

## STUDY ON TENSILE MECHANICAL PROPERTY AND MICROSTRUCTURE OF FRUIT AND VEGETABLE PEELS

### / 果蔬果皮拉伸力学性质与微观结构的研究

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#### ABSTRACT

*Fruit and vegetable peels exert a protective effect on fruits as constituent parts of the outermost tissue and their properties are of great importance to reducing fruit and vegetable mechanical injury. Four kinds of fruit and vegetable peels such as Nagafu apple, Crisp pear, Tainong mango and long eggplant were chosen to perform longitudinal and transverse tests of tensile property by means of electronic universal testing machine. Stress-strain curve, tensile strength, elastic modulus and fracture strain of peels were obtained; and the microstructures of four kinds of peels were scanned using an electron microscope (SEM). The results indicated that cubic polynomials proved superior for quantifying the stress-strain non-linear relationship of peels and the fitting error of tensile strength is less than 10 parts per thousand. Tensile strength, elastic modulus and fracture strain of peels were different in the case of different fruits and vegetables cultivated and different parts of the same peel; fruit and vegetable peels belong to anisotropic heterogeneous materials and have certain strength. The mean values of tensile strength and fracture strain of the long eggplant peel are the biggest in four kinds of peels and that of elastic modulus of Nagafu apple peel is the largest; long eggplant and Nagafu apple peels had better resistance to damage sensibility than Crisp pear peel. The bearing capacity of the peels depends on the number, width and distribution of microcracks on the surface, and the shape of the epidermal cells and fruit dot on peels; the number of microcracks is bigger and the width of microcracks is wider, the tensile strength is smaller and the elastic modulus of peel is bigger with the slippage increase of epidermis cells. This study provides basic technical parameters for mechanical equipment design for fruit and vegetable during harvesting, processing, packaging, storing and transporting and builds the correlations between macro-mechanics properties and microstructures of fruit and vegetable peels.*

#### 摘要

果蔬果皮作为果实最外层的组成部分，对果实起到保护作用，降低果蔬果实的机械损伤。在微机控制的电子万能试验机上对长富苹果、酥梨、台农芒果和长茄子果皮进行了拉伸力学性能试验，获得果皮拉伸应力—应变曲线、抗拉强度、弹性模量、断裂应变；采用扫描电子显微镜观测果皮微观组织结构。试验结果表明：不同果蔬品种及同种果蔬果皮不同部位间，果皮的力学性能均有差异，果蔬果皮属各项异性材料，具有一定的强度；4种果蔬果皮的抗拉强度、断裂应变平均值均以长茄子的为最大，酥梨的为最小，而弹性模量则以长富苹果的为最大，芒果的为最小，反映出长茄子、长富苹果果皮对损伤敏感性低于酥梨果皮；果皮承载能力取决于表皮上微裂纹的数量、宽度及分布状态、表皮细胞及果点的形状等。研究结果为苹果、酥梨、台农芒果和长茄子果皮力学模型的建立及4种果蔬采收、加工、包装等机械装备的设计提供力学参数，构建果皮宏观力学性质与微观组织结构的联系。

#### INTRODUCTION

As important sources of human dietary nutrition (Wang et al., 2013; Pan et al., 2008), fruits and vegetables have already become the second largest pillar industry of China's agriculture (Shan, 2010;), but

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fruit deformation, peel and pulp fracture can be easily caused, thus forming injury, by external loads in the storage and transportation process (Veringă et al., 2015; Veringă et al., 2018).

Fruit and vegetable peels can exert a protective effect on fruits as constituent parts of the outermost tissue and properties are of great importance to reduce fruit and vegetable mechanical injury. Meanwhile, peels can also keep fruits fresh and their microstructures can effectively characterize related fruit qualities (Homutová et al., 2006; Zamorskyi, 2007; Deng et al., 1995; Liu et al., 2012).

At present, domestic and foreign scholars have carried out studies on mechanical properties of fruit and vegetable peels and found that their mechanical properties generated effects on fruit harvest, processing, storage and transportation quality. Hetzronia et al. (2011) selected tomato peels of different varieties for tensile test and puncture test, force-displacement curves, tensile strength and elasticity modulus of peels were obtained through the tensile test and the analysis of test data variance indicated that varieties of low tensile strength and elasticity modulus were suitable for industrial processing. Whether each tomato variety was suitable for mechanical harvest could be determined via rupture force and puncture stiffness obtained through the puncture test.

