Effect of hardness on the mechanical properties of kiwifruit peel and flesh

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ABSTRACT
The mechanical properties of kiwifruit serve as the foundation for mechanical damage. In this work, the effect of hardness on the mechanical properties of kiwifruit was explored, and a hardness-mechanical property prediction model was developed. The results in this study showed that the tensile strength of the kiwifruit peel increased with decreasing hardness by 0.51, 0.75, 0.83, and 1.02 MPa in the axial direction and 0.48, 0.68, 0.92, and 1.08 MPa in the radial direction, respectively. While the peel’s elastic modulus decreased by 21.15, 14.03, 11.87, and 10.52 MPa in the axial direction and 15.04, 10.68, 8.45, and 7.54 MPa in the radial direction. At the same ripening stage, peel tensile strength did not differ significantly (\(P > .05\)), whereas peel modulus of elasticity was greater in the axial direction than in the radial direction. The results of the flesh compression test showed that the compressive strength of the flesh decreased with decreasing hardness to 0.36, 0.25, 0.09, and 0.06 MPa in the axial direction and 0.36, 0.23, 0.11, and 0.06 MPa in the radial direction, respectively. The modulus of elasticity also decreased to 1.05, 0.82, 0.42, and 0.32 MPa in the axial direction and 0.26, 0.45, 0.80, and 1.15 MPa in the radial direction, respectively. The compressive strength and modulus of elasticity of kiwifruit flesh did not differ significantly in the axial and radial directions at the same stage of ripening (\(P > .05\)). The model’s accuracy is demonstrated by correlation coefficients of tensile strength (compressive strength) and elastic modulus of kiwifruit peel and pulp in axial and radial directions, which were 0.97, 0.99 (0.99, 0.99), and 0.93, 0.90 (0.96, 0.99), respectively, for anticipating the mechanical characteristics of peel and flesh. It can provide theoretical and data references for post-harvest kiwifruit to reduce the mechanical damage.

Introduction
For its fresh taste and richness in nutrients, kiwifruit is loved by consumers all over the world \cite{1, 2, 3}. As a typical fruit mainly eaten fresh, kiwifruit is susceptible to mechanical compression damage during picking, packing, transport, and marketing because of its soft texture \cite{4}. Damaged kiwifruits can rapidly decay and deteriorate, which seriously affects their quality and economic efficiency \cite{5, 6, 7}. The study of the mechanical properties of kiwifruit will help to understand the mechanism of compression damage in kiwifruit and provide a reference for the development of kiwifruit production equipment. It will also help to reduce mechanical damage to kiwifruit in picking, packing, transporting, and marketing processes.

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In recent years, researchers have studied and analyzed the physical and mechanical properties of Hayward kiwifruit and determined parameters such as external dimension, volume, density, static friction coefficient, hardness, and adhesion force of kiwifruit fruit were determined to provide mechanical parameters for the design of mechanical equipment in the kiwifruit production chain.

The mechanical properties of kiwifruit peel, flesh, and placenta were studied, and the damage mechanism of kiwifruit was analyzed by finite element simulation. Whole-fruit compression tests were performed on kiwifruit to propose creep-time curves for kiwifruit. Much attention has been paid to the mechanical properties of different species of fruit, including apples, citrus, watermelons, banana, grape, tomatoes, pomegranate, and mulberry.

The before mentioned study focused on the mechanical properties of kiwifruit and did not take into account the differences in mechanical properties of kiwifruit at different stages of maturity. As one of the most important indicators of quality, hardness influences the mechanical properties of kiwifruit directly.

In particular, the hardness of kiwifruits changes continuously during development, ripening, and harvest. Thus, the study of the hardness of kiwifruit during storage can provide information that will serve as a parameter for determining the cultivar choice and postharvest shelf life. However, less research has been conducted on the influence of hardness on the mechanical characteristics of kiwifruit. The kiwifruit, as a berry fruit, has complex measurement mechanics properties. Thus, establishing a model to estimate the mechanical properties of kiwifruit fruits was also important based on hardness.

