# A simple mechanical index of storage quality of strawberry fruits

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# A simple mechanical index of storage quality of strawberry fruits

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## Abstract

We propose simple mechanical parameters obtained by compression testing to indicate the storage quality of strawberry fruits. We tested the effects of different storage conditions at 5℃ on measured mechanical parameters. The three conditions were control, in polyethylene bag, and packed a product that releases allyl isothiocyanate (AIT) vapor, as it is known that vaporized AIT prevents the growth of microorganisms. Although the fracture load, often referred to as firmness, did not significantly vary, the fracture strain increased and the apparent modulus decreased with storage time. The apparent modulus was demonstrated to be a good index of strawberry quality, because it is more sensitive to deterioration of strawberry fruits and calculated at a low strain that has the potential of a non-destructive measurement.

Key words: strawberry, compression test, apparent modulus, mechanical properties, cold storage

## Introduction

Strawberry (*Fragaria* × *ananassa*, Duch.) is a typical non-climacteric fruit. In other words, it does not exhibit a dramatic increase in respiratory activity after harvest, and also produces less ethylene (Tatsuki, 2007). As strawberry fruits are harvested when ripe, their quality declines rapidly. They are very susceptible to attack by microorganisms and mechanical injury during handling and transportation (Wills and Kim, 1995). Loss of quality often occurs because of water loss, softening, and bruising during handling, transportation, and storage (Bower et al., 2003; Wills and Kim, 1995). The storage life of strawberries is less than a week, even under ideal conditions (Wills, 1998).

Palatability of fruits is generally higher in sweeter individual fruit. Sweetness of strawberry fruits correlates with the ratio of soluble sugar content and to titratable acidity (Gunness et al., 2009). These results were obtained from strawberries pureed to produce a homogenous sample; many individual fruits were included in the purées used for sensory evaluation. In our study, varying mechanical properties of individual fruits were measured at similar stages of storage. A methodology that uses pureed samples or juice instead of raw fruits for sweetness determination does not detect important interactions between sweetness and mechanical properties. Softer fruits are likely perceived to have higher sweetness even though they may have soluble sugar content similar to those of harder fruits. Flavor release is modified by the texture of foods, hence there is an interaction between sugar content and mechanical properties of fruits. Sensory studies using gels and sols as model foods show that flavor

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intensity is reduced in firmer gels and thicker liquids (Calviño et al., 1993; Clark, 2002; Cook et al., 2003).

Luminance distribution most likely influences the visual assessment of fruit freshness rather than color information (Arce-Lopera et al., 2012). Freshness of strawberry fruits determined by consensus ratings is more reliable than any single indicator of freshness including firmness, soluble solids, and titratable acidity (Péneau et al., 2007). Péneau et al. (2007) determined maximum force and the gradient of the compression curve up to 75% compression of single whole strawberry fruit under a flat plate (75 mm diameter). Parameters measured by this methodology decreased slightly with storage time, but they did not correlate with subjective freshness assessments. Retailers often set shelf lives of processed foods to durations shorter than the time period through to the onset of visible damage. This is because eating quality may be determined by textural and/or flavor changes of fruits.

In the current study, we performed compression testing of strawberry fruits after harvest to establish an objective index of fruit softening. Several mechanical properties may influence the texture and flavor of strawberries. The modulus of elasticity may be calculated by compression testing of materials with convex shapes (American Society of Agricultural Engineers, 2000), but has rarely been determined for strawberry fruits. Because the strawberry fruit has an irregular shape, its heterogeneity prevents derivation of the Poisson's ratio. Furthermore, the fruit is rather diminutive in relation to many types of probe. Thus, a simple compression test, which uses a cylindrical probe with a diameter 3.0–7.5 mm to penetrate the equator of individual strawberry fruits, has commonly been adopted (Døving and Måge, 2002; Døving et al., 2005; Gunness et al., 2009; Hernández-Muñoz et al., 2006; Hietaranta and Linna, 1999; Khosroshahi et al., 2007). Firmness, determined as the peak force, is frequently used rather than the elastic modulus; firmness decreases through the storage period (Caner et al., 2008; Døving and Måge, 2002; Døving et al., 2005; Hernández-Muñoz et al., 2006; Nunes et al., 2006; Tian et al., 2000). In this study, we performed a simple compression test on strawberry fruits to calculate an apparent modulus as the ratio of stress to strain at a very small deformation.

