# MECHANICAL PROPERTIES OF CERASUS HUMILIS AT DIFFERENT TEMPERATURES FOR POSTHARVEST DAMAGE ANALYSIS

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# 欧李采后在不同温度下的力学特性研究分析

**Bin TONG, Junlin HE*), Jingpu ZHOU, Tao WANG, Huhu YANG**[1]
College of Agricultural Engineering, Shanxi Agricultural University, Taigu / China;
*Tel: +86-0354-6288400; E-mail: hejunlin26@126.com*
*Corresponding author: Junlin He*
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## ABSTRACT

*In this study, the mechanical properties of three varieties of cerasus humilis at different temperatures were systematically investigated by whole fruit puncture test, exocarp uniaxial tensile test and mesocarp uniaxial compression test. It was found that puncture test could not only reflect the shear mechanics of the exocarp in vivo at the tissue level, but also characterize the resistance level of fruit to puncture damage at the macro level. The environmental temperature had significant negative and positive effects on puncture failure stress and puncture failure deformation of cerasus humilis ($p<0.05$).The stress and elastic modulus of exocarp tension and mesocarp compression were significantly affected by ambient temperature ($p<0.05$).This study combined with temperature change to study the mechanical properties of cerasus humilis provides a necessary theoretical basis for the prediction of fruit damage and the development of postharvest treatment equipment.*

## 摘要

*本文采用全果穿刺试验、外果皮单轴拉伸试验和中果皮单轴压缩试验，系统研究了 3 个欧李品种在不同温度下的力学特性研究。穿刺试验结果反映了环境温度对欧李穿刺破坏应力和穿刺破坏变形分别有显著的负向和正向影响($p < 0.05$)。研究发现，穿刺试验不仅能在组织水平上反映果皮在体内的剪切力学，而且能在宏观水平上表征果实对穿刺损伤的抵抗水平。而外果皮拉伸试验和中果皮压缩试验结果反映了环境温度对欧李外果皮拉伸和中果皮压缩的破坏应力和弹性模量有显著的负向影响($p < 0.05$)。本研究以温度为自变量研究欧李的力学特性，为预测欧李的损伤和后续分拣储存运输等处理设备的改进提供重要的理论基础。*

## INTRODUCTION

Cerasus humilis, in the world distribution is mainly concentrated in the north of China's thirteen provinces, municipalities and autonomous region (*Liu et.al, 2005*). Its pulp contains 17 amino acids needed by the human body and a large number of vitamin C, vitamin B2, vitamin E and potassium, phosphorus, zinc, selenium and other minerals, and it is one of the fruits with the highest calcium content (*Li.,2015*). In addition to its nutrient rich characteristics, the root system of cerasus humilis is well-developed and can grow under adverse conditions such as drought and low temperature. It plays an important role in preventing soil erosion and protecting the soil and sand (*Liang et.al, 2008; Liu et.al, 2013*). At present, the bottleneck that restricts the development of the cerasus humilis industry in China is mainly the backwardness of harvesting methods and grading, packaging and transportation machines, resulting in mechanical damage to the fruit. Therefore, basic research on mechanical damage of cerasus humilis has become very urgent (*Zhang et.al, 2018*).

For the research on the mechanical properties of fruits, there were relevant studies on apples as early as 2008. The researchers used methods of stretching the exocarp and compressing the mesocarp to study the mechanical properties of fruits such as apples, tomatoes and cherries (*Li et.al, 2012; Alamar et.al, 2008; An et.al, 2020*). In the meantime, a large number of systematic studies on the tissue mechanics of other fruits have shown that environmental temperature can affect the mechanical properties of various fruits (*De et.al, 2015; Desmat et.al, 2002*). For example, in the study of tomatoes, cherries and bayberries, it was found that temperature had a significant negative effect on the failure stress, elastic modulus and failure energy of the mesocarp (*Han et.al, 2022; Lana et.al, 2005; Yang et.al, 2007*).

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[1] *Bin Tong, As.M.S.Stud.; Junlin He, Prof.Ph.D.Eng.; Jinpu Zhou, As.M.S.Stud.; Tao Wang,As.M.S.Stud.;Huhu Yang, As.M.S.Stud*

Nevertheless, the study of the sensitivity of the mechanical properties of cerasus humilis to ambient temperature is still very rare in the world. Only a few studies have investigated the basic physical and mechanical properties of cerasus humilis (*Bin et.al, 2020; Shaohua et.al, 2021*). For example, in Shilei's paper, only the compressive failure mechanical properties and elastic modulus of whole fruit were investigated (*Shilei et.al, 2023*). For the exocarp and mesocarp and the influence of temperature on the mechanical properties of differences, more in-depth research was not done.

However, the harvest period of cerasus humilis is usually from early August to October, and the process from orchard picking to market sales of cerasus humilis requires many processing operations, such as orchard picking, sorting and packaging, transportation and storage, which can expose these cerasus humilis fruits to different environmental temperatures. Therefore, the study of cerasus humilis mechanical properties combined with temperature change is necessary, which can provide a vital theoretical basis for fruit damage prediction and the development of postharvest treatment equipment.