In the present study, the effect of hardness on the mechanical properties of kiwifruit was investigated, and a prediction model of hardness-mechanical properties was established. The objectives of this paper were: (i) to analyze the effect of hardness on mechanical properties of kiwifruit, such as tensile strength of the peel transverse and longitudinal diameters and compressive strength of the flesh transverse and longitudinal diameters; (ii) to develop a prediction model of mechanical properties of kiwifruit based on hardness; and (iii) to validate the prediction model.

**Materials and methods**

**Kiwifruit sample preparation**

The fresh kiwifruit (Actinidia chinensis cv. Hayward) samples were obtained from farmland in Zhouzhi county, Shaanxi province, China in October, 2021. Within 2 hours, the fruits were transported to an experimental laboratory in Xi’an, where the damaged fruits were removed and the healthy fruits were stored in refrigerator conditions (0 ± 1°C and 85 ± 5% RH). Fruit with similar weights and colors were chosen for further investigation. The selected kiwifruit samples were packed in bags with a moderate amount of ethylene and equilibrated in a room temperature setting (20 ± 2°C) at 2 day intervals to get distinct hardness samples. Kiwifruit were selected in the hardness range of 9.83–60.35 N. Table 1 shows the hardness classification of kiwifruit at various stages of commercial processing.

**Kiwifruit peel sample preparation**

The kiwifruit peel was converted into axial and radial tensile specimens, respectively, to investigate the effect of hardness on the axial and radial mechanical properties of the peel. After marking the kiwifruit with a pen with a gap between consecutive longitudes of 15 mm, the kiwifruit was sliced into equal-

| Table 1. Criteria for classifying the hardness of kiwifruit. |
|-------------------------------------------------------------|
|                | Standard | Edible   | Selling | Packaging | Harvesting |
|-----------------|----------|----------|---------|-----------|------------|
| Hardness(N)     | 13.12 ± 1.96 d | 24.55 ± 4.68 c | 39.93 ± 5.13 b | 55.05 ± 3.53 a |
sized slices along the longitudes with a knife, and the peel was peeled off along the flesh for the axial tensile peel samples. Finally, the peel was cut into 60 samples, each measuring $50.58 \pm 1.39$ mm in length, $11.03 \pm 0.92$ mm in width, and $0.72 \pm 0.21$ mm in thickness, as measured with a digital caliper (MNT-150, China) with a measurement range of 0–150 mm and resolution of one hundredth of one millimeter. The sample preparation process of kiwifruit peel axially is shown in Figure 1(a).

Figure 1(b) depicts the radial preparation process of kiwifruit peel. The radial tensile specimens were created in the same manner as the axial tensile specimens. The kiwifruit was cut into equal-sized slices along the latitude after being marked with a 12 mm interval, and then the peel was peeled off along the flesh. Finally, the peel was made into 60 samples with the length of $50.46 \pm 1.03$ mm, the width of $11.39 \pm 0.86$ mm, and the thickness of $0.82 \pm 0.21$ mm.\[^9,30\]

**Kiwifruit flesh sample preparation**

As shown in Figure 1 (c) and (d), the residual flesh from the previous section’s peel tensile test was cut in radial and axial directions. The flesh was compressed into axial compression specimens measuring $10.63 \pm 0.76$ mm in height, $9.25 \pm 0.85$ mm in length, and $7.74 \pm 0.76$ mm in width, as well as radial compression specimens measuring $8.19 \pm 0.88$ mm in height, $10.53 \pm 0.79$ mm in length, and $9.87 \pm 0.72$ mm in width.\[^9,30\]

![Figure 1. Sample preparation of kiwifruit peel and flesh in the axial and radial direction.](image-url)
**Hardness measurement**

To measure the kiwifruit hardness, 30 kiwifruits from ripening treatment were measured using a texture analyzer (Stable Micro System-TA.XT.Plus, UK) utilizing probe P/2 at a depth of 30 cm with a pre- and mid-measurement velocity of 1 mm/s and a post-measurement velocity of 10 mm/s and 10 mm/s, respectively. Assessments were performed on two opposite sides of each kiwifruit sample.

