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Effects of hot water treatment on electrical properties, cell membrane structure and texture of potato tubers

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ABSTRACT

Hot water treatment is a common procedure during the processing and cooking of fruit and vegetables. To establish a technique that enables quality estimation during processing, we investigated the effects of hot water treatment on the electrical properties, cell membrane structure and texture of potato tubers. After hot water treatment at 50, 60, 70, 80 and 90 °C, electrical impedance spectroscopy (EIS), confocal laser scanning microscopy (CLSM) and penetration tests were conducted. In addition, the EIS results were analyzed by use of an equivalent circuit. Obtained equivalent circuit parameters (intracellular resistance, extracellular resistance and cell membrane capacitance) increased or decreased with immersion time at high temperatures. CLSM images indicated that electrical changes were caused by cell membrane damage. Textural changes were strongly correlated with the equivalent circuit parameters. We suggest that EIS is useful to assess the degree of softening of potato during heating.

1. Introduction

Electrical measurements are expected to be useful for internal quality estimations of fruit, vegetables and other agricultural products. For example, cyclic voltammetry (CV) and electrical impedance spectroscopy (EIS) are typical methods. CV was reported to be relevant for the estimation of polyphenol levels and the evaluation of antioxidant capacity in tea, wine, juices and tomato (Kilmartin and Hsu, 2003; Makhotkina and Kilmartin, 2010, 2012; Sousa et al., 2004; Domenech-Carbo et al., 2015). However, this method can only be applied for liquid samples and it has limitations related to complex sample preparation and the use of specific reagents. On the other hand, EIS consists only of applying alternating electrical current to a target. Thus, it enables fast and easy measurement using solid materials. For these reasons, EIS has become an important means to assess the internal quality of fruit and vegetables.

Demand for precooked, frozen and dried vegetables has increased because of their storage stability and convenience. In addition, quality and safety management has become increasingly important with the development of production and processing systems. In these circumstances, EIS has enormous potential for real-time, non-destructive and convenient quality estimation for vegetables during processing. Although there are many reports about EIS with fruit and vegetables (Zhang and Willison, 1992; Harker and Dunlop, 1994; Inaba et al., 1995; Bauchot et al., 2000; Juansah et al., 2012), detailed studies on changes in electrical properties of vegetables during common processing steps such as heating and freezing are limited in number. To establish a helpful technique that enables quality estimation of materials during processing, understanding these changes and clarification of the mechanisms are essential.

Hot water treatment is often used before freezing, drying and canning of fruit and vegetables (Imaizumi et al., 2013; Machida et al., 2014). In addition, large amounts of precooked foods, such as simmered food (including Nimono; traditional Japanese cooking method for vegetables), potato salad, soup and curry, are consumed in Japan and undergo boiling. Hot water treatment is one of the most basic heating methods, thus estimation of the internal quality of vegetables during heating is important for the improvement of product quality and for efficient processing.

Because understanding about the electrical changes in vegetables during processing is important, our investigation focused on the effects of hot water treatment on electrical properties, cell structure and mechanical properties of potato tubers. Potatoes (*Solanum tuberosum* L.) are consumed all over the world. Thus, our study can provide information relevant for a wide range of countries. In this study, experimental data from EIS measurements

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Nomenclature

C_m	cell membrane capacitance	$\|Z\|_{app}$	approximated absolute impedance value
F_I	inner penetration resistance	$\|Z\|_{ave}$	average absolute impedance value
j	imaginary unit	ω	angular frequency
N	number of measurements	CI	cooling in iced water
p	constant phase element exponent	CLSM	confocal laser scanning microscopy
P_L	lower yield point	CNLS	complex nonlinear squares
R	resistance of sample	CP	cooling in iced water with a plastic bag
R^2	coefficient of determination	CPE	constant phase element
R_e	extracellular resistance	DiI	1,1′-dioctadecyl-3,3,3′,3′-tetramethylindocarbocyanine perchlorate
R_i	intracellular resistance	EIS	electrical impedance spectroscopy
T	constant phase element constant	NT	non-cooled fresh sample
X	reactance of sample	RMSE	root mean square error
Z	impedance of sample		
Z_{CPE}	impedance of constant phase element		

were analyzed by use of an equivalent circuit. The obtained parameters were evaluated using confocal laser scanning microscopy (CLSM) and the results of mechanical measurements.