## MATERIALS AND METHODS

### Materials

The materials for this experiment were selected from the fruits of three varieties of cerasus humilis: Nongda No.5, Nongda No.6,and Nongda No.7. The ripening period of the cerasus humilis is divided into two stages: the orange-red stage and the bright red stage, and in order to ensure the quality of the cerasus humilis during transportation and storage, the usual choice was to pick it during the orange-red period. That's why it was chosen to pick cerasus humilis fruits during the orange-red period and then they were inspected to make sure that the fruits were intact and not damaged by hand-picking or damaged by pests or diseases. The experiment required the harvesting of approximately 300 similarly sized cerasus humilis fruits to be used for the study. Subsequently, after cleaning and drying the surface of the picked cerasus humilis samples, they were transported back to the laboratory and stored in the laboratory freezer, with a storage temperature set at 5℃.

### Determination of puncture mechanical properties

#### Test setup

All possible ambient temperatures to which cerasus humilis may be exposed from the time of picking to the time of sale are usually between 5~35°C. Therefore, three temperatures, 5°C, 20°C and 35°C, were chosen as independent variables for this experimental design. A constant temperature and humidity chamber (Zhongwei Instrument Co., Ltd., Guangdong, China) was chosen for storing the cerasus humilis fruits in order to achieve the three ambient temperatures set for the experiment. The storage time for each group of cerasus humilis specimens was 30 minutes and all tests were carried out at 60% relative humidity to ensure that the conditions required for the tests were achieved (*Alique et.al, 2005*). In this experimental study, 30 samples of each of the three varieties of cerasus humilis were used, for a total of 90 cerasus humilis samples, and each of these cerasus humilis samples was randomly assigned into three groups of 10 cerasus humilis fruits each. And these samples were used to complete the puncture test.

#### Puncture test

The instrument used for the puncture test was a texture analyzer (Chaotech Instruments Co., Ltd., Xiamen, China).The procedure of the puncture test was as follows: firstly, one fruit was randomly removed from a sample group of cerasus humilis in a constant temperature and humidity chamber, for example, one from the group with the temperature set to 5℃ was taken. Considering the influence of external environmental temperature, only one cerasus humilis fruit was selected for each experiment, and the experimental time was controlled to be about 1 minute. Next, the displacement of each experiment was set to 15% deformation, and the puncture position was selected at the bottom of the fruit (Fig.1.a). The testing mode of this puncture test was compression, with a pretest speed of 2 mm/s, a mid-test speed of 0.5 mm/s, and a post-test speed of 10 mm/s. The load trigger force was 0. 05 N, and the probe was P2. During the test, the penetration force and displacement data have been recorded in real time by the texture analyzer. Finally, formulas (1) and (2) were used to calculate the puncture failure force and puncture failure energy of cerasus humilis fruits:

$$\sigma_p = \frac{F_{p\max}}{A} \tag{1}$$

$$E_{prec} = \int_0^{D_{p\max}} F dD \tag{2}$$

In the formulas: $\sigma_p$ - puncture failure stress, MPa; $F_{p\max}$ - peak puncture force, N; $A$ - bottom area of puncture probe, mm$^2$; $E_{prec}$ - puncture failure energy, mJ; $D_{p\max}$ - puncture failure deformation, mm; $F$ - real-time puncture force, N; $D$ - real-time probe displacement, mm.

## Determination of tissue mechanical properties

### Test setup

As with the puncture test, for the study of the tissue mechanical properties of cerasus humilis, three temperatures were also set, 5°C, 20°C and 35°C, as independent variables. Humidity was set at 60%. The time for storage of each set of samples was similarly set at 30 minutes. Again, in order to minimize the influence of external factors, only one sample was taken in a single experiment and the experiment time was kept to no more than 1 minute as far as possible. The experiment entailed each cerasus humilis fruit being made into a standard exocarp or mesocarp sample. In order to investigate the effects of different varieties and ambient temperatures on the tissue mechanical properties of cerasus humilis, all samples were divided into 2 tissue types × 3 varieties × 3 temperatures for a total of 18 groups. Each group was allocated 10 fruit samples to be used for replicated tests. A total of 180 cerasus humilis fruits were used in this experiment (*Han et.al, 2022*).

### Tensile test of exocarp

For the tensile test, nine sets of fruit samples (3 varieties×3 temperatures) were selected as materials for the tensile test. The steps for a single experiment were: firstly, one fruit sample was randomly selected from the constant temperature and humidity chamber at some set temperature for each experiment. Next, the one was made into an exocarp sample with a length of 50 mm and a width of 7 mm. Preparation of exocarp samples began with a circular cut along the center transverse section of the fruit using a circular cut fruit knife to obtain a circular cut slightly larger than the standard sample size. A blade was then used to cut a standard exocarp sample of 7 mm in width and 50 mm in length from the annular section along the direction of the equatorial cross-section. Finally, the mesocarp residue was removed from the exocarp sample and the standard sample preparation was completed. The prepared samples were immediately subjected to exocarp tensile test using an electronic universal material testing machine (INSTRON, Boston, the USA) until fracture (Fig.1.b). The testing mode of this experiment was tension, and the testing speed was set to 1 mm/s. The electronic universal testing machine has recorded the test data of tensile force and displacement in real time. Finally, using the following formulas to calculate the mechanical parameters such as the elastic modulus of the exocarp (*Li et.al,2012*). Each set of experiment requires 10 repetitions.

