Title: Texture measurement of cabbages using acoustical vibration method

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Abstract

Textures of six cabbage cultivars were quantified using an acoustical vibration technique. A sample of four outer leaves of a cabbage was penetrated using a probe. The acoustical vibration signals were measured during penetration using a piezoelectric sensor. A new texture index (TI), the “energy density”, was introduced, which was determined by the integration of squared amplitudes of texture signals multiplied by a factor of a frequency band. This TI enabled evaluation of acoustical signals in the high-frequency region (> 1000 Hz) more sensitively than the previously used index (“amplitude density”), which was determined by the integration of texture signal amplitudes. Significant differences in TI among the cultivars were obtained by using ANOVA method, especially between a spring and a winter cabbage. We also examined cabbages that had been stored under 4 °C for 10 or 19 d. Most TI readings increased after the storage. These results provide useful information related to the shelf life of cabbages.

Keywords: Postharvest; Storage; Piezoelectric sensor

1. Introduction

Food textures, such as crispness or crunchiness, are important attributes of fresh commodities. Consumers use such textures to evaluate the freshness of fruit and vegetables. They also choose the right cultivar of vegetables according to cooking methods (e.g. fresh, boiled and fried). We previously proposed that an effective means of objective evaluation of such fresh commodities is direct measurement of texture using a machine (Taniwaki et al., 2006b).

Extensive studies have been made of food texture measurements using mechanical and acoustical methods (Duizer, 2001; Roudaut et al., 2002). Early work of an acoustical measurement of food texture was done by Drake (1963, 1965). He showed that crispier products produced higher amplitude of sound. Most acoustical studies of food texture have used a method of recording the sound produced by the mastication of food by a panel (Lee et al., 1990; Vickers, 1991; Dacremont, 1995). One problem of this method is that the intrinsic texture information can be lost because of the resonance of the palate or the mandible. Furthermore, the soft tissues in the mouth absorb or dampen higher-frequency sounds (Vickers, 1991). However, Christensen and Vickers (1981) suggested that vibrations produced by fracturing crisp foods might underlie the perception of crispness.

We previously developed a device for measuring the texture of fresh commodities using an acoustical vibration method (Sakurai et al., 2005a, 2005b; Taniwaki et al., 2006a, 2006b). The device consists of a piezoelectric sensor and a probe. This device can measure acoustical vibrations that are created during the fracture of a food sample over the wide range of audio frequencies (0-25600 Hz). The obtained signals are filtered using a half-octave multi-filter to calculate the texture index (TI) for each frequency band. This has made it possible to define a food’s texture more directly than the above-mentioned sound recording method.

In the present study, we applied this acoustical vibration method to texture measurement of fresh cabbages. Freshness and crispness are especially important for cabbage because it is frequently eaten fresh, especially in Japan and Korea. Cabbage textures are expected to differ among cultivars. Especially large differences in texture are expected between spring and winter cabbages. In general, spring cabbages are believed to have a more tender texture than winter ones. However, few studies have been made of cabbage texture measurement. An early work investigating cabbage texture was conducted by Holt and Schoorl (1983), who dropped a cabbage from different heights and obtained a very strong linear relationship between the total leaf crack length and the energy dissipated during the drops. Several reports have described tensile tests for leafy commodities such as lettuce (Toole et al., 2000; Newman et al., 2005). Another closely related field of study is the measurement of leaves’ mechanical properties. A punching test (penetrometer) is a commonly used technique to evaluate the strength or texture of leaves (Choong et al., 1992; Aranwela et al., 1999; Edwards et al., 2000). Other common mechanical tests are shearing tests and the tearing tests (Sanson et al., 2001). The strength and fracture of grass leaves (*Poapratensis, Holcus lanatus, Bromis hordescens, Deschampsia caespitosa, Dactylis glomerata*) were investigated using tensile tests (Vincent, 1991).

In this paper, we first introduce the improved definition of TI. This TI is more sensitive to the texture signals in high frequency region (> 1000 Hz) than the previously used definition (Taniwaki et al., 2006a, 2006b). Then we describe the obtained results of the texture differences among cabbage cultivars and the texture change after cold storage using the acoustical vibration method.