The researches on tomatoes by Amots et al. (2011) and Allende et al. (2004) showed that the mechanical properties of peels decided economic value of entire fruit processing and storage. Krishna et al. (2006) conducted tensile test and shear test of orange peels after picking, and the results indicated that rupture force, tensile strength and elasticity modulus in the peel tensile test and shear strength and shear energy in peel shear test presented declining tendencies with the storage time under whatever environment. Wang et al. (2004) carried out a tensile test of grape peel and tomato peel, obtained their elasticity modulus and breaking strength and pointed out critical importance of their mechanical properties to the analysis of mechanical injury. The mechanical property test was implemented and found that susceptibilities of peels of different varieties to injury were different (Wang et al., 2015; Wang et al., 2016; Wang et al., 2017). Fruit and vegetable microstructures are polymerized by many complicated cells. Microscopic features like cell shape, size and gap are closely related to macro-chemical properties of fruits and vegetables, so many scholars explained fruit and vegetable differences in their macro-chemical properties through their microscopic features (Oey et al., 2007; Alamar et al., 2008). Structural characteristics of peels, which are natural “packages” on edible parts of fruits and vegetables, have a great influence on fruit and vegetable qualities (Homutová et al., 2006; Sivakumar et al., 2008).

Tensile test was performed for Nagafu apple, crisp pear, Tainong mango and long eggplant peels on a microcomputer controlled electronic universal testing machine, their elasticity modulus, tensile strength and fracture strain were obtained, followed by the corresponding analysis. Microstructures of the peels were observed, and the correlations between macro-mechanical properties and microstructures of fruit and vegetable peels were established. Mechanical quantities obtained through the test provided technical parameters for mechanical equipment design for fruits and vegetables, e.g. harvest, processing and packaging, so as to provide a basis for establishing a nonlinear model of fruit and vegetable peel materials.

## **MATERIALS AND METHODS**

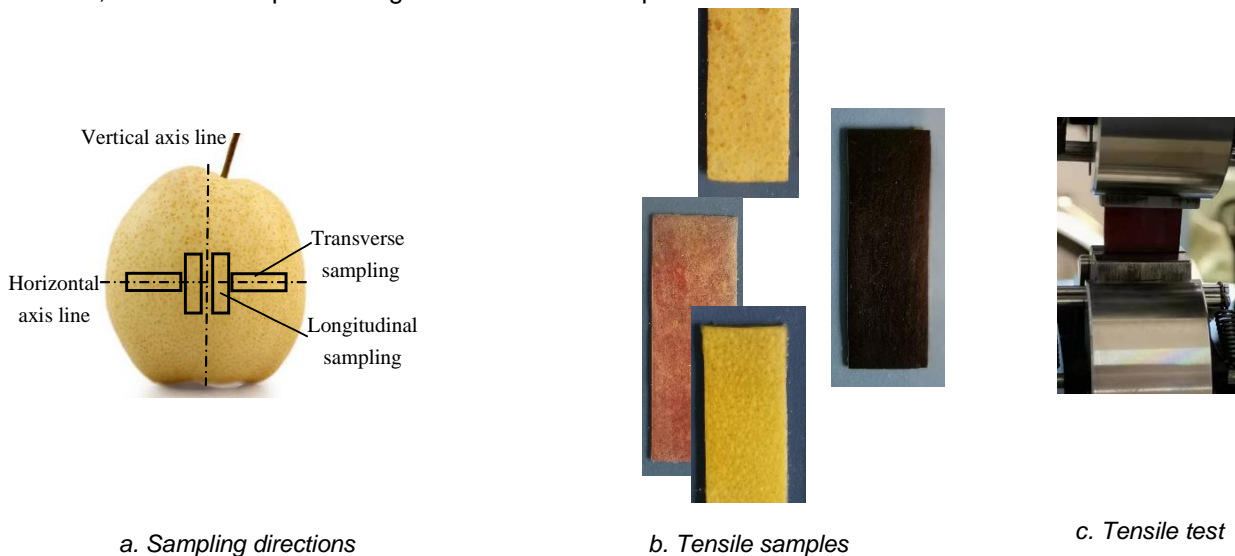
### **Materials and Instruments**

The test materials were Nagafu apple, crisp pear, Tainong mango and long eggplant. Nagafu apple, crisp pear and long eggplant were purchased from Pomology Institute, Shanxi Academy of Agricultural Sciences in September 2018. Tainong mango was bought from Tianyang, Guangxi in June 2018. The test was completed within 2 days after the fruits were transported to the laboratory. In order to reduce the loss of fruit moisture and other nutritional ingredients, they were placed in a refrigerator at 3~5°C. Fruits with regular shape, no disease or insect pest or mechanical injury were selected in the test.

A microcomputer controlled electronic universal testing machine (INSTRON-5544) was used to measure mechanical parameters of the peels with load range of 0~2 kN. It could dynamically display measured values of stress, strain, load and displacement and related curves and automatically collect and save test data. The grating thickness gauge (JC010-1, China) was utilized to measure peel thickness with a measurement range of 0~10 mm and measurement accuracy of 0.001mm. Original gauge lengths of the samples were measured in the tensile test using a digital display Vernier caliper with measurement accuracy of 0.01 mm.