Strawberry fruits were kept at 5℃ on a soft tray and covered with plastic film and/or were treated with a natural anti-bacterial product to lengthen storage life. Degradation of fruits and vegetables during distribution and storage may be moderated by allyl isothiocyanate (AIT, 3-isothiocyanato-1-propene), which is a pungent component present in some members of the *Brassicaceae*, such as horseradish (*Armoracia rusticana*), wasabi (*Wasabia japonica* Matsum.), and brown mustard (*Brassica juncea*). The growth of many microorganisms (bacteria, yeasts, and molds) is prevented by vaporized AIT. Growth of some fungi is prevented at a lower level (<20 ppm) of AIT (Goi et al., 1985; Kanemaru and Miyamoto, 1990; Issiki et al., 1992; Sekiyama, 2009). AIT has been employed on strawberry fruits to prevent mold growth and softening over three days (Takagi and Naito, 1993), but there are no detailed reports on conditions required for this effects.

In this study, we found that the apparent modulus is a more sensitive measure of changes in the mechanical properties of strawberry fruits than firmness during storage. It is a good indicator of the shelf life of strawberries stored at low temperatures.

## Materials and Methods

### 1. Strawberries

We used strawberry fruits (var. *Yayoihime*), each weighting approximately 13 g. Harvest date was March 8, 2010 (Fujio Co., Maebashi, Gunma, Japan). Fully ripened and ready-to-eat fruits were arranged on a soft tray with 25 hollows (5 rows × 5 columns, 210 × 280 × 22 mm) made from foamed polystyrene; polypropyrene (PP) film was wrapped over the tray and taped at both sides.

### 2. Transportation and storage condition

We used Wasapure® (Ageless Service Center Co. Ltd., Tokyo, Japan) was used as an AIT release agent to preserve the freshness of strawberry fruits. The product vaporizes AIT into the storage atmosphere and it releases 0.2–10.0 ppm (v/v) of AIT into containers of fresh foodstuffs with no production of an "off-flavor" from the wasabi (Oshida et al., 2010). Two gram of paste made up of horseradish and mustard extracts in filler compounds (0.35–0.45% (v/v)) was packed in small plastic bags (40 × 35 mm). The amount of AIT release product (by pack per tray) was determined through preliminary tests. Gas chromatography analysis revealed that approximately 0.6 ppm (v/v) of AIT was maintained for at least one week in the storage atmosphere of a strawberry transportation cardboard box (250 × 350 × 75 mm) wrapped by polyethylene (PE) film.

Three storage conditions were compared: (A), a pack of AIT product was inserted under the PP film in each tray and the tray was placed into an unsealed PE bag; (B), treatment as in (A) but without AIT product; (C) control with no AIT product or PE bag. Two trays were placed into each cardboard box (305 × 450 × 80 mm), and six cardboard boxes were stacked and tied. Samples were transported from the farm to the National Food Research Institute in a refrigerated truck at 5℃. They arrived without visible damage the day after harvest and were stored in a cold room at 5℃ until measurements.

### 3. Quality evaluation

Damaged fruits with mold growth or with muddy parts were visually identified by three experimenters. Sample strawberry fruits, including damaged ones in the same tray, were moved to the test room (23℃) 3 h before mechanical measurements were made 2, 4, 8, 11, and 16 days after harvest. All 25 fruits in each tray were weighed, and the diameter, length, and weight of each were recorded.

An instrumental compression test was performed using a Universal Testing Machine (Model 5542; Instron, Canton, MA, USA) with an attached load cell of 50 N. A stainless steel cylindrical plunger of 3.0-mm diameter was inserted into each fruit at a constant speed of 1.0 mm/s. Two equatorial parts (in diagonal position) and the apex of each whole fruit were tested; measurements were made on 10 fruits. Compressive strain was calculated as displacement divided by the diameter or length of each fruit. Strawberry fruits do not have a fixed shape with a flat surface; hence, Young's modulus, which can be derived from a simple tensile or compression test, could not be correctly calculated in the present experiment. Under our test conditions, the peripheral part of the plunger may affect the force value, even under small strains (< 0.1). Hence, we used the term apparent modulus rather than Young's modulus. The apparent modulus was calculated with Blue Hill software (Instron) based on the maximum slope of load versus displacement curve. This value was derived as the ratio of stress (load divided by the cross sectional area of the plunger (7.08 mm$^2$)) and strain. The fracture load and strain were determined at peak values.