$$\sigma_e = \frac{F_{e\max}}{wd} \tag{3}$$

$$\varepsilon_e = \frac{\Delta L}{L} \tag{4}$$

$$E_e = \frac{\sigma_e}{\varepsilon_e} \tag{5}$$

$$E_{rece} = \int_0^{\Delta L} F_e d\Delta L \tag{6}$$

In the formulas: $\sigma_e$ - tensile failure stress of exocarp, MPa; $F_{e\max}$ - peak tensile force of exocarp, N; $w$ - cross-sectional width of exocarp, mm; $d$ - cross-sectional thickness of exocarp, mm; $\varepsilon_e$ - tensile failure strain of exocarp; $\Delta L$ - The difference in length of the exocarp before and after the tensile test, mm; $L$ - initial length of exocarp, mm; $E_e$ - Tensile modulus of elasticity of exocarp, MPa; $E_{rece}$ - Elongation loss efficiency of exocarp, mJ; $F_e$ - actual tensile strength of the exocarp, N.

### Compression test of mesocarp

The compression test of the mesocarp of cerasus humilis fruit could be generally referred to the steps of the tensile test of the exocarp. Preparation of mesocarp samples was also done by using the blade to cut out standard samples of 10 mm length by 7 mm width by 5 mm height. It is important to note that samples should be ensured that the exocarp has been completely removed before the compression test is carried out. One cerasus humilis fruit was removed from the constant temperature and humidity chamber and prepared as a standard mesocarp sample.

Immediately thereafter, a downward compression test was performed along the vertical axis of the device using the P36R probe of the texture analyzer (Fig.1.c). Set the pre-test speed to 2 mm/s, the speed during the test to 1 mm/s, and the post-test speed to 10 mm/s. And set the load triggering force to 0.05 N and the deformation to 70%. The compression force and displacement test data have been recorded in real time by the texture analyzer, and then mechanical parameters such as the elastic modulus of the mesocarp were calculated using formulas similar to (3) to (6).

### Statistical analysis

Statistical analysis was conducted using SAS9.4 software (SAS Software Research Institute, USA), using multiple analysis of variance (MANOVA) and Pearson correlation analysis. The minimum significant difference method was used for multiple comparisons, and the significance level was set to 0.05.

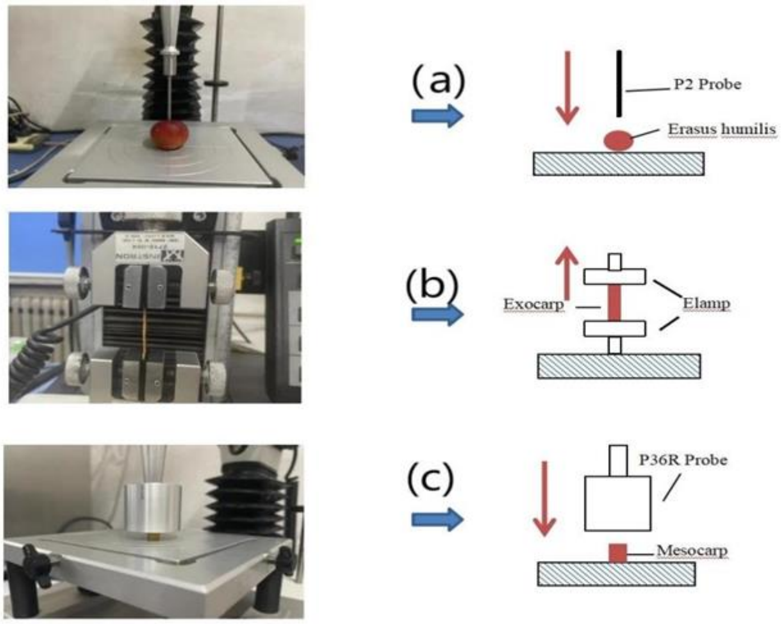


**Fig. 1 - (a) Puncture test of Cerasus humilis; (b) Tensile test of exocarp; (c) Compression test of mesocarp**

## RESULTS

### Mechanical properties of cerasus humilis

### Puncture force displacement curve of Cerasus humilis

Figure 2.a shows the puncture force displacement curve of the cerasus humilis sample during the puncture test. From the beginning, the curve rose nearly linearly until it reached the peak point A, which indicated the beginning of rupture of the exocarp of cerasus humilis. In contrast, this phase of linear relationship between puncture force and displacement reflected the role of the exocarp and mesocarp in jointly resisting the externally applied puncture load. The shaded part in the figure represented the puncture failure energy. The abscissa of the peak point was the puncture failure deformation (displacement of the probe at the time of puncture failure), which was the maximum shear deformation allowed for the entire puncture process of the exocarp of cerasus humilis in order not to rupture. The ordinate of the peak point was the peak puncture force, which was the maximum shear force that the exocarp of cerasus humilis experienced before it ruptured.