### **Tensile test samples**

In order to obtain the differences of peel materials in various mechanical properties, Nagafu apple, crisp pear, Tainong mango and long eggplant peel samples were taken along longitudinal and transverse directions under indoor temperature (Fig. 1a). Peels were taken off from fruits using a blade and then placed on a smooth and flat rubber blanket, and pulp parts of the peels were gently scraped off under a microscope to ensure that no injury occurred to peel samples. To avoid stress concentration of the tensile test samples, peels were fabricated into 40 mm×15 mm× t mm (t is peel sample thickness) long strips as shown in Fig. 1b. Sample sizes in the longitudinal and transverse peel tests were both 6. Thickness ranges of Nagafu apple, crisp pear, Tainong mango and long eggplant peel samples were  $0.215\pm 0.004$  mm,  $0.321\pm 0.028$  mm,  $0.211\pm 0.015$  mm and  $0.242\pm 0.022$  mm, respectively. To prevent moisture loss of the samples, peel samples were immediately tested on the wedge-shaped fixture of the testing machine (Fig. 1c), original gauge length of the samples was  $10.00\text{ mm}\pm 0.03$ , samples which ruptured between two fixtures were regarded as valid samples and those rupturing at the fixture root were invalid samples. Loading rate of tensile test was 1 mm/min, which was kept unchanged in the whole test process.



**Fig. 1 - Samples direction, tensile samples and test of fruit and vegetable peel**

### **SEM sample observation**

5 samples of Nagafu apple, crisp pear, Tainong mango and long eggplant were respectively collected. Samples were collected from peels and cut into proper small segments for standby use. The collected samples were rapidly placed into 3% glutaraldehyde fixative (prepared using 0.1 mol/L and pH=7.2 phosphate buffer), air exhaust was performed using a vacuum pump so that materials submerged, and then they were fixed at 0~4°C for 2 d. The samples were rinsed using the same buffer solution for 3 times (15 min each time), dehydrated using 30%, 50%, 70%, 80%, 90% and 95% ethanol by stages (20 min each time), the solution was replaced by tert-Butyl alcohol, they were frozen and dried in JEOL JFD-320, and dried materials were adhered to the sample table using a conductive adhesive and plated with platinum using JEOL JFC-1600 ion sputtering coating apparatus. Platinum plated materials were placed under JEOL JEM-6490 LV SEM for morphological observation.

### **Data analysis**

In order to obtain a mathematical model of tensile stress-strain curves of the samples, SAS (SAS Institute, Cary, NC, USA) software was utilized to conduct curve fitting for nonlinear regression analysis of test data points. For a comparison of differences between longitudinal and transverse directions of fruit and vegetable peels and between different fruit and vegetable varieties in the aspects of tensile strength, elasticity modulus and fracture strain, significance analysis was performed through ANOVA program in SAS. Meanwhile, peel microstructural indicators were determined via image processing program in MatLAB software.

## RESULTS

### Tensile test of the peels

Tensile stress-strain curves of longitudinal and transverse samples of Nagafu apple, crisp pear, Tainong mango and long eggplant are shown in Fig. 2. Stress presented a nonlinear relation with strain in their tensile test, and curves of the 4 peels had no obvious bioyield points (Fig. 2), which were similar to stress-strain curves obtained through the peel tensile test of grape, tomato and apple (Wang et al., 2004; Wang et al., 20017). Tensile test was performed for Nagafu apple, crisp pear, Tainong mango and lon [12,14]. Nagafu apple, crisp pear, Tainong mango and long eggplant fruits were quite nonplanar, especially Nagafu apple fruit was similar to spherical shape and when the peel was not stretched, peel samples presented severe micro-buckling state, which led to nonuniform stress distribution in the tensile stress-strain curves of the peels in the initial phase, and the strain increased faster than stress. As peel samples were gradually stretched and extended, stress distribution tended to be uniform until the stress reached the maximum value, and then peel samples started rupturing. However, stress didn't rapidly turn into zero, but instead, it rapidly declined to zero only after a transitional period with gentle reduction.