Immediately after the mechanical test, pH (C-73, As One Corporation, Osaka, Japan) and Brix (PAL-1, Atago Co. Ltd., Tokyo, Japan) values were measured close to the punctured holes.

### 4. Statistical analyses

Statistical analyses were performed using SPSS software (ver. 17.0J for Windows; SPSS Inc., Chicago, IL, USA) with statistical significance set at $p < 0.05$. We conducted one-way analyses of variance (ANOVA) with treatments (3) or storage periods (5) as factors. Two-way ANOVA was used to test for significant interactions between treatments and storage periods. Paired *t*-tests were performed to compare values for individual fruits.

## Results

### 1. Mechanical properties

Figure 1 shows typical compression curves for fresh and damaged strawberries. For fresh fruit, the slope of the load versus deformation curve was almost straight. There was a break point at approximately 1.4 mm compressive deformation, corresponding to strains of < 0.06–0.07, after which the load decreased rapidly. Load and deformation at the peak (gray triangle) were easily determined. We calculated the fracture load and strain after standardization using initial diameter of each fruit. The maximum slope (see auxiliary straight line in Fig. 1) of the load–strain curve up to the fracture point was divided by the cross-sectional area of the plunger (Gunness et al., 2009). The apparent modulus in MPa was subsequently obtained based on the converted slope. Strawberry fruits do not soften during the first few days, but they do over extended storage periods. Compressive load and modulus decreased significantly after a long storage, while the fracture strain increased. Damaged fruits completely covered with mold were extremely soft. Although the fracture in damaged fruits occurred at a slightly higher strain and a much lower force than in undamaged fruits, the load decrease following fracture was not significant in damaged fruits (Fig. 1). We analyzed temporal changes in the mechanical properties of strawberry fruits before fruits were completely damaged to this extent.

Among the mechanical parameters, the fracture strain increased and the apparent modulus decreased gradually with storage period (Fig. 2). The fracture load did not significantly change with storage or among treatments.

There was a significant decrease in the fracture load in damaged fruits after a long storage period (> 10 days) leading to unacceptable fruit quality. After 16 days, the standard error increased (Fig. 2) because of ones very soft, aged individual fruits (Fig. 1), but there were still a few undamaged individual fruits with mechanical properties similar to those of fresh strawberry fruits (Fig. 1).

## 2. Comparison with other measures

No damaged fruits were apparent in visual inspections of 25 fruit trays during the first several days of storage at 5℃ under any of the treatments as shown in Fig. 3. Control samples (C) demonstrated the most rapid quality degradation (20% change) during the experiment. Differences between treatments were first observed at 8 days; the rank order of proportion of undamaged samples was (C) < (B) < (A). After 11 days of storage, the differences were still apparent. There was less damage in the presence of AIT than in the other treatments. The undamaged fruit proportion at 16 days had decreased most in treatment (B), after which almost all individual fruits stored were damaged regardless of treatment.

The pH and Brix values (data not shown) did not significantly change. Slight decrease in the Brix value in damaged fruits was first observed after 11 days.

Because of elevated variances within treatment, we

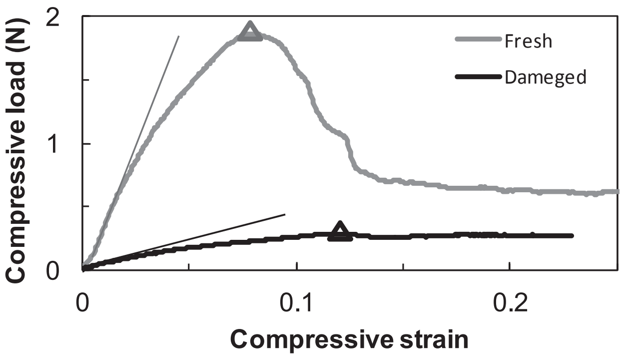


**Fig. 1 Typical compression curves for fresh and damaged strawberries.**

The equator was compressed with a probe of 3-mm diameter at 1 mm/s.
Triangle symbols indicate the fracture points, and the straight lines are the maximum slope used for calculation of the apparent modulus.