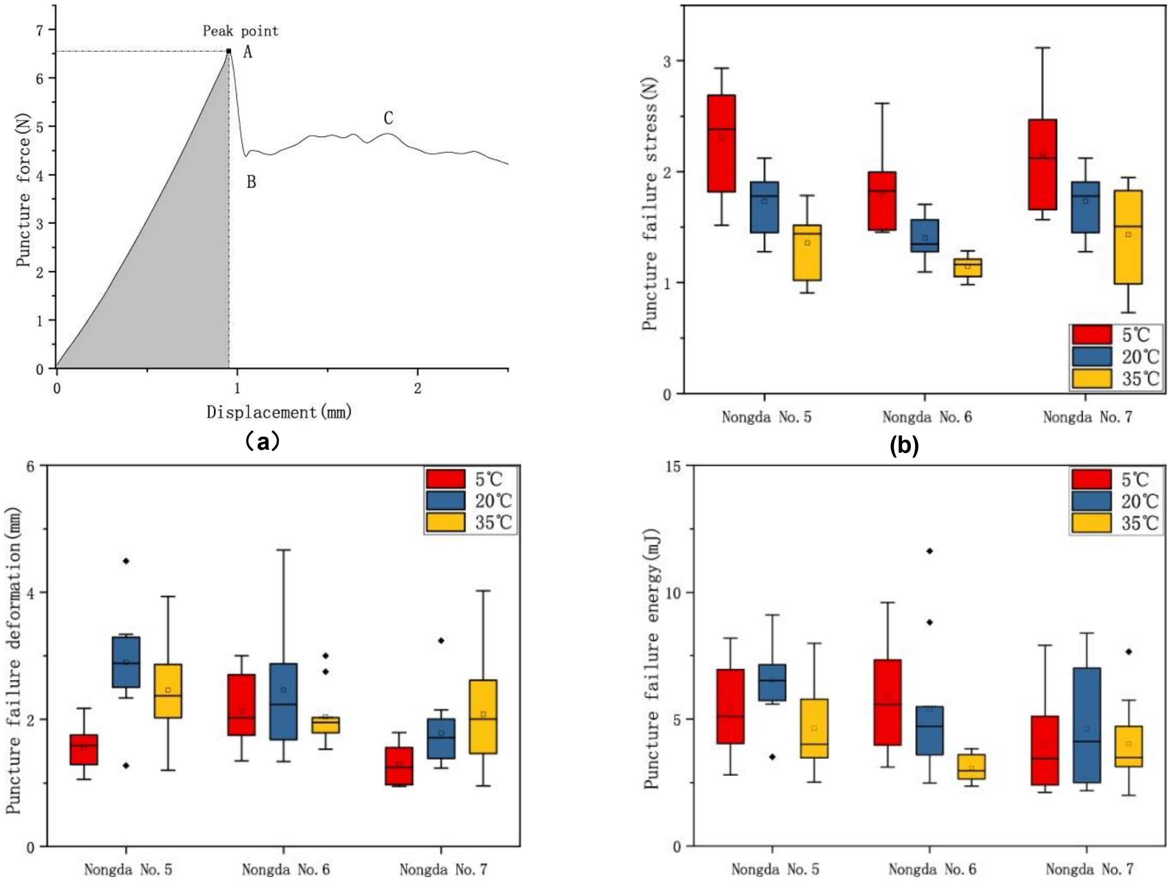
And at this stage AB in the figure, the curve dropped sharply, which indicated that the exocarp has failed and only the mesocarp was left to resist for the external puncture load. At the same time, it is easy to see that the resistance of the mesocarp was much less than the combined resistance of the exocarp and mesocarp. Therefore, the exocarp played a crucial role in resisting puncture damage and protecting the cerasus humilis fruit (*Costa et.al, 2016*). The puncture force curve of the BC segment gradually flattened in the later stage, demonstrating the resistance of the mesocarp to external puncture loads in the absence of the exocarp.

### The effect of temperature

Based on the puncture tests conducted on three different varieties of Nongda No. 5, Nongda No. 6 and Nongda No. 7 at 5°C, 20°C and 35°C, respectively, the relevant experimental data obtained are shown in Figure 2. b, c, d. In order to be able to accurately and consistently depict the discrete distribution of the experiment data, independent of outliers, the figure is presented as a box plot.

For the data obtained, SAS software was used for processing and data was analyzed using MANOVA and Pearson correlation analysis.

The results showed that the puncture failure stress of cerasus humilis was significantly affected ($p<0.05$) by changes in temperature. The puncture failure stress at 5°C was 1.70, 1.58 and 1.52 times higher than that at 35°C for Nongda No.5, Nongda No.6 and Nongda No.7, respectively. The ability of the exocarp of cerasus humilis to resist external puncture forces could be assessed using puncture failure stress values. The exocarp of cerasus humilis consists of a cuticle and several layers of dermal cells. The cuticle is a composite biopolymer composed mainly of amorphous polyesters, trace waxes and hydrolyzed polysaccharides (*Fich et.al, 2016*). At low temperatures, the polyester that formed keratin maintains limited rotational and vibrational degrees of freedom, as well as limited translational motion, while at high temperatures, it becomes more porous, allowing translational motion between the long hydrocarbon chains of the keratin network (*Matas et.al, 2004*). The decrease in exocarp puncture failure stress with increasing temperature may be attributed to this phenomenon.



