Journal of Food Engineering 121 (2014) 24–31

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Electrical impedance analysis of potato tissues during drying

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ARTICLE INFO

Article history:
Received 3 April 2013
Received in revised form 29 July 2013
Accepted 5 August 2013
Available online 14 August 2013

Keywords:
Electrical impedance spectroscopy
Potato tissue
Drying
Electrical equivalent circuit
Biological cell

ABSTRACT

We used electrical impedance spectroscopy (EIS) to explore the changes in the cell physiological status of potato tissues during hot air drying at 50–80 °C. The measured impedance data were analyzed using the modified Hayden model, which is an equivalent circuit model for cellular tissues. From the moisture content at the initial value to 1.0 (dry basis), focusing on the changes of equivalent parameters of the model, the cell membranes were apparently damaged by drying and heat stresses, and intracellular fluid leaked from the cells. At the moisture content less than 1.0, because of the destruction of cell structure, experimental data could not be fitted with the model, and due to the loss of moisture, the impedance magnitude increased rapidly as drying proceeded. These results showed the behavior of the cell physiological status of potato tissues during drying and the potential of EIS as a method for evaluating injuries to biological cells.

1. Introduction

Drying is a common processing for vegetables. The basic objectives when drying vegetables are to assure microbial stability and extend the shelf-life of the product. Even with the development of newer drying techniques, most vegetables are still air-dried because this method of dehydration remains the simplest and most economical (Mazza, 1983). However, during hot air drying, vegetables are exposed to heat stress for a long time, causing changes of color, nutrient content, flavor, mechanical properties, etc. Among these parameters, the physical properties are one of the most important factors affecting the quality of dried vegetables. The physical properties of vegetables are closely related to their cellular status.

For example, many studies have described the effects of cellular turgor and cell membrane status on physical properties (Virgin, 1955; Falk et al., 1958; Nilsson et al., 1958; Hiller and Jeronimidis, 1996). Blahovec and Lahodová (2011, 2012, 2013) conducted dynamic mechanical analyses of potato tissues and found that the changes of physiological properties at temperatures higher than 70 °C were due to the increase in cellular turgor caused by starch gelatinization. Laza et al. (2001) reported that the storage elastic modulus and the toughness of potato tissues were decreased by heating at 60 °C due to degradation of the middle lamella, cell wall, and plasmalemma while the starch in the potatoes were partially gelatinized.

As noted above, many studies have described changes in physical properties due to the changes in the cellular tissue status caused by heat and dehydration stress. In the drying of vegetables as well, physical parameters such as texture are important as a quality of products. Changes in the texture of vegetables during drying and rehydration processes have been reported (Lewicki and Jakubczyk, 2004; Troncoso and Pedreschi, 2007; Cunningham et al., 2008). These changes are likely to be due to the changes of cell status caused by heat and drying stresses. Quantitative determinations of cell status and cell damage during drying and rehydration processes will contribute to our understanding of the physical properties of dried vegetables.

Electrical impedance spectroscopy (EIS) measures the physical state of materials as a function of frequency. Dielectric analysis (DEA) is frequently confused with EIS, but although DEA is essentially similar to EIS, DEA measurement are generally conducted in high frequency areas (100 MHz–10 GHz are generally used) to estimate moisture content and bulk density, etc. (Nelson, 1994, 2005; Mckeown et al., 2012; Jha et al., 2011; Trabelsi and Nelson, 2006; Kandala et al., 1989). The frequency area in which the properties of cell structures appear is approx. 100 Hz–10 MHz, and EIS is often used in this frequency area.

In the present study therefore, we used EIS to evaluate the status of cells. Since EIS is a fast and simple technique, it has been widely used to estimate the physiological status of various biological tissues (Ando et al., 2012; Damez et al., 2007; Yamamoto and Yamamoto, 1976; Greenham, 1966). EIS generally makes use of electrical equivalent circuits of materials to characterize the

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http://dx.doi.org/10.1016/j.jfoodeng.2013.08.008

Nomenclature

C_m	capacitance of cell membrane
j	imaginary unit
M	moisture content
p	constant phase element exponent
R	resistance (real part of the impedance)
$\hat{R}$	approximated values of R
$\bar{R}$	average value of R
R_i	intracellular resistance
R_e	extracellular resistance
R_m	resistance of cell membrane
R_R^2	determination coefficient for R
R_X^2	determination coefficient for X
SD	standard deviation
T	constant phase element coefficient
X	reactance (imaginary part of the impedance)
$\hat{X}$	approximated values of X
$\bar{X}$	average value of X
Z	impedance of sample
Z_{CPE}	impedance of constant phase element
θ	phase angle
ω	angular frequency
EIS	electrical impedance spectroscopy
CPE	constant phase element
CNLS	complex non-linear least square
DEA	dielectric analysis

experimental frequency response of impedance. Physical properties of the materials can be quantified by monitoring the changes in parameters at the equivalent circuit. Among several equivalent models proposed to represent biological tissues (Zhang and Willison, 1991; Yamamoto and Yamamoto, 1977), we focus on the Hayden model proposed by Hayden et al. (1969). In this model, cellular structures (i.e., the cell membrane and extra and intracellular fluid) are represented by parameters of the electrical equivalent circuit.