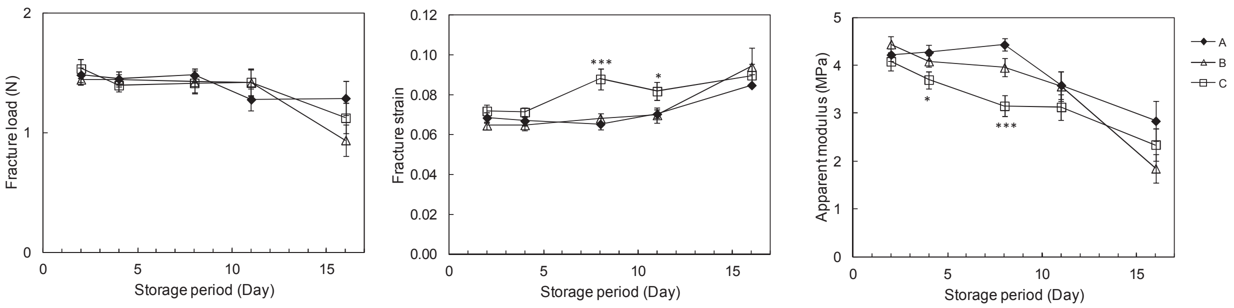


**Fig. 2 Changes in the mechanical properties of strawberries during storage under different conditions at 5℃.**

Test condition ◆, in a polyethylene bag with AIT release product (A); △, in a similar bag without AIT (B); and □, control without AIT or bag (C). Asterisks beside the symbols indicate significant difference among the three conditions determined by one-way ANOVA (*, $p < 0.05$; ***, $p < 0.001$). The equator was compressed with a probe of 3-mm diameter at 1 mm/s. Values are means and standard errors, n=20.

found no significant experimental effects on the absolute values of fruit weight over the entire storage period (data not shown). We measured the weights of 25 samples on fixed trays under each treatment condition during the test period. The weight losses of samples enclosed in PE bags were very small even though bags were not sealed. Weight loss in (C) without bags was very large (Fig. 4).

The fracture load, which is often used as a softening index, was not suitable for the evaluation of post harvest changes in mechanical characteristics. The values did not differ significantly until 11 days. The apparent modulus and fracture strain were better measures of fruit damage during storage. The differences among the three treatments were most significant at *ca*. 8 days after harvest (Fig. 2), but there were no significant effects in the first few days after harvesting. Damage was evaluated by increasing fracture strain and reducing apparent modulus. The rank order of modulus measures among treatments was (C) < (B) < (A) after 8 days of storage. Damage was significant after 2 weeks of storage under all test conditions. Most of this damage was attributed to the growth of molds, which increased the variance within treatment. By the 16th day of storage, some fruits were undamaged but softened by fungi. Molds damaged strawberry quality. The modulus in treatment (B) was lower than that in (C) because after 16 days and longer storage period, there were fewer molds in treatment (C). The

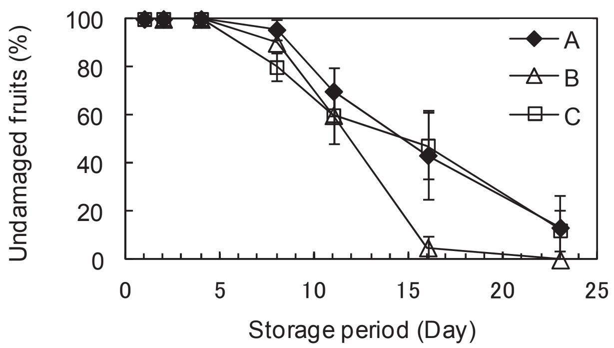


**Fig. 3 Ratio of undamaged fruits under different conditions at 5℃.**

Test condition ◆, in a polyethylene bag with the AIT release product (A); △, in a similar bag without AIT (B); and □, control without AIT or bag (C). Values are means and standard errors for two or three batches.