(a)

(b)

(c)

(d)

**Fig. 2 - (a) Puncture force-deformation curve; (b)~(d) Result of fruit puncture tests at different ambient temperatures - puncture failure stress, puncture failure deformation and puncture failure energy**

The change in temperature also had a significant effect ($p<0.05$) on the puncture failure deformation of Nongda No.5 and Nongda No.7. The effect on them was that their puncture failure strain decreases with the increase of temperature. However, the puncture failure deformation of Nongda No.6 at 5~35℃ seems to be inconsistent with this rule. The probe displacement of Nongda No.5, Nongda No.6 and Nongda No. 7 when puncture failure occurred at 35℃ was 1.59, 0.97 and 1.62 times that at 5℃. The pericarp of cerasus humilis consists of two layers: the exocarp is on the outside, and the mesocarp is between the exocarp and the core. In the process of puncture, the probe first applied puncture force to the exocarp, and the exocarp was supported by the lower mesocarp. Therefore, the displacement of the probe when the puncture failed indicates the comprehensive resistance of the exocarp and mesocarp to the external puncture force. The higher displacement of the probe during puncture failure indicated that the exocarp was malleable while the mesocarp was soft. The mesocarp of cerasus humilis is composed of many cells, and its cell wall is mainly composed of cellulose. Its polysaccharide matrix is formed by pectin binding to proteins through Ca2+bridges (*Posé et.al, 2019*).

As the temperature increased, the viscosity of pectin and cellulose decreased, and the adhesion between cells weakened, resulting in a paste like appearance of the mesocarp under external mechanical puncture (*Karatas et.al,2016*). According to the experimental results, in general, the mechanical properties of the mesocarp and exocarp were affected by temperature to some extent. So, it can be stated that the temperature affected the puncture failure deformation of cerasus humilis.

In addition, the temperature did not significantly affect ($p>0.05$) the puncture failure energy of Nongda No.5 and Nongda No.7. Nevertheless, it had a significant effect on the puncture failure energy of Nongda No.6 ($p<0.05$). Figure 2.a shows that when the puncture failure energy reached its peak, the shadow area surrounding the curve was the puncture failure energy. According to formulas (1-4), it can also be seen that the peak puncture force and its corresponding real-time probe displacement determine the puncture failure energy during the puncture process. Therefore, the puncture failure energy in the process of cerasus humilis puncture would be affected by the puncture force and puncture failure deformation. This result seems to explain that the puncture failure energy of Nongda No.5 and Nongda No.7 was not affected by the temperature, but the temperature had a negative impact on the puncture failure energy of Nongda No.6. In summary, the puncture test could reflect the ability of cerasus humilis to resist puncture damage. Therefore, data such as puncture failure stress could be obtained through puncture tests, and was used as an indicator to evaluate the ability of this cerasus humilis to resist puncture damage.

## Tissue mechanical properties of cerasus humilis

### Organizational loading force displacement curve

According to Figure 3, when the tensile test began, the exocarp began to deform under the action of the universal testing machine. The curve of the tensile force from the beginning to the peak of the tensile force was approximately linear. After reaching the peak point, the tensile force began to decline sharply, indicating that the exocarp had completely broken. And what happened was that the tension decreased very quickly to zero after the break. The peak tensile value and the maximum tensile deformation value were the vertical and horizontal coordinates of this point respectively, and the shadow area surrounded by the curve before the peak tensile value represented the tensile failure energy. During the compression process of the mesocarp, its phenomenon was similar to the tensile test of exocarp. The curve also raised linearly, and the compressive force gradually decreased after reaching the peak point. But a little differently, the force did not decrease to zero. Subsequently, the curve showed an upward trend. This phenomenon indicated that at the peak point, the mesocarp tissue was partially damaged and several cracks were produced. The external load continued to be applied, leading to crack propagation. The reason why the compression force did not decrease to 0 was that there were still residual tissues that can withstand external forces after local damage to the mesocarp. As the compression deformation gradually expanded, the contact area of the sample under compression was increasing, which led to an upward trend in the subsequent compression force curve. The peak compressive force and maximum compressive deformation values are the vertical and horizontal coordinates of the first peak point, respectively, while the compressive failure energy is the shadow area enclosed by the curve before the first peak point.