The Hayden model has widely been applied to EIS analyses of various plant tissues, and its use has provided much useful physiological information about matters such as ripening (Juansah and Budiastra, 2012), cold injury (Cooley and Evert, 1979) and heat injury (Zhang et al., 1993). Although many EIS studies of plant tissue have focused attention on the natural physiological properties, there are few reports about the behavior of electrical impedance characteristics of vegetables during commonly used food processing techniques such as drying. The use of EIS for investigations of the cellular physiological status could provide valuable information about the physical qualities of the dried vegetables.

Here we applied EIS to potato tissues during hot air drying under several temperature conditions, and we examined the resulting changes in cellular status. We also investigated the impedance characteristics during the rehydration of dried samples to understand how the moisture content influences the impedance characteristics. The objectives of this study were: (1) to analyze the impedance characteristics of drying potato tissues in order to clarify the behavior of cells in plant tissues, and (2) to evaluate the effects of moisture content on the EIS results.

2. Materials and methods

2.1. Sample preparation

Since potato tubers are often used as a model plant tissue because of their homogeneity, we chose potatoes to use as the sample. Potatoes (*Solanum tuberosum* L.) of the variety of ‘Danshaku-imo’ were purchased from a local market and stored at room temperature before the experiment. ‘Danshaku-imo’ is a mealy-type potato with a relatively high starch content. The average moisture content of the fresh potatoes was 4.30 on a dry basis (g/g).

A schematic diagram of the experimental system used in this study is shown in Fig. 1. Samples were placed in a thermostatic chamber (SH-241, ESPEC, Osaka, Japan) and hot-air dried at 50 °C for 12 h, or 60 °C, 70 °C or 80 °C for 10 h (5–7 samples for each temperature). The relative humidity (RH) was kept under 10%. After specified drying times, the sample was taken out from the chamber and weighed. The decrease in the weight was taken as the amount of water evaporated. Soaking experiments were conducted at 30 °C water temperature for the samples dried at each temperature. Water absorption was performed by soaking a dried sample in a beaker containing 200 mL of distilled water. The beaker was placed in a thermostatically controlled water bath at the soaking temperature. At predetermined soaking time intervals, the sample was removed from the soaking water, blotted with filter papers to remove surface moisture, and weighed. The soaking experiment was repeated from three to four times and measured data were averaged. The moisture content M (dry basis (g/g)) of the samples was determined gravimetrically by drying the samples in the thermostatic chamber at 60 °C for 12 h, and then milling and drying them in an infrared drying moisture meter (EJ-610, A&D, Tokyo, Japan) at 100 °C for 30 min.

2.2. Impedance measurement

The impedance data of the samples were measured using an impedance analyzer (HP4194A, Hewlett-Packard) with steel needle electrodes (Fig. 2). The electrodes were connected to the impedance analyzer with coaxial cables by means of the four-terminal pair configuration (Agilent Technologies, 2013). The impedance magnitude $|Z|$ and phase angle θ of the sample were measured at predetermined times during drying and water absorption at 81 points (logarithmic frequency intervals) over the frequency range from 100 Hz to 10 MHz and automatically recorded by a computer for analysis. The impedance measurement during drying at each drying temperature was replicated from five to seven times, and the soaking experiment was repeated three to four times for the samples dried at each temperature.

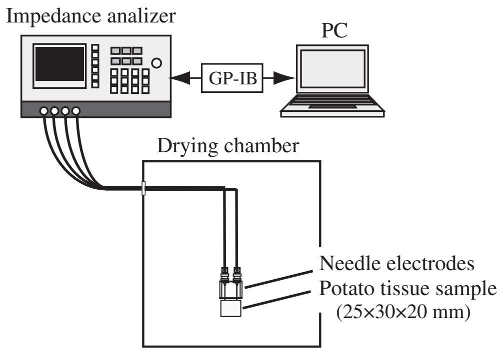

Fig. 1. The system for impedance measurement.