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A new descriptive method for fruit firmness changes with various softening patterns of kiwifruit

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ABSTRACT

We have proposed a new interpretation of fruit softening. This was accomplished by generating a hypothesis that probabilities of decay of fruit structure obey the Weibull probabilistic model that has been used in the field of reliability engineering. The elasticity of individual kiwifruit after harvest was continually and nondestructively measured until decomposition by using a laser Doppler vibrometer. The obtained decreasing pattern of elasticity of individual fruit was complex, diverse, and inhomogeneous. Nonetheless, it was satisfactorily explained by a tandem combination of 2 Weibull models involving 4 types of parameters: "shape" related to probability; "scale," to velocity of decay; "location," to time lag; and "mixing ratio," to contribution of the 2 models. Averages of location, shape, and mixing ratio parameters obtained by the measurement of 33 fruit were significantly different between the 2 models, but the scale parameter was not. The results suggested that the complex softening patterns of individual kiwifruit could be described using the tandem model of Weibull distribution, and that the softening process of kiwifruit consisted of at least 2 independent decay phases that are characterized by 2 of 5 parameters: location and mixing ratio. Commencement of the first decay phase could be caused by ethylene treatment after harvest, and the second one spontaneously triggered after a certain time lag.

1. Introduction

Most fruit begin to lose their firmness after harvest, and this phenomenon is termed fruit softening. Fruit softening may be nondestructively monitored using a laser Doppler vibration method by measuring the elasticity of fruit (Taniwaki and Sakurai, 2010). The softening process is apparently complex and non-uniform, and individual fruit exhibit diverse patterns of softening. Ethylene is one of the factors that triggers this softening process; however, other factors such as low temperature have recently been considered (Mworia et al., 2012), suggesting the complexity of this process. Fruit ripen at different dates after harvest, even if they belong to the same cultivar and are harvested on the same day after anthesis. Controlling the ripening period of fruit is of great commercial value since uniform ripeness of fruit enables the prediction of the date of optimum fruit ripeness so that consumers can be informed about it. Hence, many researchers have developed methods to store fruit after harvest in order to ensure delivery of good quality fruit to consumers (Johnston et al., 2001; Antunes and Sfakiotakis, 2002; De Ketelaere et al., 2004). However, few researchers have focused on the reason for the inhomogeneous manner of fruit softening.

Fruit softening is a consequence of decreased mechanical strength (elasticity) of composite tissues (Taniwaki and Sakurai, 2010). Developmental processes responsible for modifying the structure of cell wall polysaccharides are usually involved in the changes in elasticity (Huber, 1983; Wakabayashi, 2000; Rose, 2003). Numerous reports have shown that pectic polysaccharides (Huber and O'Donoghue, 1993; Redgwell et al., 1997; Rose et al., 1998; Wakabayashi et al., 2003; Wakabayashi and Huber, 2001), hemicelluloses (Redgwell and Fry, 1993; Sakurai and Nevins, 1997; Terasaki et al., 2001a), or cellulose (O'Donoghue et al., 1994; Rose and Bennett, 1999) undergo specific modifications in the cell wall during fruit softening.

Abbott et al. (1968) first reported a detailed method that estimated the elasticity of an intact fruit by using nondestructive measurement of the resonance frequency of a fruit. This

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method allowed monitoring of continual changes in the elasticity of individual fruit. Thereafter, many studies have conducted such measurements and have reported curves of fruit softening by using various equations such as exponential (Thai et al., 1990; Schotte et al., 1999; White et al., 2005), polynomial (Shmulevich et al., 1996; Olmo et al., 2000), or reciprocal equations (Terasaki et al., 2006). However, thus far, few studies have interpreted the softening pattern of individual fruit on the basis of one or more fruit softening events.

Muramatsu et al. (1997, 1999a,b) used a unique sensor, the laser Doppler vibrometer (LDV), to measure fruit softening of various fruit including kiwifruit, and Terasaki et al. (2001b, 2006) investigated capability of the LDV measurement system using kiwifruit and pear and confirmed that the system can be used to precisely obtain reproducible measurements of fruit vibration. Murayama et al. (2006) applied the LDV measurement system to study the softening behavior of 'La France pear' under various storage conditions and first clarified that individual fruit soften in a biphasic manner that is difficult to explain with conventional approximating curves. Since changes in fruit elasticity reflect the fruit softening mechanism, we paid attention to this unique biphasic pattern. To interpret this complex mechanism, we introduced a reliability theory.

The objectives of this study were (1) to develop a theoretical model that explains the complex mechanism of fruit softening by using the reliability theory and (2) to suggest the theoretical characteristics of the fruit softening process using this model.

2. The theoretical model for fruit softening

Reliability theory has been widely used to analyze the life span of industrial products such as vacuum tubes and space shuttle parts (Kao, 1959; Gulino and Phoenix, 1991; Attardi et al., 2005; Oswald et al., 2008). At present, this theory has been applied to the analysis of the mortality rate of animals and humans (Finch et al., 1990; Ricklefs and Scheuerlein, 2001).

We assumed that a decrease in fruit elasticity during fruit softening is the result of degradation of the fruit structure. Fruit softening is closely related to the stochastic disruption of cell wall polysaccharides as a function of time (Rose and Bennett, 1999). When the degradation of cell wall polysaccharides during the softening obeys a weakest link model, a Weibull probabilistic model can be applied to the probability of its breakage.

