologija u praksi, te ocrta buduće perspektive za poboljšanje točnosti otkrivanja i smanjenje gubitaka nakon berbe.

Ključne riječi: kvaliteta plodova nakon berbe, rukovanje, intenzitet oštećenja, destruktivne i nedestruktivne metode

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