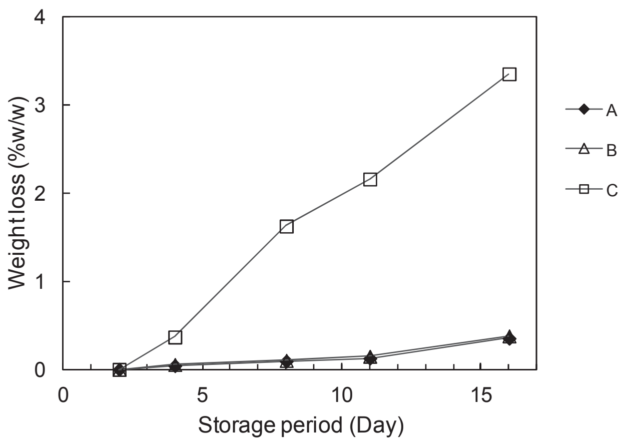


**Fig. 4 Weight losses from 25 strawberries in a tray during storage under different treatments at 5℃.**

Test condition ◆, in a polyethylene bag with the AIT release product (A); △, in a similar bag without AIT (B); and □, control without AIT and the bag (C).

AIT product was effective through 2 weeks after harvest.

### 3. Comparison of equator and apex

Strawberry fruits are small and humans do not consume a part of the strawberry. However, the effects of storage may differ in different parts of the fruit, though it is the equatorial part that is usually tested. Figure 5 shows some parameters measured at the equator and apex during storage. The Brix value was much higher (*ca*. 12) at the apex than at the equator (*ca*. 8), but pH (3.5–3.7) did not differ between the two positions (data not shown) through the whole storage period. The apical Brix values decreased with storage time, unlike the equatorial values. The fracture load at the equator was higher than or similar to that at the apex. The fracture strain at the equator was always higher than that at the apex. The tendencies in pH, Brix, and mechanical properties were similar between treatments (A) and (B), in which the rate of deterioration was faster, as stated above. Generally the apex was softer than the equator as indicated by the lower values of the fracture load and strain. The fracture point was not clearly detected in 50% of fruits stored under treatment (C) for 16 days because the strawberry fruits were very soft. The apparent modulus measured at the apex tracked a different trend. The apical modulus was significantly higher than the equatorial modulus in fresh fruits 2, 4 and 8 days after harvest, decreasing steeply with storage time, and reaching the same level as the equatorial modulus by 11 days post harvest; subsequently, both moduli decreased similarly in aged fruits.

## Discussion

### 1. Best quality index

We aimed to develop a new index for strawberry fruit quality post harvest. Palatability is determined by sweetness, which is mainly dependent on sugar content, and influenced by sourness and softness of fruits. Brix, pH, and fracture load values did not significantly change among storage times or treatments. Mean values were not stable and had large standard errors (Figs. 2 and 5). Weight loss without

