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Characterization of Vegetable Surface during Drying Using Fractal Analysis Technique

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Abstract. Combined fractal and image analysis technique was used to quantify the changes of vegetable surface characteristics during drying. Cabbage leaves were used as a test material and were allowed to undergo hot air drying, vacuum drying or low-pressure superheated steam drying (LPSSD) at 60 °C. Images of cabbage samples at time intervals during drying were obtained using a scanning electron microscope. An original image was transformed from gray scale to a black and white format. The fractal dimension (FD) of a black and white image was calculated using the box counting method. The changes of surface characteristics were quantified in terms of $\triangle FD/FD_0$. By comparing among the samples having similar moisture content, samples dried by hot air drying and vacuum drying exhibited more shrinkage (wrinkle) than those dried by LPSSD. The evolution of $\triangle FD/FD_0$ was found to relate well with % volumetric shrinkage of cabbage during drying.

Keywords: cabbage, fractal dimension, low-pressure superheated steam drying, vacuum drying

1. Introduction

Image analysis has been suggested to be one of the most promising techniques for the evaluation of the microstructural and textural changes of fresh foods and foods being processed [1], [2]. Among several image based analysis techniques, fractal analysis has caught attention of many researchers as it has proved to be adequately capable of characterizing the degree of irregularity of food microstructures or food surfaces [3], [4]. For example, Sansiribhan et al. [5] used the normalized change of fractal dimension to describe the changes of carrot cubes and intercellular spaces of carrot tissues during drying by using different methods, i.e., hot air drying, vacuum drying and low-pressure superheated steam drying (LPSSD).

In this study, an image analysis technique was developed and used to characterize the vegetable surface topographical feature during drying. It is important to note that leafy vegetable exhibit non-uniform surfaces and are structured with interconnected networks of veinlets or additional crinkle (or wrinkle) characteristics, making the characterization and, in particular, quantification, of the changes rather difficult. In this study, attempt was made to quantify the changes of the surface topographical features of vegetables as affected by drying methods (i.e., hot air drying, vacuum drying and low-pressure superheated steam drying (LPSSD)) at 60 ℃. Cabbage leaves were selected to represent the non-uniformity of the naturally topographical features of vegetables.

2. Materials and methods

2.1. Sample Preparation

White cabbages (*Brassica oleracea* var. capitata) were obtained from a local market (Pracha u-tid 61 Market, Bangkok, Thailand). Two to three outer leaves were removed; the remaining edible leaves of

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cabbages were washed with tap water for 2 min and cut into the sizes of 20×20 mm. The average thickness of the cabbage leaves was 1.5±0.3 mm.

2.2. Drying Experiments

Hot air drying experiments were conducted in a hot air oven (Termaks, model TS8000, Bergen, Norway). Three trays, each containing approximately 300 g of the cabbage sample, were prepared for each batch of the experiments. Drying experiments were conducted at 60 ℃ and at a constant air flow velocity of 0.8 m/s. The relative humidity of the ambient air (~30 ℃) was approximately 60–68%. The moisture content of a sample was determined using a standard gravimetric method [6].

Vacuum drying and low-pressure superheated steam drying (LPSSD) experiments were conducted in the same equipment but under different operating modes [7]. Approximately 30 g of the cabbage sample was placed as a single layer on a sample holder with the dimensions of 30×40 cm. The experiments were again performed at 60 ℃ at the absolute pressure of 10 kPa. The change of the sample mass was followed by means of a load cell.

2.3. Shrinkage Evaluation

Determination of the volumetric shrinkage was based on the concept of fluid replacement. Shrinkage is expressed in terms of the percentage change of the volume of a sample as:

$$\% \text{ Shrinkage} = \frac{V_i - V}{V_i} \times 100 \quad (1)$$

where V_i and V are, respectively, the initial and instantaneous (at any drying time t) volumes of the sample.