2. Materials and Methods

Figure 1 depicts a perpendicular cross-sectional view of cabbage (*Brassica oleracea* var. *capitata*) samples. Six cultivars (SK-1, T-520, M-3, Fuyu-nobori, Fuyu-kuguri and Kinkei-201) were used for the texture measurement. SK-1, T-520, M-3, Fuyu-nobori, and Fuyu-kuguri were winter cabbages with dense leaf structures. Winter cabbages in general have a crispy texture. In contrast, spring cabbages (Kinkei-201) have a tender texture because of their curly and softly structured leaves. Two sets of cabbage samples were used for two independent experiments: measurement of texture and measurement of change in the texture due to cold storage. The set for the texture measurement included two to three whole cabbage samples: SK-1 (2), T-520 (3), M-3 (3), Fuyu-nobori (3), Fuyu-kuguri (3) and Kinkei-201 (2) (Numbers in parentheses indicate set size). Another set of four samples for texture change measurement included T-520 (4), M-3 (5), Fuyu-nobori (5), Fuyu-kuguri (1). The measurements started a day after the samples had been harvested.

The texture measurement device (AMC; Applied Vibro-Acoustics Inc., Higashi-Hiroshima, Japan) used for this study was previously reported by Taniwaki et al. (2006b). The device mimics the mastication process of human beings. The device measures the vibrations created during the penetration of a probe into a sample by using the piezoelectric sensor of 1 mm thick and 10 mm in diameter (2Z10D-SYX, Fuji Ceramics Corp., Fuji, Japan). The signal detection covers wide audio frequency range (0-25600 Hz). The vibration amplitudes (in Volts) were detected by the piezoelectric sensor. The probe used was a wedge of 5 mm width and 20 mm length, with a 30-deg tip angle (Fig. 2). The probe speed was 22 mm s^{-1}, which was inferred to be within the range of typical human mastication speed (Roudaut et al., 2002). The data sampling rate was 80 kHz. The obtained texture signals were filtered using a half-octave multi-filter for analyses in the frequency domain (Taniwaki et al., 2006a, 2006b).

The "amplitude density" of the vibration was introduced previously as TI to quantify the texture of food (Taniwaki et al., 2006a, 2006b). However, the vibration amplitudes become lower as the frequency increases. For that reason, the amplitude density tends to underestimate the TI in the high-frequency region (> 1000 Hz). To overcome this problem, we introduced other definition. It is based on the concept of vibration energy of waves (sum of the potential and kinetic energy of waves). This energy E is defined by the amplitude a of a wave and its frequency f as

$$E \propto (2\pi f)^2 a^2 \;, \qquad (1)$$

(Feynman et al., 1963). The amplitude a can be expressed as $\sqrt{2}\, a_{rms}$ using the rms amplitude a_{rms}. We here define the frequency by the representative central frequency of each frequency band as $\sqrt{f_l \times f_u}$, where f_l and f_u respectively represent the lowest and the highest frequency of each frequency band determined by the half-octave multi-filter. Using the definitions above, the energy density can be defined as

$$(f_l \times f_u) \cdot \frac{1}{n} \sum_{i=1}^{n} V_i^{\,2} , \qquad (2)$$

where V_i is the amplitude of the texture signal, and n is the number of data points. Note that this equation was applied to the texture signal data of each frequency band after the raw texture signal data was filtered by using the half-octave multi-filter. The output signal can be converted to the equivalent pressure applied to the probe by using the following equation: $P = -1.0 \times 10^6 + (1.1\times 10^7)\, V$, where P (Pa) represents the pressure applied to the probe and V (V) is the output signal. This relation was obtained by applying a force to the probe and measuring the force by a platform scale.

For texture measurements, the samples were prepared as follows: two or three outer green leaves were removed because this part is usually not eaten. Then the first to the fourth leaves were cut into approximately 5 cm × 5 cm square shapes. The numbers of the leaf sample were: 24 for (SK-1, Kinkei-201), 36 for (T-520, M-3, Fuyu-nobori, Fuyu-kuguri). The experimental setup for texture measurement of cabbages is shown in Fig. 2. A group of four leaves was sandwiched between two acrylic plates with a hole in the center (φ10 mm); then the probe was made to penetrate the four leaves completely. We tried not to penetrate main and sub-main veins so that the standard errors within one cultivar were small enough for comparison with other cultivars. The maximum pressure applied to the cabbage samples was measured to be 31.4 Pa, with which no change was observed in the leaf surface structure. The difference in the TI among the cultivars was analyzed by using ANOVA statistical software package SPSS (SPSS Inc., IL, USA).

TI changes of cabbages during storage were also investigated. The numbers of leaf samples were: 48 (T-520), 12 (Fuyu-kuguri), 60 (M-3, Fuyu-nobori). Test samples were prepared as earlier described. Each set of four leaves was packed in a polyethylene bag and stored in a refrigerator at 4 °C to keep them in humidity of nearly 100 % (because packed in a polyethylene bag) for 10 or 19 d.

3. Results

Figure 3 shows typical output signals of four piled cabbage leaves of each cultivar. The texture signals of T-520 and Fuyu-kuguri showed four clear peaks that corresponded to the penetration of four leaves (arrows in Fig.