**Tensile test of kiwifruit peel**

The mechanical characteristics of kiwifruit were determined using the ASABEs 368.4 standard. The mechanical properties of kiwifruit peel and flesh were tested using an electronic universal testing machine (Shanghai Kaiyan Testing Instrument Co., LTD, KY-5KNW, China). The condition of the kiwifruit peel before and after the tensile test is shown in Figure 2. As a valid specimen, the kiwifruit peel was broken in the middle. The loading speed was adjusted to 5 mm/min during the test, and an electronic universal testing machine captured the stress-strain curves and test data.

**Compression test of kiwifruit flesh**

The condition of the kiwifruit flesh before and after compression is shown in Figure 3. The universal testing machine’s loading speed was set to 5 mm/min, and the loading button was pressed. When the flesh specimen was compressed, the stress value dropped to its lowest point and then progressively increased when the loading was halted. A universal testing apparatus was used to record the stress-strain curves and test results.

**Parametric solution of the mechanical properties**

The kiwifruit peel and flesh were mounted between two parallel plates of the universal testing machine, and their force-deformation curves were recorded by computer. Based on these curves,
the modulus of elastic modulus, failure strain, and failure stress were calculated. According to Hook’s and Hertz’s theory, the tensile (compression) strength and modulus of elasticity of the peel and flesh can be calculated as follows. When peel tensile tests and flesh compression tests were conducted for kiwifruits, interaction force will be generated between various parts in the peel and flesh. The internal force per unit area of the peel and flesh is called stress, and the formula is expressed as:

$$\sigma = \frac{F}{S} \quad (1)$$

where, $\sigma$ means the stress (N/mm$^2$), $F$ denotes the tensile force (N), $S$ indicates cross-sectional area of the material in the direction of tensile (compression) (mm$^2$). The peel and flesh of the fruit will be deformed under external force. The degree of deformation is called strain, and the formula is expressed as:

$$\varepsilon = \frac{\Delta L}{L} \quad (2)$$

where, $\varepsilon$ means the tensile (compression) stress (%); $\Delta L$ denotes the length after deformation (mm), $L$ indicates the original pitch length before deformation (mm). At the elastic deformation stage, the material’s stress and strain become positively proportional, and the proportional coefficient is called the elastic modulus, which is expressed as:

$$E = \frac{\sigma}{\varepsilon} = \frac{FL}{S\Delta L} \quad (3)$$

where, $E$ means the elastic modulus of the material, N/mm$^2$ or MPa.

**Statistical analysis**

A completely randomized group design was used in all of the studies. The data on the mechanical properties of kiwifruit by hardness was analyzed using a single component analysis of variance (ANOVA). When utilizing Duncan’s test with SPSS 19.0, differences were judged significant if $P < .05$. 

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[Figure 3. The status of kiwifruit flesh before and after compression.]
Results and discussion

Mechanical properties of kiwifruit peel with hardness

The results obtained from the tensile test are given in Figure 3. Kiwifruit mechanical properties, such as tensile strength and modulus of elasticity, are related to hardness. As the kiwifruit peel’s hardness increased, so did its axial and radial tensile strength, as illustrated in Figure 4 (A). Experimental data showed that the tensile strength of kiwifruit peel ranged from 0.51 to 1.02 MPa in the axial direction and from 0.48 to 1.08 MPa in the radial direction. During the edible, selling, packaging, and harvesting, the axial tensile strength of the kiwifruit peel was 0.51, 0.75, 0.83, and 1.02 MPa, while the radial tensile strength was 0.48, 0.68, 0.92, and 1.08 MPa, respectively. In a similar study, Tian studied the tensile strength of kiwifruit peel in axial and radial directions. The results showed that there was a small significance of kiwifruit peel in axial and radial directions at the same maturity stage (p > 0.05).