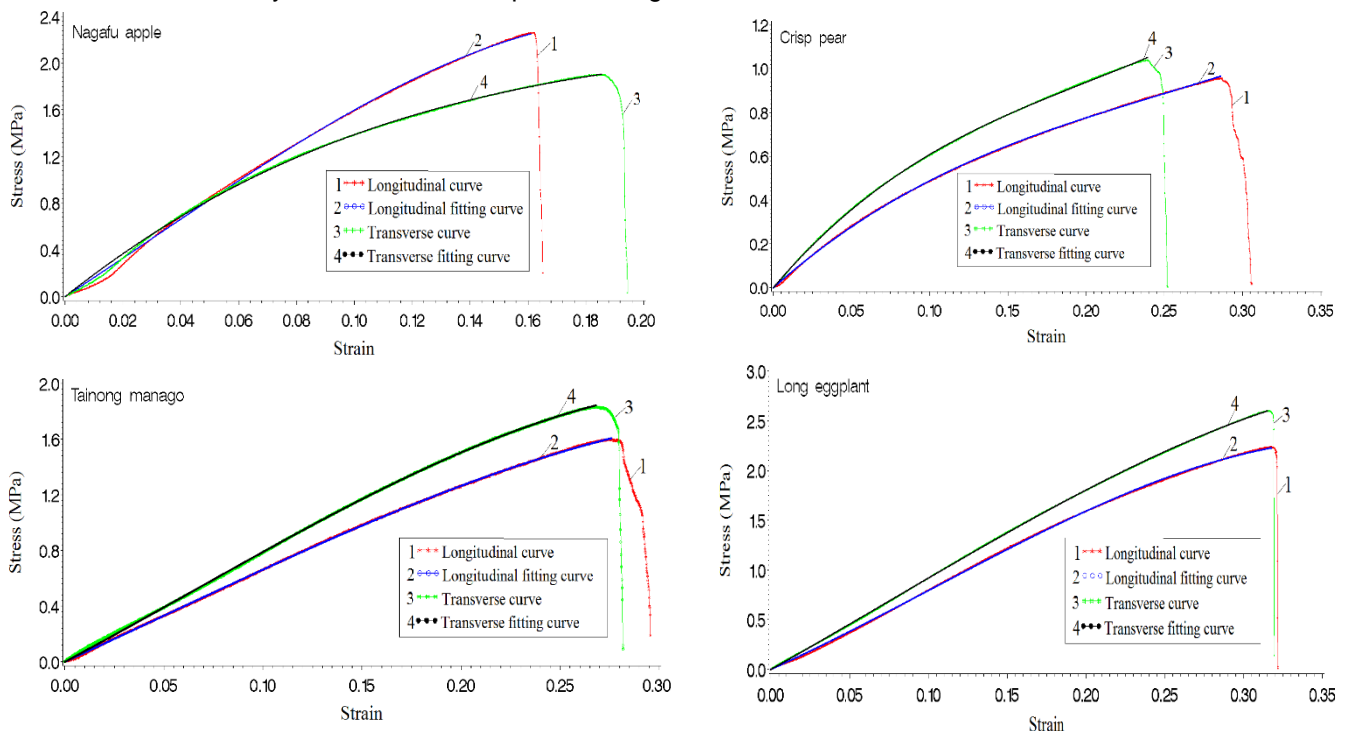


Fig. 2 - The polynomial fitting curves of peel tensile stress-strain of fruit and vegetable

### Relationship between elasticity modulus and deformation of the peels

Mechanical property indicators like elasticity modulus and tensile strength of peels as the outmost layer of fruit, decide mechanical injury degrees of fruits and vegetables in the harvest, packaging, storage and transportation processes to a great extent (Allende et al., 2004; Desmet et al.2002; Krishna et al., 2006), and peel elastoplasticity has an influence on fruit and vegetable quality (Wang et al., 2004). As an important index used to measure difficulty level of elastic deformation of peels, elasticity modulus can be characterized by the material stress-strain relation. In comparison with common metallic materials, stress-strain relation of peels, which belong to soft biological microstructures, doesn't follow Hooke's law, but instead, it is a nonlinear relation. In order to obtain elasticity modulus values of peels under different deformation degrees, the least square method of curve fitting was used to conduct cubic polynomial fitting of test data of peels when they started rupturing and before their rupture. Curve fitting results of longitudinal and transverse samples of the 4 kinds of peels are shown in Fig. 2.

The cubic fitting polynomial is:

$$\sigma = \alpha_1 \varepsilon^3 + \alpha_2 \varepsilon^2 + \alpha_3 \varepsilon \quad (1)$$

where:  $\sigma$  is tensile stress, [MPa];  $\alpha_1$  is cubic coefficient of the fitting polynomial;  
 $\alpha_2$  is quadratic coefficient of the fitting polynomial;  
 $\alpha_3$  is linear term coefficient of the fitting polynomial;  $\varepsilon$  is tensile strain;

The elasticity modulus E of each peel can be acquired through the cubic fitting polynomial as:

$$E = d_{\sigma}/d_{\varepsilon} = 3\alpha_1\varepsilon^2 + 2\alpha_2\varepsilon + \alpha_3 \quad (2)$$

Elasticity modulus of corresponding point can be solved with known deformation value using equation (2). Coefficients of polynomial fitted tensile stress-strain curves of the fruit and vegetable peels are shown in Table 1. Tensile strength, elasticity modulus, fracture strain, fitted value and fitting error obtained through the test are shown in Table 2.

### Tensile property analysis

It can be seen from Table 1 that, fitting coefficients of cubic stress-strain curves of longitudinal and transverse fruit and vegetable peel samples of different varieties are different and as shown in Table 2, fitting errors k of their tensile strength are all lower than 10%, indicating that the cubic polynomial fitted curve can be used to describe nonlinear tensile stress-strain relations of the 4 kinds of fruits and vegetables very well.