3). On the other hand, Kinkei-201 showed no such distinctive four sharp peaks: it showed lower signals after the first increase in the signal (ca. 1.2 s) than the other cultivars.

Figure 4 shows the TI of cabbage samples in the frequency domain calculated by Equation (2). In the frequency bands between 0 and 1600 Hz, the cultivars could be classified into two groups by their TI: Group A (higher TI: T-520, M-3, Fuyu-nobori, Kinkei-201) and Group B (lower TI: SK-1, Fuyu-kuguri). Above 1600 Hz to 8920 Hz, the TI of Fuyu-kuguri moved from Group B to Group A. The TI of T-520 left Group A for much higher TI. It was the highest among the cultivars in the high-frequency region (1120-8920 Hz). The TI of Kinkei-201 moved from Group A to Group B. It was almost constant throughout 1120-8920 Hz, where the other cultivars exhibited increasing TI. The level of TI for six cultivars depending on three frequency bands were summarized in Table 1. The table also shows the classification of the cultivars by the TI in each frequency band using ANOVA method. The significance was 5 % level. When ANOVA was applied to the TI of three frequency bands (10-1120 Hz, 1120-8920 Hz, 8920-25600 Hz), the cultivars were able to be classified into two groups in the frequency band 10-1120 Hz and three groups in 1120-8920 Hz and 8920-25600 Hz bands (denoted by a, b and c in Table 1).

Figure 5 shows changes in TI with time. The results show that some TI increased after storage at a low temperature. Both T-520 and Fuyu-nobori showed much higher TI after 10 and 19 d of storage than either M-3 or Fuyu-kuguri did.

4. Discussion

Clear differences in the texture signals between the cultivars were apparent with data obtained using our texture measurement device (Fig. 3). The differences were attributable to the different structural patterns of leaves among cultivars. As presented in Fig. 3, Kinkei-201 had an especially different pattern attributable to its curly structure of leaves. With the help of ANOVA method, six cabbage cultivars were able to be completely distinguished by the combination of the TI level in three different frequency bands (Table 1). Especially, characteristic differences in the TI between a typical winter cabbage (T-520) and a spring cabbage (Kinkei-201) were apparent in the middle frequency range (1120–8920 Hz) (Fig. 4). These results are inferred to reflect the tenderness of the spring cabbage cultivar and the crispy attribute of winter cabbage cultivars.

Results of changes in the TI with the storage period (Fig. 5) showed that stored leaves tended to exhibited higher TI than these of fresh ones. The results revealed a different tendency from that of some fruits such as apples and pears (Taniwaki et al., 2006b). The TI of these fruits gradually decreased with time, while most of the TI of the cabbage samples increased. This difference occurred probably because these fruit softened drastically as they ripened after the harvest. Increasing of TI following the cold storage may be attributed to the loss of water in the cabbage samples during storage and decreasing their cell turgor. This was shown by results of Zdunek and Konstankiewicz (2004) that showed the failure stress of potato increased with the lower turgor. In addition, our results are explainable according to the finding by Lee et al. (1988) that fresh potato chips produced a greater amount of higher-frequency sound than stale chips. That finding was explainable using the change in the water contents of the potato chips.

The new TI, the "energy density", enhanced the texture indices in the high-frequency region (> 1000 Hz) compared to the TI determined by the "amplitude density" introduced previously by Taniwaki, (2006a, 2006b).

The “energy density” was determined by the integration of squared amplitudes of texture signals multiplied by a factor of a frequency band, while the “amplitude density” was integration of amplitudes of texture signals. Figure 6 shows the difference between two TI definitions by using the “energy density” and the “amplitude density”. In this case, the enhancement factor was 1.2×10^3 at the frequency band of 800-1120 Hz. This enhancement factor was calculated by the following equation:

$$\frac{TI_{eng(800\text{–}1120\mathrm{Hz})} / TI_{eng(0\text{–}50\mathrm{Hz})}}{TI_{amp(800\text{–}1120\mathrm{Hz})} / TI_{amp(0\text{–}50\mathrm{Hz})}}, \tag{3}$$

where $TI_{eng(0\text{-}50\mathrm{Hz})}$ is the TI of the frequency band 0-50 Hz defined by the “energy density”, and $TI_{amp(0\text{-}50\mathrm{Hz})}$ is that defined by the “amplitude density”. This enhancement in the high-frequency region enabled discernment of clear differences in the TI of cabbage cultivars, especially in the high-frequency region (Fig. 4, Table 1).