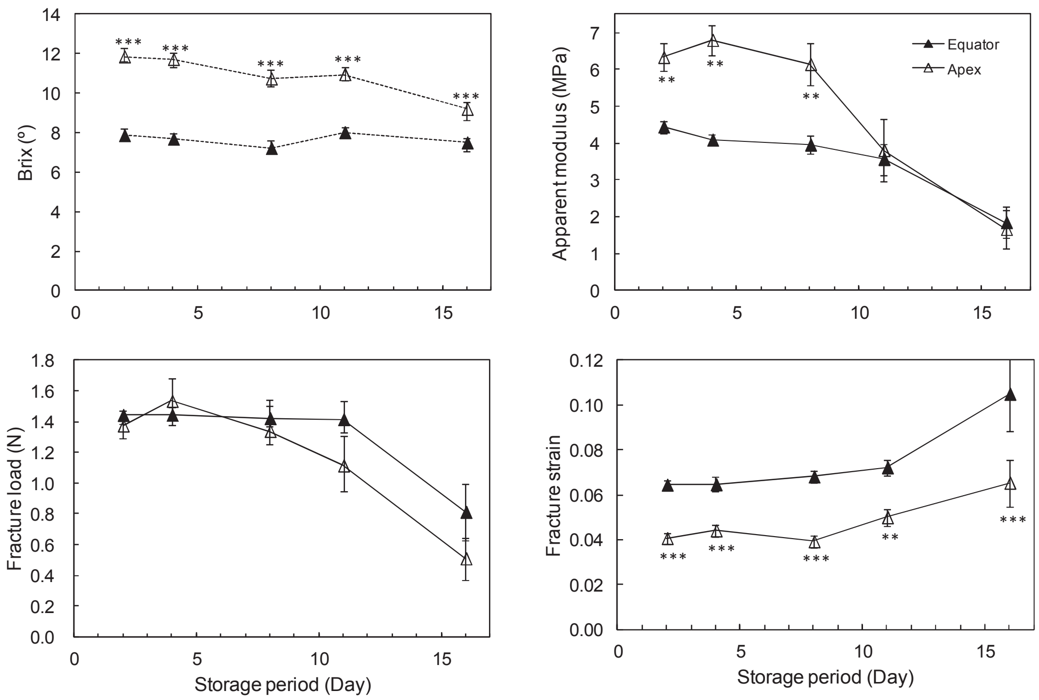


**Fig. 5 Differences in Brix and mechanical properties between the fruit equator (closed symbols) and apex (open symbols) during storage at 5℃.**

Values are mean and standard errors of 10 individual fruits stored under the treatment (B). Apex symbols with asterisks are significantly different from the equator positions determined by paired *t*-tests (**, $p < 0.01$; *** $p < 0.001$).

the PE bag was greater than in other treatments when the same samples were measured repeatedly (Fig. 4). However, the PE bag effect was not significant when different fruits were measured on different days because there were large variations in condition among different fruits. Gunness et al. (2009) emphasized the importance of fruit-to-fruit evaluation for strawberry fruits. Thus, trends observed in mechanical properties were much more significant among treatments and storage times when inter-individual variation was factored out; destructive tests do not allow resampling of the same individuals at different times.

There was also great variation in fruit size, and this was difficult to take into account. We conducted puncture tests with a thin cylinder to reduce the contact area between fruit samples and plunger. The deformation was standardized to strain divided by diameter of each fruit and the stress can be derived when the deformation is enough small as the contact area was only bottom of the plunger.

Among mechanical parameters, the fracture strain increased and the apparent modulus decreased gradually over storage time; however, the fracture load did not change significantly (Fig. 2). The same phenomena are commonly observed in other plant materials, as Thiel and Donald (2000) reported for fresh and aged carrots. A post harvest change was not detected during short-term storage (less than 4 days). Differences among the three treatments were most significant at *ca*. 8 days after harvest (Fig. 2). At that time, the extent of damage measured by increasing the fracture strain and reducing modulus was in the rank order (C) > (B) > (A). Damage became significant after 2 weeks of storage under all treatment conditions.

The decrease in the modulus and increase in the fracture strain (Fig. 2) occurred before visual damage was observed in groups of strawberry fruits stood under the storage conditions (Fig. 3). The threshold for strawberry quality using visual assessment occurred when the proportion of acceptable berries fell to 80% (Wills and Kim, 1995). This occurred after *ca*. 10 days for treatment (A), 9 days for (B) and 8 days for (C) conditions. The apparent modulus and fracture strain changed significantly before these points in time. Thus, mechanical parameters were more sensitive for the detection of undesirable changes in strawberry fruits stored under different conditions than visual assessment. Individual variations among fruits were very large, and we accordingly prefer non-destructive tests because they allow repeated measurements on the same individual fruits. We were able to derive the modulus at approximately 0.02 compressive strain (Fig. 1); hence, modulus would be a good indicator of fruit quality if an inexpensive and portable tester were to be developed. A fruit hardness tester is useful, but only measures a fracture force, which we found inappropriate for evaluating postharvest changes in mechanical characteristics. The fracture load decreased significantly in damaged fruits after a long storage period when the fruits were no longer edible. This is also true for the Brix, which is easily measured, but changes appear too late in the storage period when fruits are no longer suitable for consumption. Parameters used as quality indices should detect differences among treatments early in the storage period.

### 2. Partial differences in a fruit

Apical parts of the fruits had higher Brix and apparent modulus values, and lower fracture load and strain values than equatorial parts (Fig. 5). Lower values in fracture properties at the apex suggest that fruit damage during storage is likely to start at the apex. Decreasing apparent modulus at the apex occurred earlier in the storage period than in the equatorial part. Modulus at the apex measured through non-destructive procedures that allow detection of changes early in storage may provide an excellent mechanical index of storage quality for strawberry fruits.