**Table 1**

**Curve fitting coefficients of fruit and vegetable peels under tensile loading**

Variety	Sample number	Longitudinal fitting coefficients			Transverse fitting coefficients		
		$\alpha_1$	$\alpha_2$	$\alpha_3$	$\alpha_1$	$\alpha_2$	$\alpha_3$
Nagafu apple	1	187.75	16.19	16.25	-187.43	24.58	13.22
	2	-356.11	51.41	14.53	-325.30	46.27	12.33
	3	-723.65	132.58	10.01	-679.09	108.24	10.75
	4	-274.25	13.53	18.89	-153.34	-0.54	16.20
	5	-969.40	163.02	11.27	-403.07	32.74	14.40
	6	-479.31	48.54	17.11	86.34	-66.81	19.70
Crisp pear	1	7.94	-12.49	7.38	-10.73	-3.68	5.73
	2	60.89	-35.03	8.87	147.21	-61.19	11.86
	3	58.78	-35.24	9.61	48.68	-34.46	11.29
	4	22.64	-16.83	6.34	45.92	-27.69	8.39
	5	72.95	-41.35	10.33	13.86	-20.20	9.00
	6	36.64	-25.19	8.20	30.99	-26.44	9.25
Tainong mango	1	-25.10	5.61	6.06	-11.77	1.96	6.61
	2	-27.94	5.05	7.27	-20.24	4.56	6.61
	3	-20.31	3.08	6.52	-8.14	-6.47	9.68
	4	-9.85	3.62	8.19	-21.97	-8.02	8.98
	5	-94.33	22.42	6.90	-33.99	6.45	7.59
	6	-30.51	5.46	6.99	-29.89	2.80	7.90
Long eggplant	1	13.16	-15.49	10.69	-9.62	8.14	8.19
	2	8.41	-15.10	12.23	-34.87	14.38	9.81
	3	-38.17	11.72	7.15	-23.29	5.34	8.89
	4	-0.81	-1.98	6.92	-20.59	6.79	10.10
	5	10.25	-15.17	12.12	-18.79	8.00	10.71
	6	7.33	-9.60	9.42	-21.43	9.58	9.54

**Table 2**

**Mean value of property parameters and fitted error of fruit and vegetable peels under tensile loading**

Variety	Fracture strain	Tensile strength/MPa			Elastic modulus /MPa	
		Experimental value	Fitted value	Fitting error $k$		
Nagafu apple	Longitudinal	0.15±0.01a	2.16±0.08a	2.13±0.09	0.0042	20.75±1.94a
	Transverse	0.17±0.02a	1.90±0.20b	1.86±0.20	0.0049	18.16±1.25b
Crisp pear	Longitudinal	0.28±0.03a	1.12±0.15a	1.13±0.15	0.0016	7.68±1.02a
	Transverse	0.24±0.03b	1.16±0.17a	1.15±0.18	0.0026	8.89±1.41a
Tainong mango	Longitudinal	0.27±0.04a	1.69±0.10a	1.69±0.09	0.0011	7.60±0.75a
	Transverse	0.29±0.05a	1.84±0.24a	1.83±0.24	0.0023	7.85±0.82a
Long eggplant	Longitudinal	0.47±0.09a	3.09±0.48b	3.10±0.49	0.0010	9.25±1.36b
	Transverse	0.44±0.09a	4.19±1.00a	4.17±1.00	0.0022	11.48±1.23a

Note: Fitting error of tensile strength indicated the relative error of tensile strength of peel between fitted values and experimental values.



As shown in Table 2, tensile strength, elasticity modulus and fracture strain were different in longitudinal and transverse parts of the same peel variety. Average tensile strength and elasticity modulus of crisp pear, Tainong mango and long eggplant peels were all maximum in their transverse parts, while they were the maximum in longitudinal part of Nagafu apple peel. Average transverse fracture strains of Nagafu apple and Tainong mango peels were both greater than their average longitudinal fracture strains, and average transverse rupture strains of crisp pear and long eggplant peels were both smaller than their average longitudinal rupture strains. Independent-samples *t* test was performed for transverse and longitudinal tensile strength, elasticity modulus and rupture strain of the same peel variety, and the results showed that no significant differences existed between longitudinal and transverse tensile strength and elasticity modulus of crisp pear and Tainong mango peels, but significant differences existed between those of Nagafu apple and long eggplant ( $p < 0.05$ ). Longitudinal rupture strain of crisp pear was significantly different from transverse rupture strain ( $p < 0.05$ ), and differences between longitudinal and transverse ruptures of other varieties were insignificant.