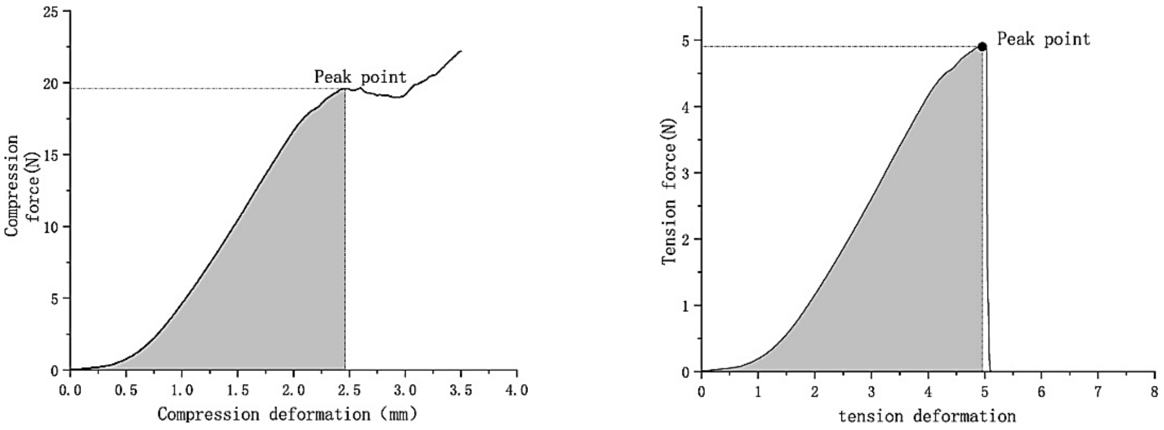
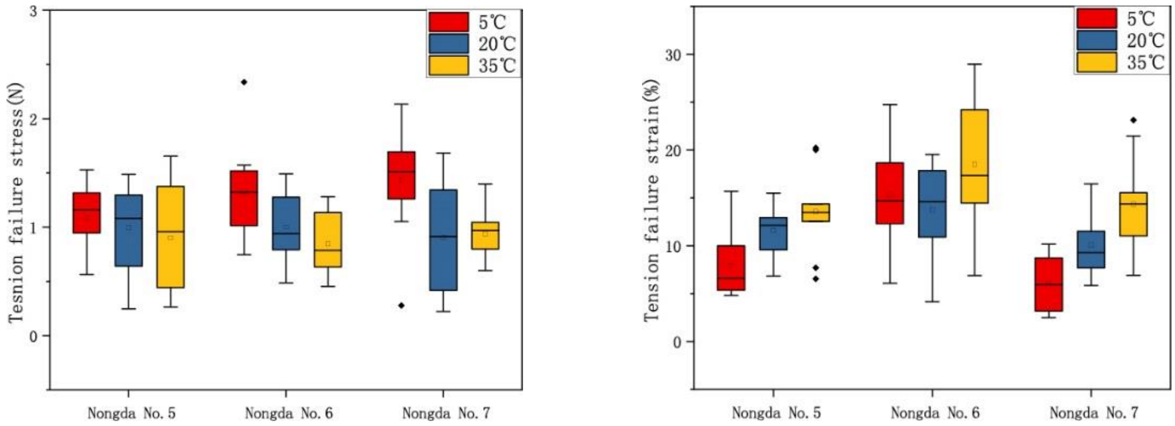


**Fig. 3 - Compression force - compression deformation and tension force - tension deformation**

## Mechanical properties of exocarp during stretching process

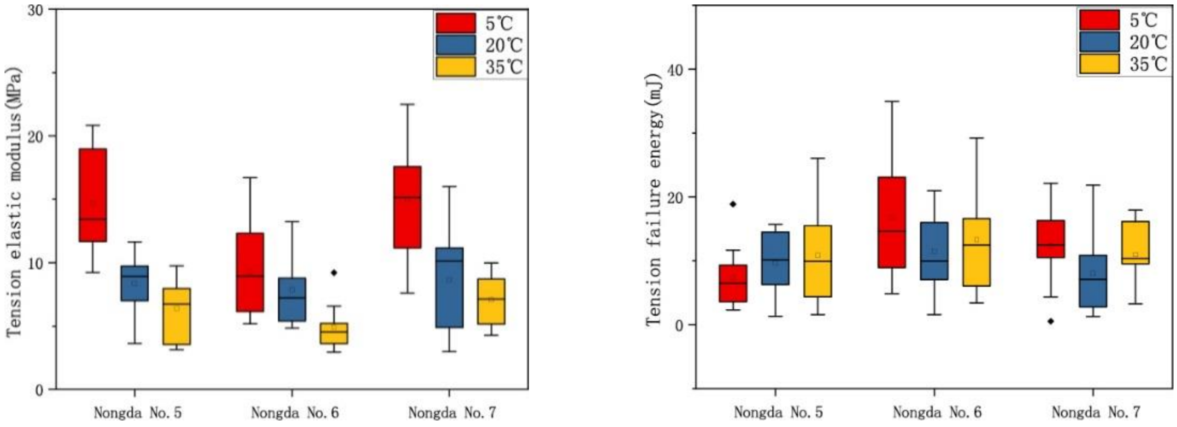
The mechanical properties of the exocarp of three varieties of cerasus humilis fruits subjected to tensile tests under three different temperature conditions are shown in Figure 4. The tensile failure stress of the exocarp of cerasus humilis was significantly affected by temperature ($p < 0.05$) and decreased with increasing temperature. The tensile failure stress of the exocarp of Nongda No.5, Nongda No.6 and Nongda No.7 at 5°C was 1.21, 1.57 and 1.52 times higher than that at 35°C, respectively. In addition, temperature had a significant positive effect ($p < 0.05$) on the tensile failure strain of the exocarp of Nongda No.5 and Nongda No.7, with the tensile failure strains of the exocarp of Nongda No.5 and Nongda No.7 at 35°C being 1.71 and 1.42 times higher than that at 5°C.The failure strain is related to the ductility of the exocarp, so the test results seem to indicate that temperature can raise this property.