Since the actual softening behavior of pears often shows a biphasic elasticity decline (Murayama et al., 2006), we assumed that the fruit softening process comprises at least two softening phases. Therefore, we hypothesized that these phenomena are explained by a mixed Weibull distribution model consisting of 2 independent Weibull probability distributions. The cumulative distribution function $F(t)$ using Weibull probability distribution for a biphasic decline is expressed as follows:

$$F(t) = 1 - P_1 \cdot \exp\left\{-\left(\frac{t-\gamma_1}{\eta_1}\right)^{m_1}\right\} - P_2 \cdot \exp\left\{-\left(\frac{t-\gamma_2}{\eta_2}\right)^{m_2}\right\}, \tag{1}$$

where "P" is a mixing ratio of the 2 distributions and defined as follows:

$$P_1 + P_2 = 1 \tag{2}$$

and where "t" is time, "m_1" and "m_2" are shape parameters that decide the type of degradation of load-bearing bonds of polysaccharides (breaking probability), "η_1" and "η_2" are scale parameters that determine the velocity of the reaction, and "γ_1" and "γ_1" are location parameters that set the initiation time for the process. As a scale parameter increases, the velocity of breakage of load-bearing bonds of the polysaccharides decreases. As a location parameter increases, the initiation of breakage is delayed.

The first or second term of Eq. (1) is the cumulative distribution for the first or second fruit-softening phase, respectively. The residue that subtracted the cumulative distribution from the initial value ($t = 0$) means the fruit elasticity. Residue $R(t)$ is calculated from Eqs. (1) and (2) as follows:

$$\begin{aligned} R(t) = 1 - F(t) &= P_1 \cdot \exp\left\{-\left(\frac{t-\gamma_1}{\eta_1}\right)^{m_1}\right\} \\ &+ P_2 \cdot \exp\left\{-\left(\frac{t-\gamma_2}{\eta_2}\right)^{m_2}\right\} = P \cdot \exp\left\{-\left(\frac{t-\gamma_1}{\eta_1}\right)^{m_1}\right\} \\ &+ (1-P) \cdot \exp\left\{-\left(\frac{t-\gamma_2}{\eta_2}\right)^{m_2}\right\} \end{aligned} \tag{3}$$

Since Weibull distribution defines that the event does not occur when "t" is less than the location parameter, the exponential of the corresponding term in the above equation is 1 at this period, that is, fruit degradation does not occur at this period. Also we premised that the magnitude relationship of each location parameter is "γ_1" < "γ_2". Thus, fruit softening with a biphasic decline in elasticity $E(t)$ is expressed as using Eq. (3) as follows:

$$\begin{aligned} E(t) = E_0 \cdot \Bigg[& P \cdot \exp\left\{-\left(\frac{t-\gamma_1}{\eta_1}\right)^{m_1}\right\} \\ & + (1-P) \cdot \exp\left\{-\left(\frac{t-\gamma_2}{\eta_2}\right)^{m_2}\right\}\Bigg] \end{aligned} \tag{4}$$

where "t" is the time of fruit softening process and "E_0" is initial elasticity of fruit at $t = 0$.

We adopted Eq. (4) as the model for kiwifruit softening and have designated it as the tandem Weibull model. The first and second terms in Eq. (4) are residual components of the first and second softening phases, respectively. The tandem Weibull model for fruit softening expresses a summation of the 2 distinctive softening phases.

3. Methods

3.1. Plant material and measurement of changes in the elasticity of individual kiwifruit

Kiwifruit [*Actinidia deliciosa* (A. Chev.) Liang et Ferguson, cv Hayward] were grown in a commercial orchard at Saijo, Ehime, Japan, and harvested at the mature stage. Harvested kiwifruit were immediately transferred to the laboratory for nondestructive measurement of the elasticity index (EI) by using the measurement system of an LDV. Of the 147 fruit, 33 with similar initial elasticity E_0 ($62 \pm 0.3 \times 10^6$ Hz^2 g$^{2/3}$) were selected. Here, 62×10^6 Hz^2 g$^{2/3}$ corresponds to 8 N according to our previous report (Terasaki et al., 2001b). The weight of these fruit ranged from 95.2 to 162.4 g, with a mean and standard error of 127.5 ± 3.42 g.

All the fruit were stored in a cardboard box (560 mm in width, 250 mm in depth, and 90 mm in height) containing the ethylene-generating reagent (Kanjukupakku; Shiraishi Calcium Co., Ltd., Tokyo, Japan) to trigger the softening process. The box was placed in an incubator (model MIR-153; SANYO Electric Co., Ltd., Osaka, Japan). The temperature was maintained at 20 °C throughout the experiment. After the initial 48 h, the ethylene-generating reagent was removed from the box, and the box containing the kiwifruit was further incubated until the end of the experiment. Each fruit was transferred to the laboratory for EI measurement, and the date and time of measurement were recorded. EI of individual fruit were continually measured by LDV to the end of experiment. LDV was conducted at room temperature (from 20 to 25 °C), and the fruit were returned to the incubator immediately after the measurement.