For evaluating the texture or quality of fresh commodities, non-destructive measurement methods have been available. One such method used a laser Doppler vibrometer and a shaker to measure the vibrations of a sample (Muramatsu et al., 2000). However, that method was inappropriate for measuring the texture of cabbages because of their leafy shape. A destructive measurement method such as tensile testing has also been used to measure the mechanical properties of leaf products such as lettuce (Toole et al., 2000; Newman et al., 2005). The method was good for mechanical property measurement, but it was inappropriate for texture measurement of cabbages because of the effect of their veins. A cabbage leaf is, like a lettuce leaf, an extremely complex structure, as noted by Newman et al. (2005). The network of veins complicates the measurement of mechanical properties. In our measurement method, we carefully avoided the main and sub-main veins during probe penetration.

We applied the previously developed acoustical vibration method to measurement of the cabbage texture.

Significant differences in texture among cabbage cultivars were obtained. Time-dependent changes in the cabbage texture after cold storage revealed different patterns for different cultivars. These results can support evaluation of the shelf-life of cabbage.

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Figure captions

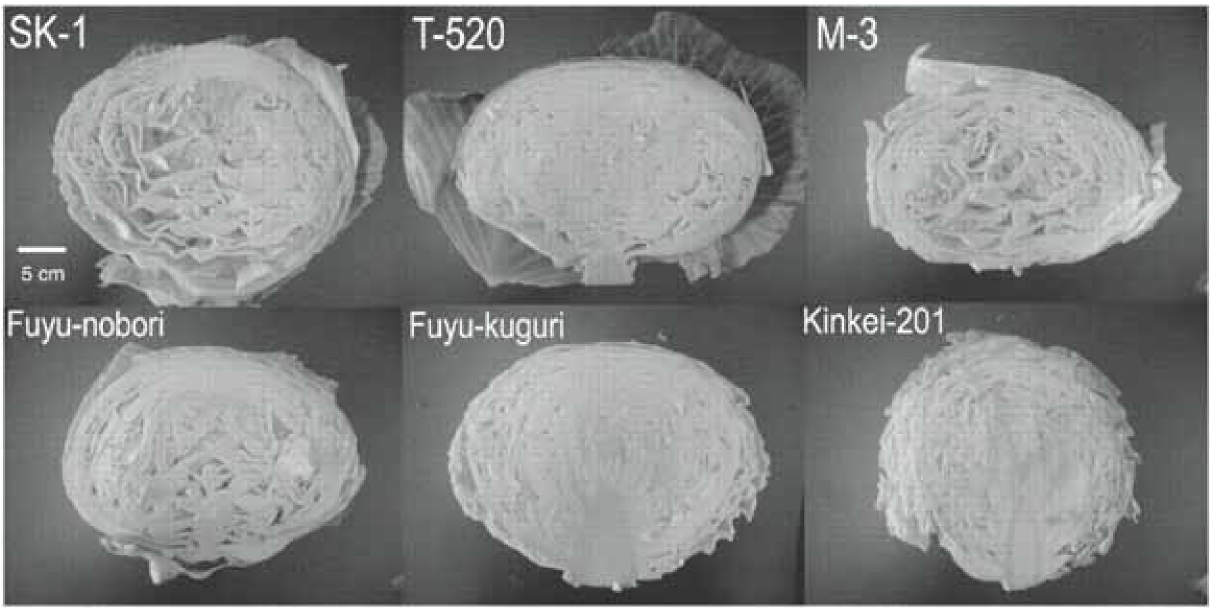

Fig. 1: Perpendicular cross-sectional view of the cabbage cultivars used for texture measurements.