Like the tensile failure stress, the tensile elastic modulus of the exocarp of cerasus humilis was also significantly ($p < 0.05$) affected by temperature, decreasing as temperature increased. The tensile modulus of elasticity of the exocarp of Nongda No.5, Nongda No.6 and Nongda No.7 varied from 14.48 ~ 6.41 MPa, 9.30 ~ 4.93 MPa, and 15.00 ~ 7.07 MPa, respectively, within the range of temperature change from 5°C to 35°C. The tensile modulus of elasticity of the exocarp of Nongda No.5, Nongda No.6 and Nongda No.7 at 5°C was 2.26, 1.89 and 2.12 times higher than that at 35°C, respectively. Moreover, the effect of temperature on the tensile failure energy of the exocarp of the three cerasus humilis species can be seen in Figure 4. However, the tensile damage energy of the exocarp of Nongda No.5 Nongda No.6 and Nongda No.7 was not significantly affected by temperature ($p > 0.05$).



(a)Tension failure stress

(b)Tension failure strain



(c)Tension elastic modulus

(d)Tension failure energy

**Fig. 4 - Mechanical properties of Cerasus humilis exocarp during tension test**

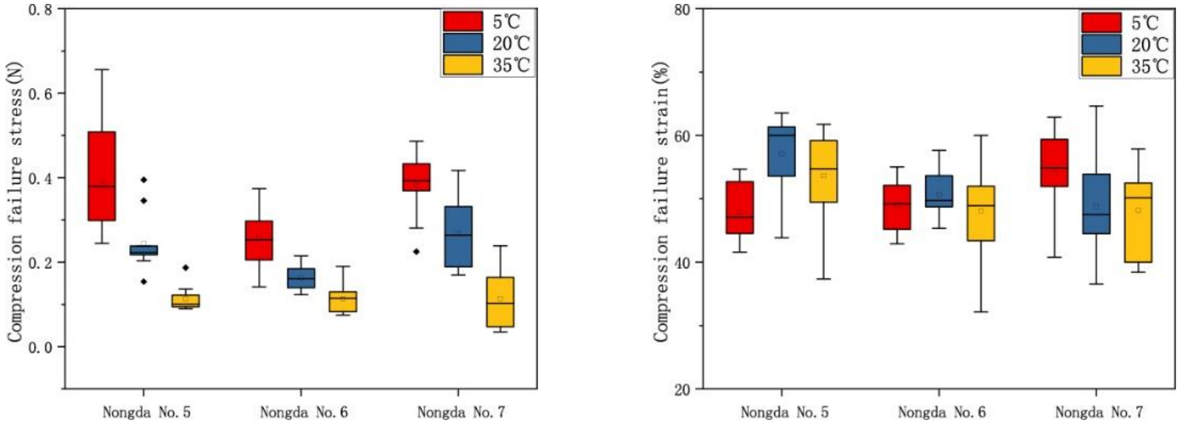
It is easy to see that the tensile mechanical properties of the exocarp of different varieties of cerasus humilis were different at different temperatures. During stretching, the rupture of the exocarp specimen at the macroscopic level was actually the rupture of the cuticle of the exocarp specimen, while at the microscopic level it was the separation of the dermal cell layers of the exocarp specimen from each other.

Since the microstructural morphology of the cuticle network and the viscosity of the pectin in the cell wall could be affected by temperature (*Brüggenwirth et.al, 2016*), which in turn affected the state of movement of the exocarp during stretching. The higher the temperature, the less viscous the pectin in the cell wall of the exocarp, and the easier it was for neighboring cells to segregate. This was characterized on a macroscopic level by a reduction in tensile force. So, it can be affirmed that temperature was significantly affecting the tensile mechanical properties of the exocarp of cerasus humilis.

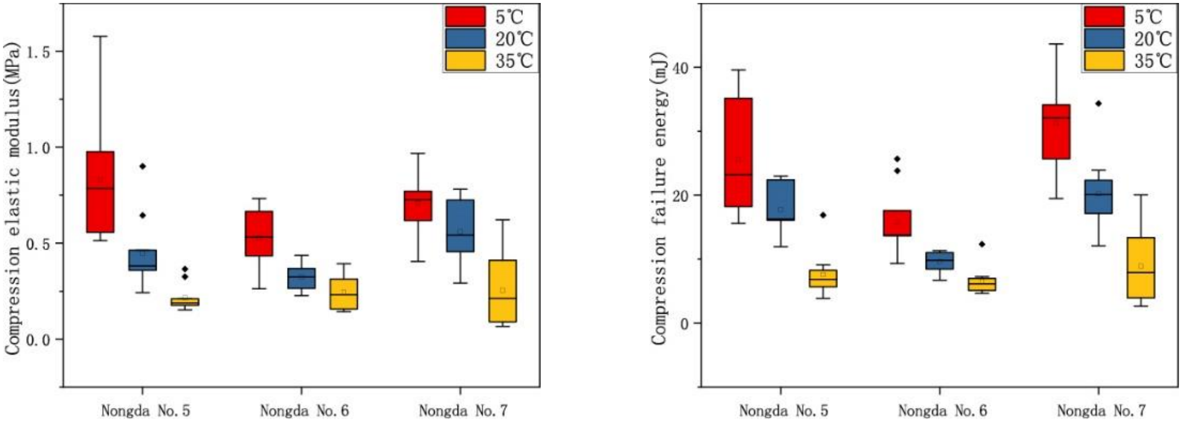
## Mechanical properties of mesocarp during compression

The tissue mechanical properties of mesocarp of three varieties of cerasus humilis fruits when subjected to compression tests at three different ambient temperature conditions are shown in Figure 5. As in the case of exocarp stretching, temperature also significantly affected ($p < 0.05$) the compressive failure stress of the mesocarp of cerasus humilis. The compressive failure stress of mesocarp decreased with increasing temperature. The compression failure stress of the mesocarp of Nongda No.5, Nongda No.6 and Nongda No.7 cerasus humilis at 5°C was 3.47,2.27and 1.52 times higher than that at 35°C, respectively.