Tensile mechanical property parameters of different fruit and vegetable varieties are compared as shown in Fig. 3. Mechanical property parameters of peels, which are the outmost microstructures of fruit and vegetable fruits, exert a very important effect on the abilities of fruit and vegetable peels of different varieties to resist cracks and mechanical injury (Wang *et al.*, 2004; Wang *et al.*, 2016; Grimm *et al.*, 2012). Fruit and vegetable peels of different varieties were different in tensile strength, elasticity modulus and fracture strain (Fig. 3). For the four cultivars, average tensile strength of eggplant was the maximum, being 3.64 MPa, crisp pear had the minimum average tensile strength (1.14 MPa), and those of Nagafu apple and Tainong mango were 2.03 MPa and 1.76 MPa, respectively. Tensile strength of long eggplant was remarkably different from those of Nagafu apple, crisp pear and Tainong mango ( $p < 0.001$ ), average elasticity modulus of Nagafu apple was the maximum, being 19.46 MPa, that of crisp pear presented an extremely significant difference from those of Nagafu apple and Tainong mango, that of Tainong mango was the minimum (7.72 MPa) and those of long eggplant and crisp pear were 10.36 MPa and 8.29 MPa, respectively. Elasticity modulus of long eggplant was extremely significantly different from those of crisp pear, Tainong mango and long eggplant ( $p < 0.001$ ), the difference between long eggplant and Tainong mango in this aspect was rather notable and that between long eggplant and crisp pear was significant, but that between crisp pear and Tainong mango was insignificant. Long eggplant had the maximum average fracture strain (0.46), Nagafu apple had the minimum average fracture strain (0.16) and those of long eggplant and crisp pear were 0.28 and 0.26, respectively. Long eggplant had extremely significant differences from Nagafu apple, crisp pear and Tainong mango in fracture strain ( $p < 0.001$ ), Nagafu apple was also extremely significantly different from crisp pear and Tainong mango in fracture strain, and the difference between crisp pear and Tainong mango was insignificant.

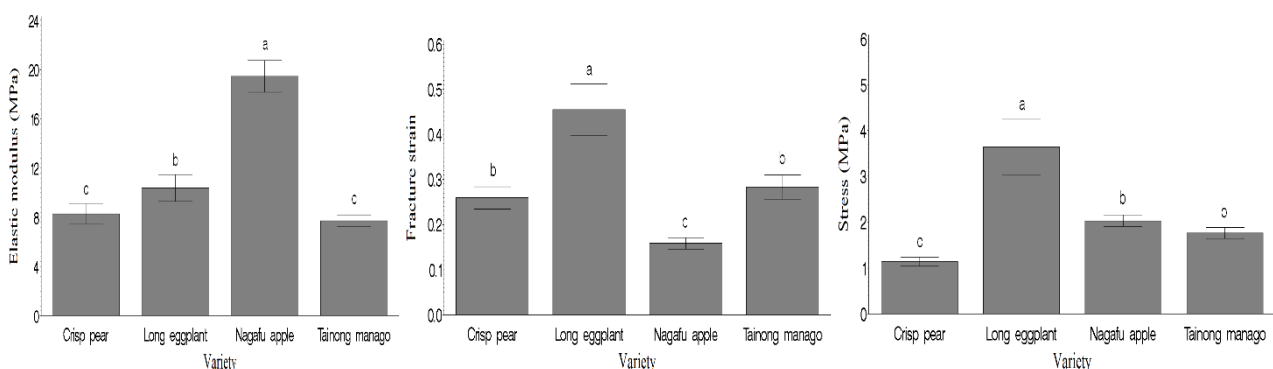


Fig. 3 - Comparison of peel tensile mechanical parameters of different fruit and vegetable varieties

### Peel image analysis

Fruit and vegetable microstructures have a direct impact on their macroscopic texture features (Cai *et al.*, 2015; Wei *et al.*, 2016).

For a deeper understanding of differences between Nagafu apple, crisp pear, Tainong mango and long eggplant peels in their macro-chemical properties, peel microstructures were investigated.

Peel surface microstructures. Fig. 4 shows surface microstructures of fruit and vegetable peels. Epithelial cells in Nagafu apple peel presented pentagonal shape or hexagonal with microcracks on the surface, which presented parallel arrangement, and fracture surfaces of which were disorderly. Small hill-like protuberances appeared on the crisp pear peel surface, so epithelial cell shape could not be identified, and moreover, there was a large quantity of microcracks which were under net-shaped distribution with orderly fracture surfaces. Tainong mango peel was rough surface with horny patterns and formed a number of microcracks under irregular distribution. No microcracks appeared on the long eggplant peel surface, epithelial cells presented long strip shape under regular distribution. Microcracks appearing in the structural chart obtained through SEM were measured via MatLAB program, and the microcrack width range of four kinds of peel samples is shown in Table 3. The average width range of microcracks for Nagafu apple, crisp pear and Tainong mango was  $7.28\mu\text{m}$ ,  $4.34\mu\text{m}$  and  $5.86\mu\text{m}$ , respectively. Based on the above results, microcracks on peel surfaces were formed due to fruit development and expansion during the fruit growth process (Veraverbake *et al.*, 2001), there were a large quantity of microcracks on rough peel surfaces (Knoche *et al.*, 2008), and the quantity of microcracks on the peel surface had an effect on tensile strength of peels of different fruit and vegetable varieties (Wang *et al.*, 2015; Wang, *et al.*, 2017).