The post-harvest tensile strength is higher than at other stages, including edible, storage, and sale. In other words, when subjected to the same force, ripe fruit may be more vulnerable to injury due to its soft texture. This is the same result as that of Costa. The skin of the kiwifruit, as the fruit’s outermost tissue, plays a big role in determining damage during harvesting, packing, and transportation, particularly the mechanical qualities of the skin. The degradation of pectin during storage strongly correlated with the decline in the hardness of the fruit. The pectin degeneration weakened the cell wall, decreased the integrity, and increased the porosity of the cell walls, which led to an increase in loss of moisture. Pectin begins to break down when kiwifruit hardness decreases and intercellular adhesion decreases, resulting in a loss in rind tensile strength. During the stretching process, the cell shape changed more on the transverse axis than on the longitudinal axis, most likely because the cells on the axis were small and short.

The relationship between the modulus of elasticity and the hardness of kiwifruit peel is depicted in Figure 4 (B). Experimental data showed that the modulus of elasticity of kiwifruit peel ranged from 10.52 to 21.15 MPa in the axial direction and from 7.54 to 15.04 MPa in the radial. During the edible, selling, packaging, and harvesting, the axial modulus of elasticity of the kiwifruit peel was 21.15, 14.03, 11.87, and 10.52 MPa, while the radial modulus of elasticity was 15.04, 10.68, 8.45, and 7.54 MPa, respectively. The modulus of elasticity of kiwifruit peel axially is greater than radially, indicating that the peel’s fibers are arranged along its cell walls parallel to the axial direction, which strengthens the pericarp in that direction. Kiwifruit fruits have high axial resistance and high sensitivity to pressure stress, and therefore are placed axially when packing kiwifruit. The axial and radial modulus of elasticity of the kiwifruit peel decreased as its hardness increased. It was discovered that the difference in modulus of elasticity and hardness was statistically significant (p ≤ 0.05). The viscoelastic behavior of...
the fruit is linked to mechanical injury. When compared to less mature fruit, ripe fruit had higher flexibility and were more sensitive to harm.

The modulus of elasticity is a measurement of the deformation resistance of fruit. The findings of this study also revealed that fruit at an early stage of maturity was more resistant to damage. They did the same research on the Cukurova tomato, and got a similar result. However, the variation in axial and radial modulus of elasticity of the kiwifruit peel is related to the tensile area of the kiwifruit peel being different.

Singh and Reddy, who analyzed orange’s physic-mechanical properties after harvest, concluded that the slight decrease in rupture force, tensile strength and modulus of elasticity with storage period might be due to drying effect and softening of peel tissues that reduced the turbidity. The trend in the modulus of elasticity of kiwifruit peel was opposite to that of oranges, probably because kiwifruit is a berry fruit and as the hardness decreases, the kiwifruit peel becomes softer and the modulus of elasticity increases.

**Mechanical properties of kiwifruit flesh with hardness**

The change in mechanical properties of kiwifruit flesh with hardness is shown in Figure 5. The axial and radial compression strengths of kiwifruit flesh increased with the gradual increase in hardness. The axial compression strength of kiwifruit flesh was 0.06, 0.09, 0.25, and 0.36 MPa, whereas the radial compression strength was 0.06, 0.11, 0.23, and 0.36 MPa during the edible, selling, packaging, and harvesting, respectively. By comparing the compressive strength of kiwifruit flesh in the axial and radial directions, we can consider kiwifruit flesh as an isotropic material. This is different from the results of the study by Tian and may be due to the differences in varieties.

According to the figure, the harvest had the highest compression strength value, while the edible showed the lowest compression strength value. As seen in the figure, the compression strength of kiwifruit flesh in four stages is significantly different at a 5% level of confidence. This difference reveals that kiwifruit flesh has different tissue responses to external loads and forces at different maturity stages. In order to minimize mechanical damage, the pressure generated during the transfer of different harvested, packed, sold, and edible kiwifruit must be reduced to a minimum of 0.36, 0.25, 0.23, and 0.06 MPa, respectively. Fruits and vegetables are viscoelastic by nature. Viscoelasticity is the property of a material that exhibits both viscosity and elasticity during deformation. The degree of maturity determines the different viscoelasticity of the pulp and therefore the different hardness of the pulp has different compressive strength, which is consistent with the results of.[43]

The axial and radial modulus of elasticity of kiwifruit increases with hardness increasing, as demonstrated in Figure 5 (B). The axial modulus of elasticity of kiwifruit flesh was 0.32, 0.42, 0.82,
and 1.05 MPa in edible, salable, packed, and harvested, respectively, while the radial direction was 0.26, 0.45, 0.80, and 1.15 MPa, respectively. There were no significant differences in axial and radial directions for the same maturity period. A markedly significant difference (p ≤ .05) in modulus of elasticity was found between the different maturity stages.