There was a significant negative correlation ($p < 0.05$) between the compression failure strain of mesocarp of Nongda No.7 and the ambient temperature, whereas the ambient temperature did not significantly affect the compression failure strain of mesocarp of Nongda No.5 and Nongda No.6 cerasus humilis ($p > 0.05$). With reference to the mesocarp compression test of tomato, the maturity of the tomato fruit and the type of force applied affect the magnitude of the compressive strain. Therefore, the reason for this test result may be the different shape of mesocarp cells of these three cerasus humilis after ripening, as well as the difference in microstructure causing the type of force applied to their mesocarp when compressed.



**(a) Compression failure stress** **(b) Compression failure**



**(b) Compression elastic modulus** **(c) Compression failure energy**

**Fig. 5 - Mechanical properties of cerasus humilis mesocarp during compression test strain**

There was a significant negative correlation ($p < 0.05$) between mesocarp compressive elastic modulus and failure energy and temperature in cerasus humilis compared to failure strain. In the interval of temperature conditions from 5°C to 35°C, the compression elastic modulus of mesocarp of Nongda No.5, Nongda No.6 and Nongda No.7 varied in the range of 0.83 ~ 0.22 MPa, 0.52 ~ 0.24 MPa, and 0.71 ~ 0.26 MPa, respectively; and the compression failure energy of mesocarp of Nongda No.5, Nongda No.6 and Nongda No.7 varied in the range of 25.69 ~ 7.60 mJ, 15.79 ~ 6.60 mJ and 31.25 ~ 8.92 mJ, respectively. The compressive elastic modulus of mesocarp of Nongda No.5, Nongda No.6 and Nongda No.7 at 5°C was 3.77, 2.17 and 2.73 times higher than that at 35°C, respectively. The compression failure energy of mesocarp of Nongda No.5, Nongda No.6 and Nongda No.7 at 5°C was 3.38, 2.39 and 3.50 times higher than that at 35°C, respectively.

During compression, mesocarp specimens of cerasus humilis first experienced elastic-plastic deformation, followed by microcrack development and expansion. Pectinase activity, viscosity of pectin and cellulose, and water content in mesocarp cells were altered by temperature (*Chahal et.al, 2020*), which in turn affected mesocarp firmness. This changed the moment of onset, the initial state (e.g., type, direction, number), and the rate of expansion of the cracks in the mesocarp specimen. Therefore, the effect of temperature on the mechanical properties of the mesocarp of cerasus humilis should not be neglected.

## CONCLUSIONS

In this study, the puncture mechanical properties and tissue mechanical properties of cerasus humilis fruits at different temperatures were investigated by puncture, tensile and compression tests. Firstly, based on the results of the cerasus humilis fruit puncture test, the methodology used and the data obtained not only reflect the shear mechanical properties of the cerasus humilis exocarp at the tissue level, but at the same time characterize the degree of resistance of cerasus humilis fruits to puncture damage at the macroscopic level. Temperature had a significant negative effect on cerasus humilis puncture failure stress and a significant positive effect on cerasus humilis puncture failure deformation ($p < 0.05$).

Additionally, based on the tensile and compression test, temperature had a significant effect ($p < 0.05$) on the tensile failure stress of cerasus humilis exocarp and the compressive damage stress of mesocarp, as well as on the modulus of elasticity of both of them. As the temperature increased from 5°C to 35°C, the modulus of elasticity of the exocarp of Nongda No.5, Nongda No.6, and Nongda No.7 varied from 14.48 to 6.41 MPa, 9.30 to 4.93 MPa, and 15.00 to 7.07 MPa, respectively; and the modulus of elasticity of the mesocarp of Nongda No.5, Nongda No.7, and Nongda No.5 varied from 0.83 to 0.22 MPa, 0.52 to 0.24 MPa, and 0.71 to 0.26 MPa, respectively. At the same time, it is not difficult to see that as the temperature increases, the tissue damage stress and elastic modulus of cerasus humilis were gradually decreasing. Therefore, in combination with the results of the puncture test, it could be concluded that low temperatures had a positive effect on reducing mechanical damage in cerasus humilis.

Furthermore, due to the textural differences between different parts of the cerasus humilis caused by the distribution of lithocyte, the modulus of elasticity, destructive stress, and destructive strain of the exocarp of the cerasus humilis and the mesocarp of the cerasus humilis differed significantly, with the value of the modulus of elasticity of the exocarp of the cerasus humilis being higher than that of the mesocarp of the cerasus humilis. So, the exocarp was more protective against mechanical damage to the fruit.

Eventually, this study provided systematic mechanical property parameters of cerasus humilis and its tissues, which provided systematic basic parameters for numerical simulation methods to predict mechanical damage of cerasus humilis.

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