As the above results showed, because microcracks exist on fruit and vegetable surfaces, average tensile strength values of Nagafu apple, crisp pear and Tainong mango peels were lower than that of long eggplant peel. The quantity, width and distribution of microcracks on the peel surface would all generate an effect on tensile strength of fruit and vegetable peels: the larger the quantity of microcracks, the smaller the tensile strength. Epithelial cell shape on the peel surface would impact its elasticity modulus, and slippage of epithelial cells which were pentagonal or hexagonal in the tensile process was greater than that of long strip-shaped epithelial cells, which might be one of the reasons for large elasticity modulus of Nagafu apple peel.

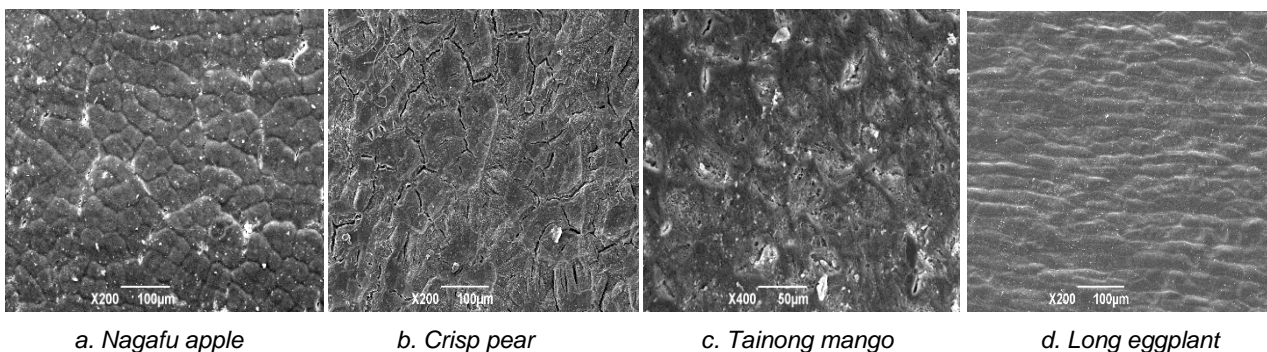


Fig. 4 - The surface microstructure of fruit and vegetable peels

Table 3

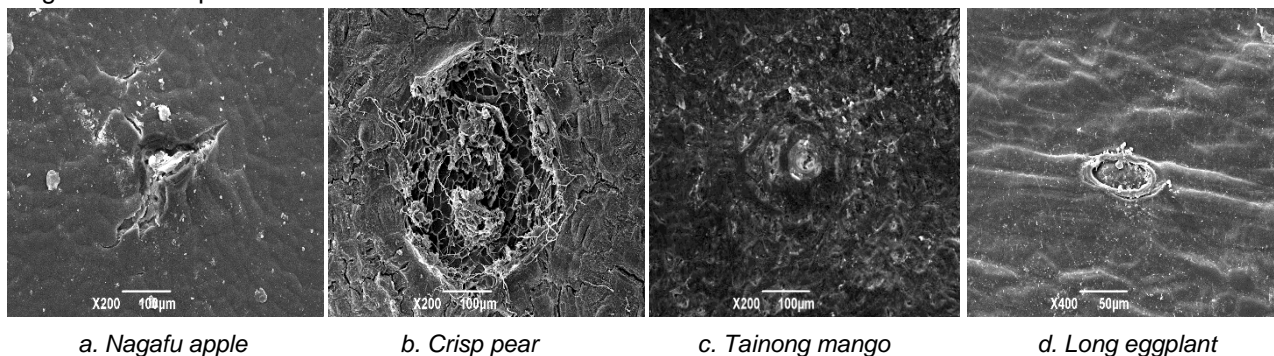
Width range of microcracks on t fruit and vegetable peels

Variety	Peel micro crack width/ $\mu\text{m}$
	Mean value ( min-max )
Nagafu apple	7.28 (2.88-17.02)
Crisp pear	4.34 (1.12-15.42)
Tainong mango	5.86 (1.41 ~ 13.54)
Long eggplant	0

Fruit dot microstructures. Fruit dots were formed by young fruit epidermis pores that act as the channel for substance exchange of fruits with the outside environment in the early fruit development phase, and the fruit dots are filled by phellem tissue during the fruit maturing period (Yu *et al.*, 2002; Li, *et al.*, 2009), therefore the fruit spots were considered the stress concentration points in the process of peel tensile (Wang *et al.*, 2015).