Fruit tissue hardness is one of the parameters that can be affected by static and dynamic loads, and fruit quality might decrease as a result of change in hardness. Modulus of elasticity is one of the parameters that can be used to measure fruit tissue hardness.\textsuperscript{[19]} As the hardness of the kiwifruit grew, the elastic modulus of the peel fell, while the elastic modulus of the flesh increased. The higher the modulus of elasticity is, the harder the fruit tissue will be. In a similar study, Jahanbakhshi examined the mechanical properties of snake melon and banana fruit.\textsuperscript{[44]} The findings indicate that the space between fruit cells grew as kiwifruit hardness decreased and the phenomenon of palm wall separation occurred, leading to a drop in the elastic modulus of kiwifruit flesh.

Variations in the mechanical parameters of kiwifruit flesh during compressive loading can be explained by tissue microstructure. Lower ripeness reduces compression strength and elastic modulus, which could be due to cellular rearrangement and compression of the intercellular space during compressive pressure. Additionally, because the kiwifruit specimen’s border cells were cut during sample extraction, some fluid would be ejected at the start of the test. The modulus of elasticity and compressive strength rose with increasing hardness, most likely due to cell pressurization.\textsuperscript{[35,45]}

Mechanical properties prediction model based on hardness of kiwifruit

Awareness of the mechanical properties of agricultural products for estimating and predicting the changes in their shapes when compressed is important because the forces would lead to excessive deformation and damage to the products, influencing marketing and their economic value.\textsuperscript{[46]} Kiwifruit has a softer texture than other fruits and it is more susceptible to damage, and hardness is one of the most important factors in evaluating the quality of kiwifruit. Therefore, we needed to develop a predictive model based on the mechanical properties of kiwifruit hardness.

In the tensile and compression tests, mechanical properties consisted of tensile (compressive) strength of peel (flesh), modulus of elasticity of peel and flesh, and hardness. The correlations between mechanical properties and hardness values of tensile strength of peel, modulus of elasticity of peel, compressive strength of flesh, and modulus of elasticity of flesh are shown in Figure 6. The correlation coefficient was high between the mechanical properties and the hardness value in each prediction model, as shown in Figure 6(A,D). All values exceeded 0.9, indicating that the models based on hardness and mechanical properties can accurately and reliably predict the quality of samples.

The correlation coefficients for the mechanical properties of kiwifruit flesh were higher than those of the peel, which may be due to water dissipation from the kiwifruit peel. In similar studies, researchers reported that the moisture content is very important and influential in determining the mechanical properties of fruits.\textsuperscript{[35–37]} Therefore, rapid sampling is required to measure the mechanical properties of the peel, which makes the operation more difficult. By analyzing the tensile test process and combining the problems that occurred in the study of Dahdouh, in the early stages of the test, the peel was hard and there was little juice, which facilitated the conduct of the test.\textsuperscript{[47]} The friction between the tool and the bottom groove was small, and the error was negligible. In the middle and late stages of the experiment, the flesh gradually became softer and more juice appeared. As a result, the friction was improved and the sample appeared cracked before the stretching process. The measured values became smaller and the relative errors increased. This suggests that they may include both systematic and accidental errors.\textsuperscript{[48]}

Validation of the prediction model

To further validate the performance of this prediction model, four sets of data that were not utilized in the modeling were used as validation samples to test prediction results. The mechanical properties of kiwifruit were verified according to the linear regression equation in Figure 6. The experimental and anticipated values of the mechanical characteristics of kiwifruit are shown in Table 2. The results
shown that the model and predicted values of the kiwifruit mechanical properties correspond well, with average relative errors of predicted and experimental values of 10.31%, 15.63%, 5.54%, and 20.99%, respectively. As a result, the mechanical properties of kiwifruit can be accurately predicted using the kiwifruit mechanical properties-hardness model.