2.4. Fractal Analysis of Cabbage Surfaces

Cabbage sample was cut into the size of 5×5 mm. The sample was then treated with 2.5% (w/v) glutaraldehyde in 0.1 M phosphate buffer at pH 7.2 and left in a refrigerator (~ 4 ℃) overnight. The treated sample was washed twice with phosphate buffer and dehydrated sequentially for 10 min in aliquots of 30%, 50%, 70%, 90%, and 100% (v/v) of ethanol. The sample was then dehydrated in liquid CO_2 using a critical point dryer (Tousimis, model Samdri 780-A, Rockville, MD). The dehydrated sample was coated with gold in a sputter coater (Structure Probe, West Chester, PA). Finally, images of each sample was obtained using a scanning electron microscope (Jeol, model JSM-540LV, Tokyo, Japan) at 350× magnification. An original bitmap image was then cropped into the size of 720×720 pixels. Image processing was performed using ImageJ version 1.37c (Natl. Inst. of Health, Bethesda, MD). Each image was filtered by a rotationally symmetric Gaussian low-pass filter to diminish noise. The image was then transformed from gray scale (8-bit) to a black and white format before a calculation of the fractal dimension (FD) was performed. A suitable threshold used in this study was between 120 and 155. The fractal dimension of a black and white image (binary image) was calculated using the box counting method [3], again via the use of ImageJ. To express the changes of the surface characteristics of the cabbage sample, the changing values of *FD*, which represent the changing irregularity of the surfaces subjected to drying, are reported as:

$$\frac{\Delta FD}{FD_0} \quad (2)$$

$$\triangle FD = FD_t - FD_0,$$

where FD_0 and FD_t are the fractal dimensions of the fresh sample and of the sample at any instant during drying, respectively.

2.5. Experimental Design and Statistical Analysis

The experiments were conducted at three levels of the drying methods (hot air drying, vacuum drying and LPSSD) and one level of drying temperature at 60 ℃. A 2-factor factorial design was used to schedule the experiments. The effects of the drying methods and drying temperature were determined by univariate full-factorial analysis of variance (ANOVA) using MINITAB® software (version 14, State College, PA).

3. Results and discussion

Figure 1 shows the evolution of the moisture content of cabbage samples during drying in terms of X/X_0; where X and X_0 are the moisture content of sample at any sampling time and initial moisture content of sample, respectively. The initial moisture content of cabbage samples were approximately 18.62±0.36 g/g (dry basis, d.b.) (or 94.87±1.72% wet basis, w.b.). The sample moisture content decreased rapidly during the early period of drying. After that, the moisture content decreased at a much slower rate until reaching the equilibrium. It was observed that vacuum drying and LPSSD led to higher drying rates than hot air drying due to the reduced boiling temperature of moisture at a lower pressure. The vacuum drying rates were slightly higher than those of LPSSD. This might be due to the fact that during the first few minutes of LPSSD the samples gained a small amount of moisture due to steam condensation and hence the lower drying rates [7].

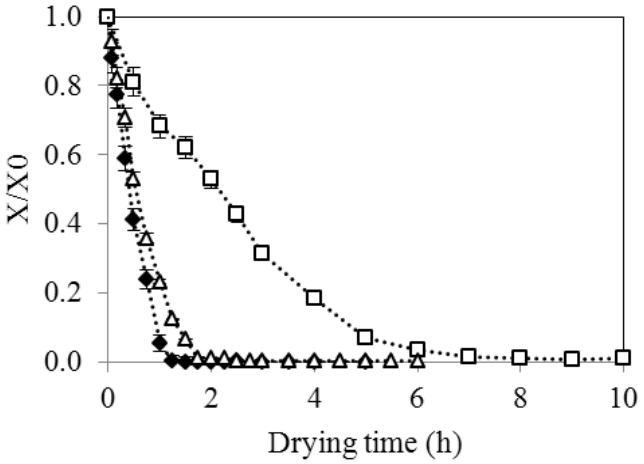

Fig. 1: Drying curves of cabbage samples at different conditions: (□) hot air drying; (◆) vacuum drying; (△) low-pressure superheated steam drying at 60 °C.

Figure 2 exemplifies the surface characteristics of cabbages during hot air drying. The intact surfaces of fresh cabbages appeared as a clear cell periphery and the network of venation was observed (Figure 2a). The degrees of wrinkle on cabbage surfaces were more pronounced at prolonged drying time (Figure 2b-Figure 2d). Similar trends were observed for vacuum drying and LPSSD (images not shown).