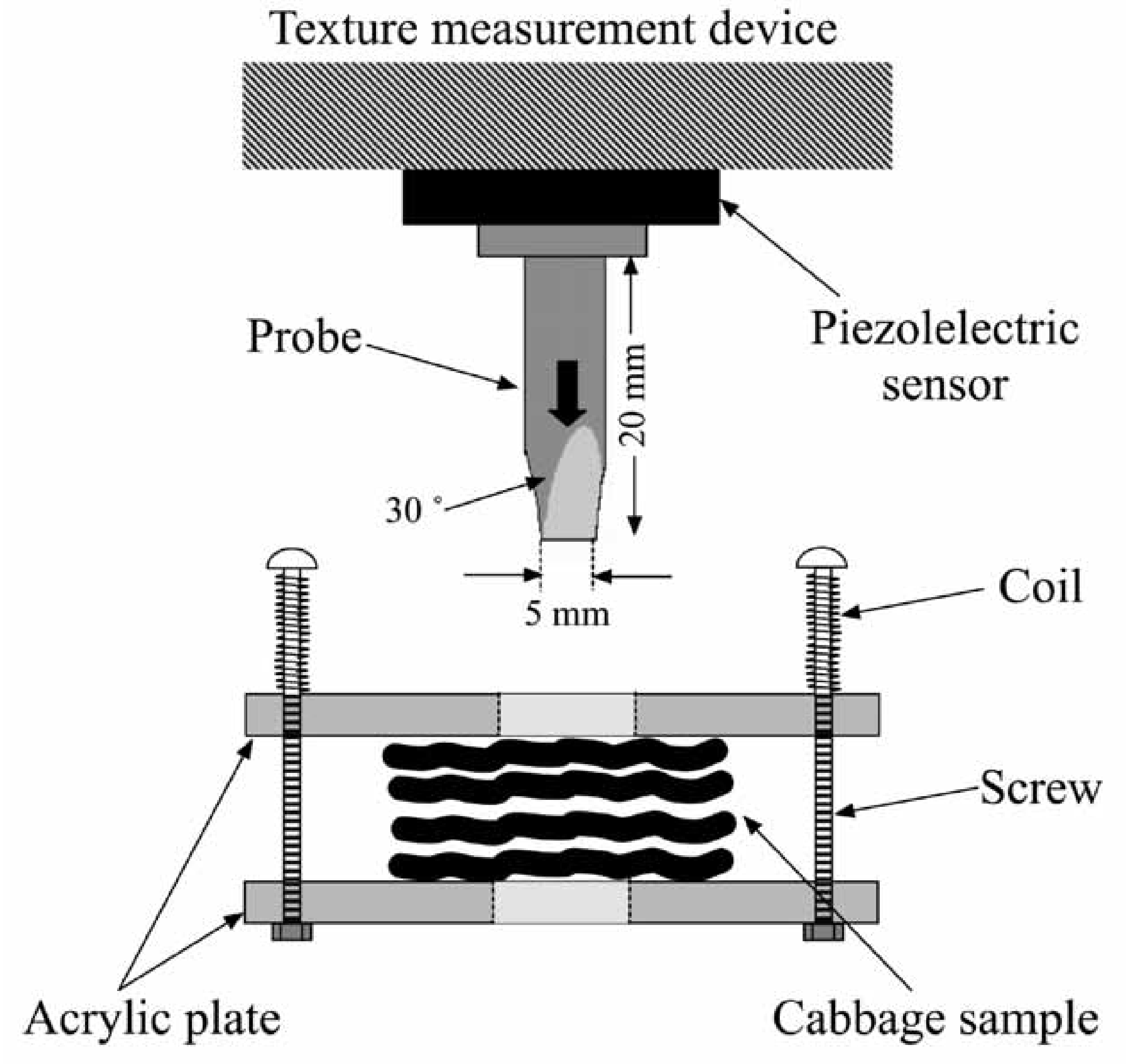

Fig. 2: Schematic of the experimental setup for measuring the cabbage sample textures. The probe was made to penetrate the four leaves of cabbage samples completely to obtain the texture signals.

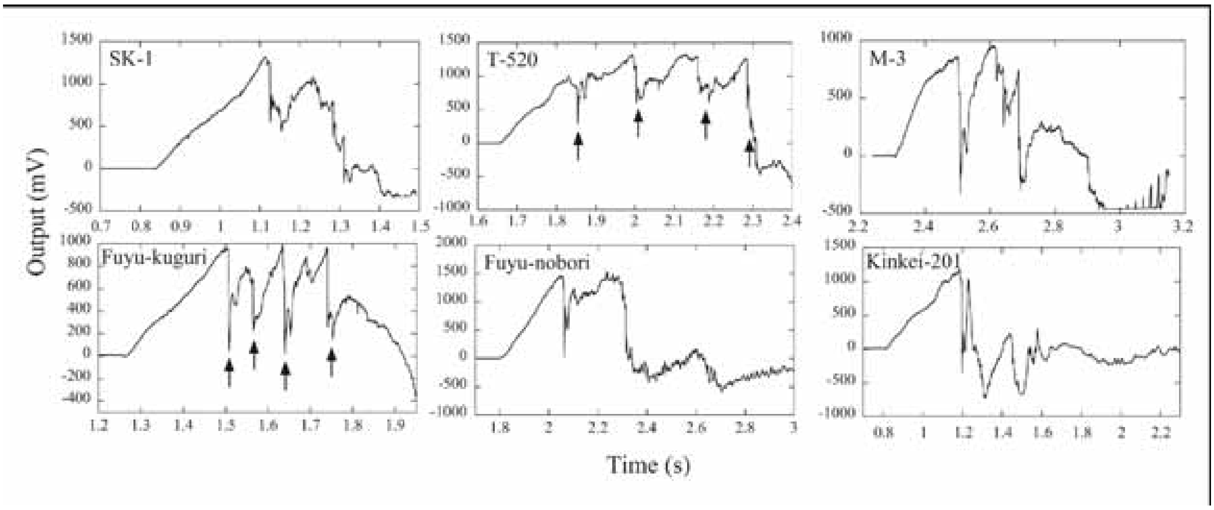

Fig. 3: Typical texture signals of the six cabbage cultivars obtained using the texture-measurement device. The arrows indicate the peaks due to the penetration of different leaves.