According to Table 2, relative errors were compared, where the relative errors of kiwifruit flesh were higher than those of fruit peel in the axial direction and radial direction. The reason for obtaining the errors is mainly related to the arrangement of the flesh cells, which have different compositions,

Table 2. Experimental and predicted values of mechanical properties of kiwifruit.

| Hardness (N) | Experimental value | Predicted value | Relative error (%) |
|--------------|--------------------|-----------------|--------------------|
|              | axial (MPa)        | radial (MPa)    | axial (MPa)        | radial (MPa)    | peel | flesh | Peel | flesh | Relative error | peel | flesh | Peel | flesh | peel | flesh | peel | flesh | Peel | flesh | Peel | flesh | peel | flesh | Peel | flesh |
| 17.61        | 0.54874            | 0.05451         | 0.58534            | 0.05651           | 0.59528         | 0.06078         | 0.56536            | 0.06358           | 8.48 | 11.50 | 3.41 | 12.51 |
| 25.04        | 0.65445            | 0.08992         | 0.72640            | 0.09411           | 0.67806         | 0.09568         | 0.67179            | 0.11868           | 3.61 | 6.40  | 7.52 | 26.12 |
| 43.90        | 0.94509            | 0.32384         | 0.88271            | 0.30827           | 0.88830         | 0.39352         | 0.94210            | 0.37554           | 6.01 | 21.51 | 6.73 | 21.82 |
| 56.86        | 1.34393            | 0.40016         | 1.17588            | 0.38096           | 1.03278         | 0.49259         | 1.12786            | 0.47048           | 23.15 | 23.10 | 4.08 | 23.50 |
| Average relative error (%) | 10.31 | 15.63 | 5.44 | 20.99 |
internal structures and are susceptible to changes during the sampling process.\textsuperscript{[49,50]} The same results were found by Ma in the study of the mechanical properties of pineapple flesh.\textsuperscript{[51]}

**Conclusion**

In this study, the effect of hardness on the mechanical properties of kiwifruit peel and flesh in different directions was investigated by tensile and compression tests. For the first time, the tensile (compression) strength and elastic modulus of kiwifruit peel and flesh were obtained at different maturity stages. The main conclusions can be drawn as below: (i) The tensile strength of kiwifruit pericarp axially was not significantly different from radially at the same maturity stage. This is due to the isotropic nature of kiwifruit peel. As the hardness decreased, the tensile strength of kiwifruit peel also decreased. Hardness is closely related to pectin, and pectin denaturation weakens the cell wall, decreases the integrity, increases the porosity of the cell wall, leads to water loss, and reduces the tensile strength of kiwifruit peel. (ii) At the same stage, the axial modulus of elasticity of kiwifruit peel was greater than the radial modulus. This is because the peel’s fibers are arranged along its cell walls parallel to the axial direction, which strengthens the pericarp in that direction. The modulus of elasticity of kiwifruit peel increases with decreasing hardness due to the viscoelasticity of the fruit. Kiwifruit peel in the edible stage have higher elasticity and are more sensitive to damage. As a result, the most recent focus is on the investigation of specific packaging materials. (iii) Compression tests on kiwifruit flesh showed no significant difference in tensile strength in axial and radial directions, while the tensile strength of the flesh decreased with decreasing hardness. This was due to the softening of the fruit. (iv) The modulus of elasticity of kiwifruit in the axial direction was not significantly different from that in the radial direction. The modulus of elasticity increased with increasing hardness due to the fact that the modulus of elasticity is related to the hardness of the flesh, the higher the modulus of elasticity, the higher the hardness. (v) The linear correlation coefficients of tensile strength (compressive strength) and elastic modulus of kiwifruit peel and pulp in axial and radial directions were 0.97, 0.99 (0.99, 0.99), and 0.93, 0.90 (0.96, 0.99), respectively. It is shown that the models based on hardness and mechanical properties can accurately and reliably predict the quality of samples.

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**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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