2. Material and methods

2.1. Sample preparation

Potato (cv. May Queen) was used in the present study. Potato tubers were purchased from a local market and stored at room temperature until the experiment. Cylindrical samples, each of 29 mm diameter and 15 mm in thickness, were cut from the central part of potato tubers.

2.2. Effects of the cooling process on electrical properties

Processing of fruit and vegetables is required to operate under low temperature to avoid unnecessary chemical and biochemical reactions. Therefore, the material temperatures are decreased by washing and water cooling in whole process and also after blanching and sterilization. In this experiment, the influence of the cooling process on potato tissue was investigated. Raw samples were cooled down by immersion in iced water for 5 min (represented as CI). In addition, samples packed in a polyethylene bag were cooled in iced water for 10 min (CP). The internal temperatures of the samples decreased from 25 °C (±2 °C) (room temperature) to 5 °C (±2 °C) by CI and CP. The electrical properties of cooled and non-cooled samples were compared.

2.3. Effects of hot water treatment on electrical properties

For the hot water treatment, 200 mL of distilled water in a beaker was kept at 50, 60, 70, 80 or 90 °C (±0.5 °C) using a thermostatically controlled water bath (BO500, Yamato, Japan). Potato samples were heated in the beaker for 5–40 min, then immediately cooled down by immersion in iced water for 5 min. These samples were measured the electrical properties and the texture, then observed by CLSM.

2.4. Electrical impedance measurement

A schematic diagram of the EIS measuring system used in this study is shown in Fig. 1. Two needle electrodes (diameter: 0.25 mm) connected to a LCR tester (3532-50, HIOKI, Japan) were inserted into the sample. The impedance $|Z|$, resistance R and reactance X of the sample were measured at 100 points over the frequency range from 50 Hz to 5 MHz at a measuring voltage of 1 V, and automatically recorded by a computer for analysis. The measurement was replicated from 12 to 16 times.

2.5. Equivalent circuit analysis

The results of recent EIS studies suggested that the impedance spectra of plant tissue can be characterized by equivalent circuit models composed of resistors and capacitors representing plant cell structures (Wu et al., 2008). In particular, Hayden's model (Hayden et al., 1968; Juansah et al., 2012) (Fig. 2(a)) has been adopted in many kinds of plant tissues such as potato (Zhang and Willison, 1992), eggplant (Wu et al., 2008) and citrus (Juansah et al., 2012). Although this model assumes a structure of one cell, actual tissues are composed of many cells and each cell has a different dielectric relaxation behavior. Thus, Hayden's model has a risk of poor fitting accuracy with measured values. Ando et al. (2014) corrected for this by use of a constant phase element (CPE) (Abouzari Shoar et al., 2009; Clemente et al., 2014) instead of cell membrane capacitance (C_m) (Fig. 2(b)) in the equivalent circuit analysis of potato tissues. Therefore, we also used this CPE model and compared the fitting accuracy with Hayden's model. CPE is used to correct the distribution of dielectric relaxation time by non-uniformity of plant tissue, and it is represented as an imperfect capacitor. The impedance of CPE is calculated by the following equation:

$$Z_{CPE} = \frac{1}{(j\omega)^p T} \tag{1}$$

$$= \frac{\cos\left(\frac{\pi}{2}p\right)}{\omega^p T} - j\frac{\sin\left(\frac{\pi}{2}p\right)}{\omega^p T} \tag{2}$$

where j is an imaginary unit, ω is angular frequency, T is a constant and p is a CPE exponent ($0 \leqslant p \leqslant 1$). From the electrical circuit in Fig. 2(b) and Eq. (2), the complex impedance of the CPE model as a function of angular frequency can be derived from the equation below:

$$Z = \frac{R_e[1 + \omega^p T\{(2R_i + R_e)\cos(\frac{\pi}{2}p) + \omega^p T R_i(R_e + R_i)\}]}{\{\omega^p T(R_e + R_i)\}^2 + 2\omega^p T(R_e + R_i)\cos(\frac{\pi}{2}p) + 1} - j \times \frac{\omega^p T R_e^2 \sin(\frac{\pi}{2}p)}{\{\omega^p T(R_e + R_i)\}^2 + 2\omega^p T(R_e + R_i)\cos\left(\frac{\pi}{2}p\right) + 1} \tag{3}$$

where R_e is extracellular resistance and R_i is intracellular resistance. The equivalent circuit parameters (T, p, R_e, R_i) were estimated using complex nonlinear least squares (CNLS) curve fitting (Macdonald, 1992). To evaluate the goodness of fit, coefficients of determination