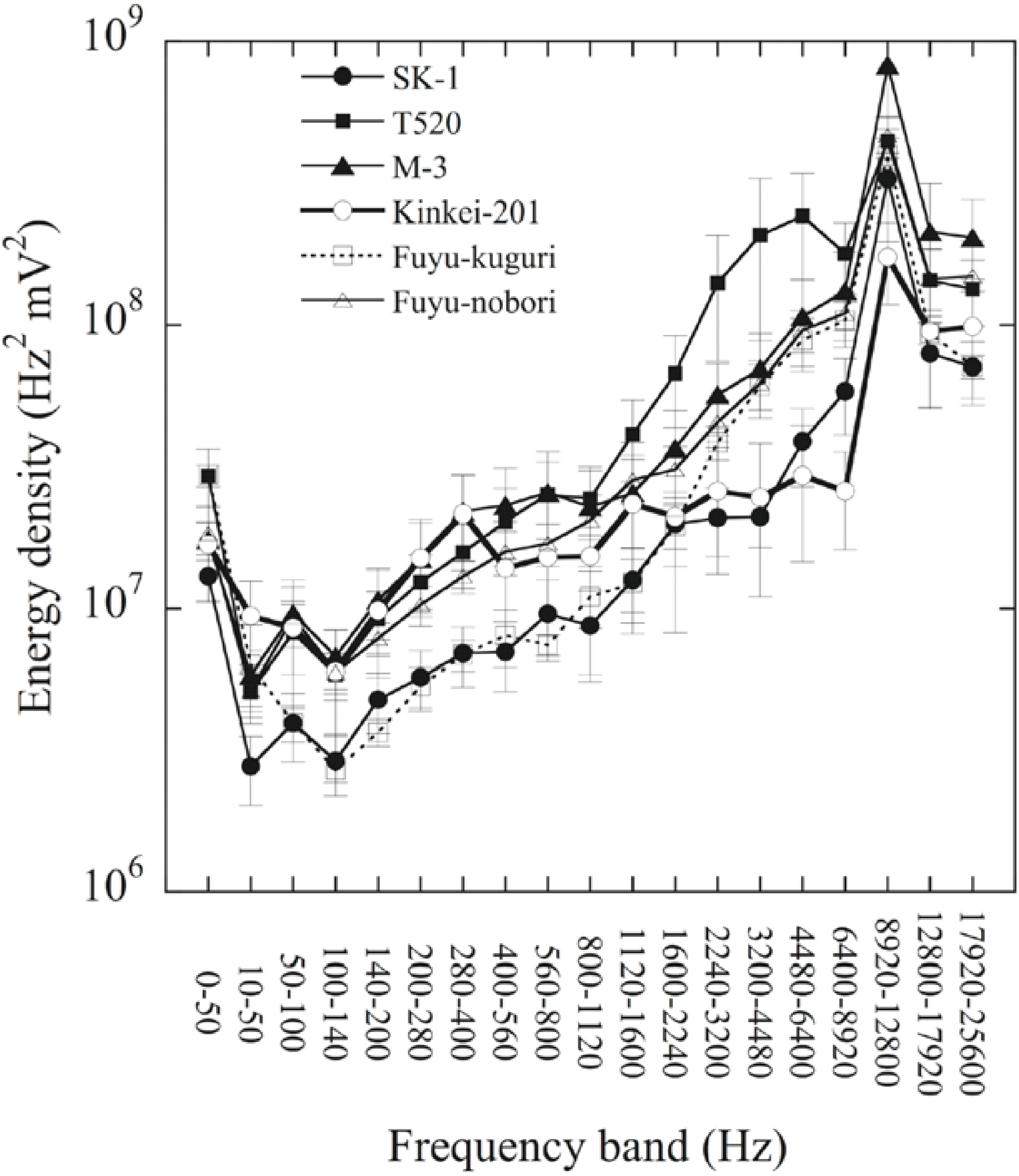

Fig. 4: Texture indices of the six cabbage cultivars. The bars indicate S.E. (n = 24 for SK-1 and Kinkei-201; n = 36 for other cultivars).