Fig. 5 shows fruit dot microstructures of fruit and vegetable peels. Fruit dots on fruit and vegetable peels of different varieties were differently shaped: fruit dots of Nagafu apple were polygonal and included the angle between edges that was sharp, crisp pear fruit dots were circular and smooth and could be approximated to round shape, but tissues at its edges were discontinuous with slightly protuberant tissues in the center. Fruit dots on Tainong mango peel were round with sunken tissues in the center. Fruit dots on long eggplant peel were approximately elliptical with smooth transition, indicating stress concentration degree of fruit dots in the tensile process of long eggplant peel was lower than those of other varieties, and tensile strength of long eggplant peel was great. Stress concentration degree at fruit dots in the tensile process of Nagafu apple peel was quite severe, it might be ruptured in advance due to severe stress concentration of fruit dots before it reached the real tensile strength, so tensile strength of its peel was relatively small.

Fruit shape made a difference in mechanical properties of longitudinal and transverse peel samples. Nagafu apple fruit was approximately spherical, so its peel was extended greatly in transverse direction in the growth process and average tensile strength of transverse sample was lower than that of longitudinal sample in the tensile process. Fruits of crisp pear, Tainong mango and long eggplant were approximately cylindrical, long oval shape and long round oval shape, respectively. Longitudinal extension of peels during the fruit growth process was large, so average tensile strength of transverse sample was higher than that of longitudinal sample.



**Fig. 5 - The fruit dot microstructure on the peels**

## CONCLUSIONS

(1) Stress and strain present a nonlinear relation in the tensile process of the 4 fruit and vegetable varieties. There are no obvious bioyield points in their stress-strain curves. The tensile stress-strain curves of longitudinal and transverse peel samples are fitted using a cubic polynomial. Fitting coefficients of the fitted curves are not the same and fitting errors  $k$  of tensile strength are all lower than 10%, showing that the cubic polynomial can describe nonlinear relations in the tensile process of the 4 peels very well and provide a reference basis for establishing the nonlinear model for peel materials.

(2) Longitudinal and transverse samples of the same fruit and vegetable variety are different in elasticity modulus, so fruit and vegetable peels are anisotropic materials. Elasticity modulus of fruit and vegetable peels can characterize the material ability to resist against deformation, and Nagafu apple has the maximum elasticity modulus, Tainong mango has the minimum value. Nagafu apple is extremely significantly different from crisp pear, Tainong mango and long eggplant in the aspect of elasticity modulus ( $p < 0.001$ ), indicating that Nagafu apple has the strongest ability to resist against deformation, followed by long eggplant.

(3) Average tensile strength of long eggplant is the maximum and over 3.2 times of that of crisp pear which has the minimum average tensile strength. Long eggplant is extremely significantly different from Nagafu apple, crisp pear and Tainong mango in tensile strength ( $p < 0.001$ ). Tensile strength of peel is an important index used to evaluate fruit injury or destruction. Crisp pear peel has higher susceptibility to injury than other 3 peels in the harvest, transportation and storage processes, followed by Tainong mango peel. Average tensile strength values of transverse peel samples of crisp pear, Tainong mango and long eggplant are all greater than those of their longitudinal samples, average tensile strength of longitudinal Nagafu apple peel sample is larger than that of transverse one, so the difference of the optimal clamping direction between different fruit and vegetable varieties should be considered in the design of recovery machinery.



(4) Average fracture strain of long eggplant is the maximum, followed by Tainong mango, crisp pear and Nagafu apple in succession, and the maximum value is over 2.9 times of that of minimum value. Long eggplant is extremely significantly different from Nagafu apple, crisp pear and Tainong mango in fracture strain ( $p < 0.001$ ). Average fracture strain of transverse Nagafu apple and Tainong mango peel samples are both greater than those of their longitudinal samples, but the case is the opposite for crisp pear and long eggplant peels, demonstrating that extensibility of transverse Nagafu apple peel sample and that of longitudinal crisp pear and long eggplant peel samples are strong.

(5) Macro-mechanical properties of fruit and vegetable peels, which are polymerized by complex cells, vary from microstructures. Mechanical properties of fruit and vegetable peels mainly depend on quantity, width and distribution state of microcracks on the peel surface, shapes of epithelial cells and fruit dots, etc. Peel strength is reduced with increasing quantity and width of microcracks on the peel surface, but its elasticity modulus will increase with the slippage of epithelial cells.

Therefore, the effects of different directions of peels of different fruit and vegetable varieties should be taken into consideration in the design of harvesting machinery and processing, storage and transportation equipment following the harvest. Susceptibilities of long eggplant and Nagafu apple peels to the injury are lower than those of other two peels, and Nagafu apple has the most powerful ability to resist against penetration of blunt parts. Storage endurance of different fruit and vegetable varieties is not only closely related to microstructures of their outmost peels but has also a high correlation with their pulp qualities.

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