### 3. Effects of storage conditions

Strawberries, which are non-climacteric fruits, produce less ethylene gas than climacteric ones. Under our test conditions, bruising was not significant after handling and transportation, and there was no serious damage during the first 2 days, though damage by fungi appeared to be the greatest problem. Thus, we can conclude that the AIT product was effective in extending the storage period at 5ºC to 2 weeks post harvest. During this period, a low level of AIT (<1 ppm) was detected in the atmosphere (Oshida et al., 2010). The manufacturer (Ageless Service Center) claims that the product is effective in prolonging the storage lives (up to 14 days) of some non-climacteric fruits, such as strawberries and grapes. Preservative effects were evaluated by the subjective appearance of fruits, but no objective indices were reported. Firmness, as measured by a fruit tester, acidity, and sugar content were not affected by the product.

In our study, the AIT effects most likely ended at 16 days because the undamaged fruit proportion in treatment (A) had fallen to the level in the control (C), though it was still higher than in treatment (B). Humidity in the PE bag was higher than in the control (C), as indicated by reduced weight loss in the fruits (Fig. 4); however, molds may have grown more rapidly in the bags after the first appearance. The higher moisture loss in treatment (C) than in treatment (B) may reflect the greater values of the apparent modulus and fracture properties at 16 days in (C). Drying of fresh fruits may result in a high modulus, but it is an unfavorable effect, and this should be taken into account when a mechanical property is used as a quality index.

### 4. Effects of AIT on strawberries

Ripening of non-climacteric fruits is not accelerated by ethylene (Kader, 1990; Shimokawa, 1990). However, some researchers reported that ethylene exposure increased the softening of strawberries (Bower et al., 2003; Tian et al., 2000; Wills and Kim, 1995). As AIT inhibits 1-aminocyclopropane-1-carboxylic acid synthase, which produces ethylene, the ripening and senescence of vegetables and fruits are retarded (Shimokawa, 1990). The ripening mechanism of strawberries has not been clarified and the effects of ethylene on ripening are still controversial (Iannetta et al., 2006; Trainotti et al., 2005).

The mechanism by which AIT acts has not yet been determined. We did not test a high concentration of AIT because the strong and undesirable smell of wasabi adhered to the strawberries when AIT concentration exceeded 1 ppm. Consumers never accept such fruits, though they are fresh, because strawberry fruits and wasabi flavors are quite incongruent. We postulate that the AIT release product most probably prevented fungal growth since no molds were found over the 2-week storage period post harvest at 5℃. Further study is required to clarify the mechanism by simultaneous analysis for AIT quantity and sample damage.

### 5. Application study

The variety *Yayoihime* can be harvested in March, and the fruit characteristics are excellent; the fruits are firm and have a long storage life. Different varieties and/or different geographical regions and times should be tested before practical application of the method presented here.

## Conclusions

The apparent modulus and fracture strain, two mechanical parameters obtained by simple compression testing, measured the softening of strawberry fruits. The modulus decreased and strain increased, but other parameters, such as the fracture load, pH, and Brix, did not significantly change with time after harvest. The presence of the AIT release product and storage in PE bags clearly extended the period before softening from several days to 2 weeks in cold storage. The proposed modulus has good potential as an indicator of fruit damage because it is more sensitive than other parameters and is obtained by a non-destructive compression test.

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# イチゴ果実の貯蔵中の品質を示す簡易な力学指標

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## 要　旨

イチゴの貯蔵中の品質を示す圧縮試験で求められる簡単な力学指標を提案する．力学的変数に対する５℃における異なる貯蔵条件の効果を試験した．イチゴの貯蔵条件としては，袋なしのコントロール，ポリエチレン袋内に入れたもの，ポリエチレン袋内にアリルイソチアシアネート（AIT）を蒸散させる製剤入りの系を比較した．気化したAITは微生物の成長を抑制することが知られているからである．一般に果実硬度として用いられる破壊荷重は，有意差が認められなかったが，貯蔵時間が長くなると破壊歪の増加，見かけの弾性率の減少が認められた．イチゴ果実の劣化に対して感度が高く，非破壊試験の可能性がある小さい歪領域で計算されることから，見かけの弾性率はよい指標であることが示された。

キーワード：イチゴ，圧縮試験，見かけの弾性率，力学特性，低温保存