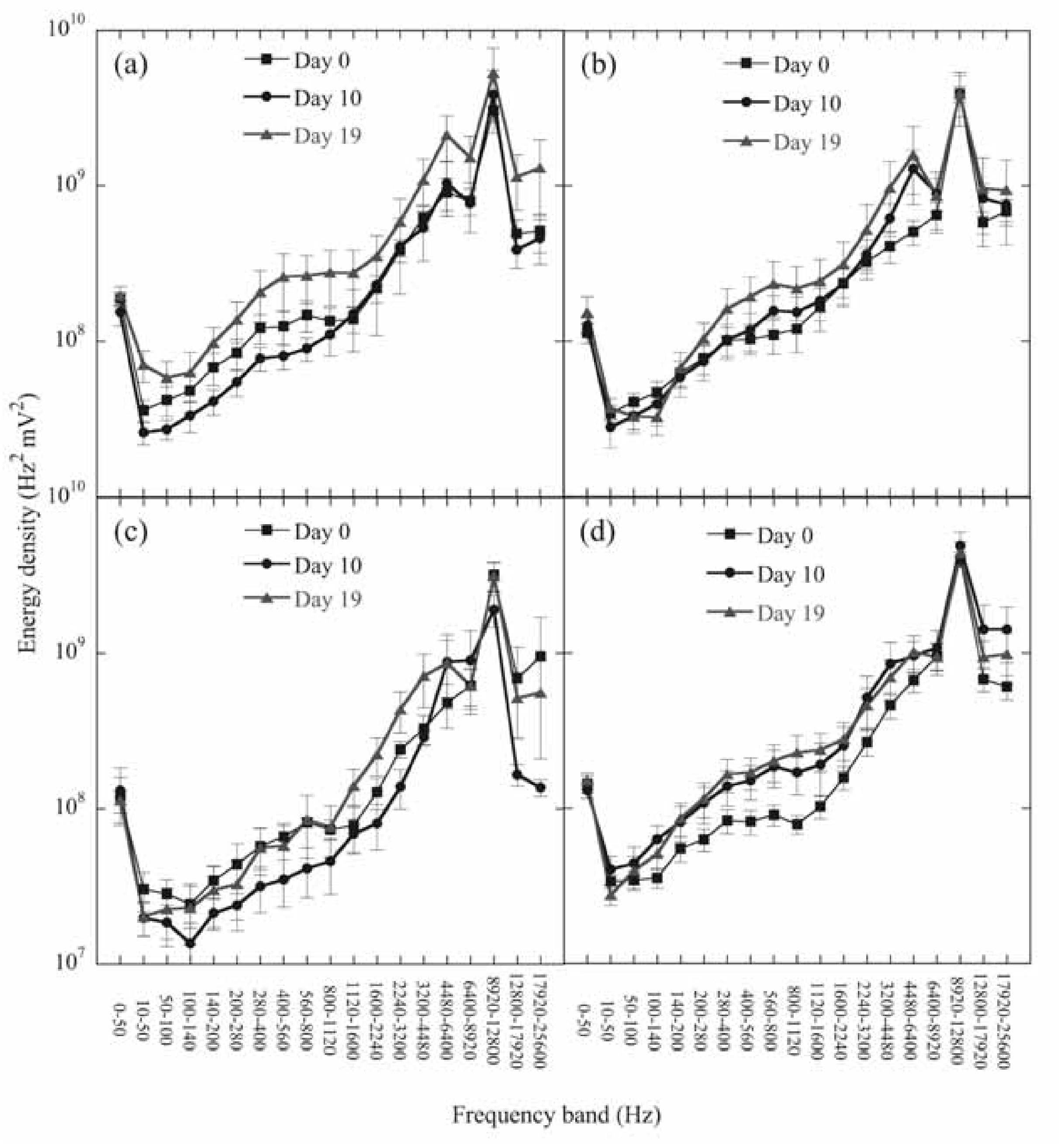

Fig. 5: Changes in the texture indices of the four cabbage cultivars after cold storage for 10 or 19 d: (a) T-520, (b) M-3, (c) Fuyu-kuguri, and (d) Fuyu-nobori. The bars indicate S.E. (*n* = 48 for T-520; *n* = 12 for Fuyu-kuguri; *n* = 60 for M-3 and Fuyu-nobori).

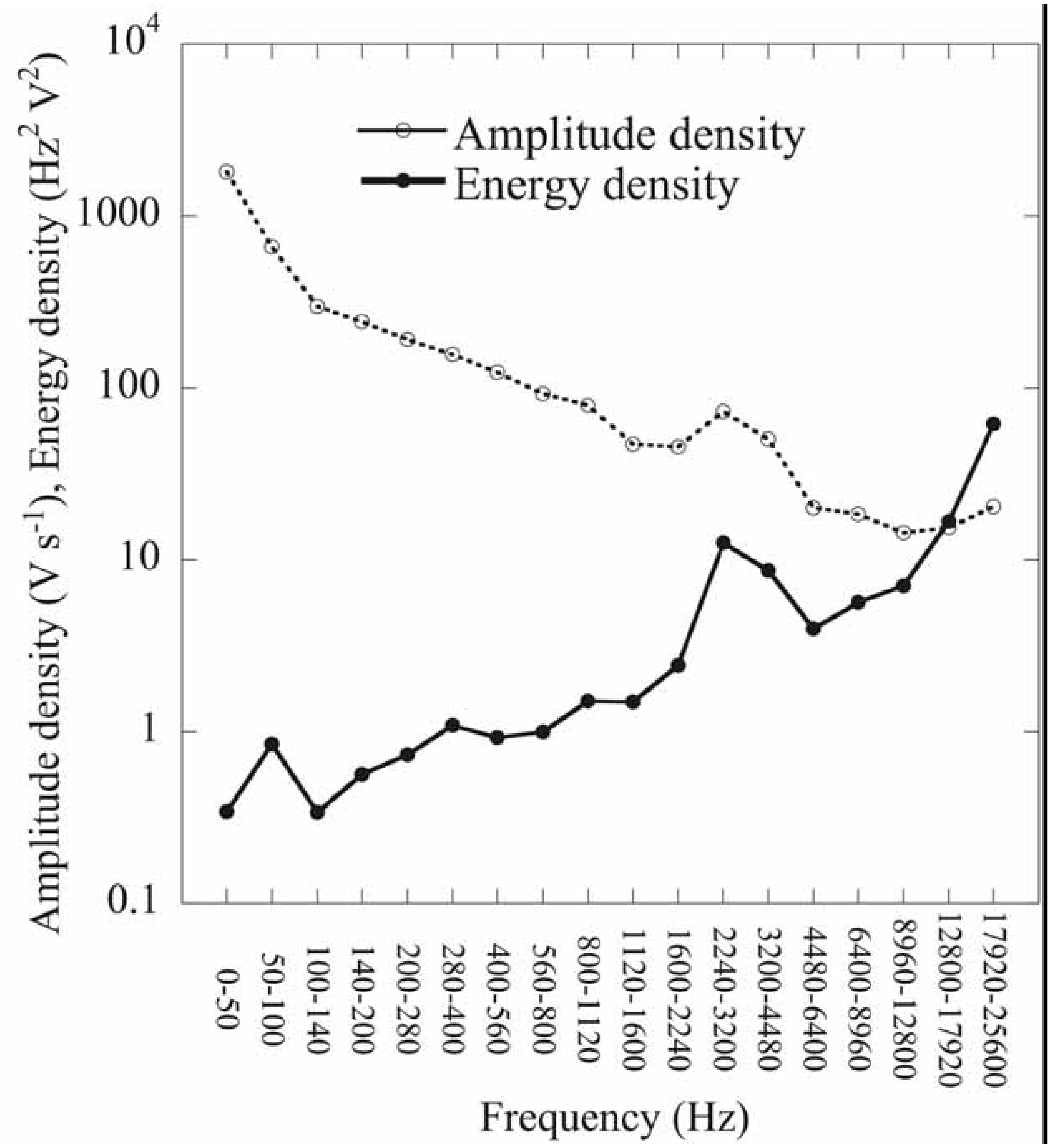

Fig.6: Comparison of the TI defined by the "energy density" with the "amplitude density". The "amplitude density" was defined by $(1/T)\sum|V_i|$, where T (s) was the time of sampling and V_i (V) was the amplitude of each data point (Taniwaki et al., 2006ab). The data was taken with an apple sample.

Table 1

Texture index level of different cabbage cultivars and their classification by the TI in different frequency band.

Cultivar	Frequency band (Hz)		
	10 - 1120	1120 - 8920	8920 - 25600
T-520	High ^{a}	High ^{a}	Middle ^{b}
M-3	High ^{a}	Middle ^{b}	High ^{a}
Fuyu-nobori	High ^{a}	Middle ^{b}	Middle ^{b}
Fuyu-kuguri	Low ^{b}	Middle ^{bc}	Low ^{c}
SK-1	Low ^{b}	Low ^{c}	Low ^{c}
Kinkei-201	High ^{a}	Low ^{c}	Low ^{c}

a, b, c: classification in each frequency band by the TI using ANOVA ($P < 0.05$).