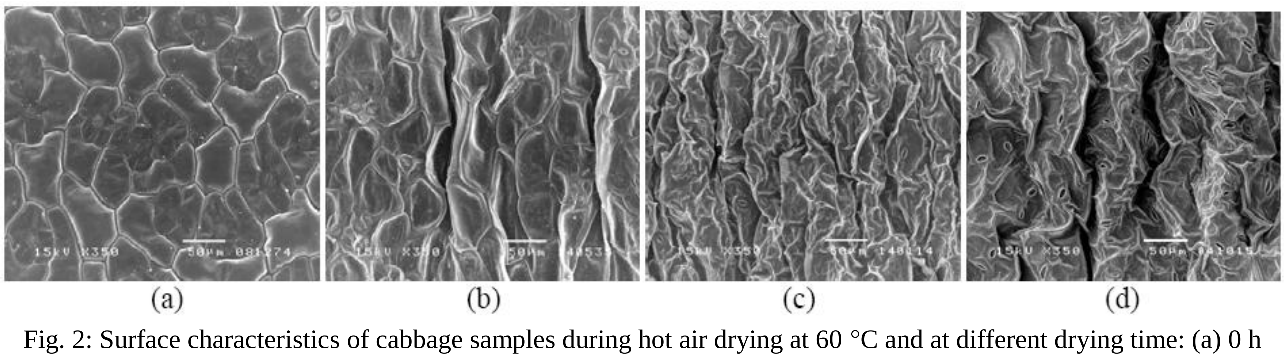

Fig. 2: Surface characteristics of cabbage samples during hot air drying at 60 °C and at different drying time: (a) 0 h (fresh cabbage); (b) 2 h; (c) 6 h; (d) 10 h.

The effects of drying methods on the surface characteristics of cabbages during drying are illustrated in Figure 3a, Figure 3b, Figure 3c. By comparing among the samples having similar moisture content, samples dried by hot air drying and vacuum drying exhibited more shrinkage (wrinkle) than those dried by LPSSD. A series of SEM images taken for the cabbage surfaces was converted into the binary images using an appropriate thresholding (Figure 3d, Figure 3e, Figure 3f). The areas appearing as black color indicated a background or a smooth surface, while the white areas represented the rough surfaces. FD of each binary image taken from different drying time was obtained and presented in terms of $\Delta FD/FD_0$. The relationship between $\Delta FD/FD_0$ and drying time are shown in Figure 4a. It is seen that $\Delta FD/FD_0$ increased sharply during an early period of drying and reached a certain value by the end of drying. It was also observed that LPSSD led to smaller values of $\triangle FD/FD_0$ than vacuum drying. This might be due to the more rigorous internal vaporization of moisture during the first period of LPSSD [7]. More extensive vaporization and hence more uniform moisture movement within the sample structure led to a decrease in the moisture-gradient induced stresses, which resulted in the lower FD [4]. The changes of the volumetric shrinkage of cabbage samples undergoing different drying methods and conditions are shown in Figure 4b; similar patterns of changes in $\triangle FD/FD_0$ were observed.

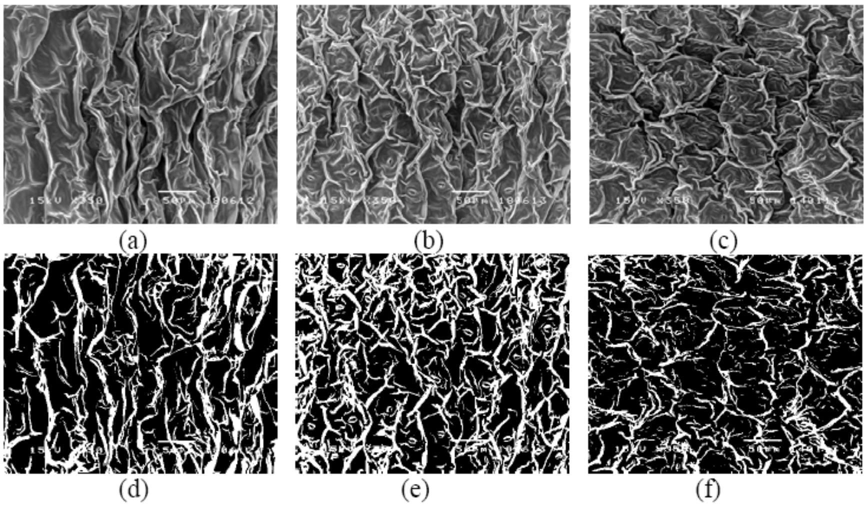

Fig. 3: Surface characteristics of cabbage samples (a, b, c) and their binary images (d, e, f) undergoing hot air drying (a, d), vacuum drying (b, e) and LPSSD (c, f) at 60 °C (all micrographs were compared for the samples having similar final moisture content of 0.10 g/g d.b.).

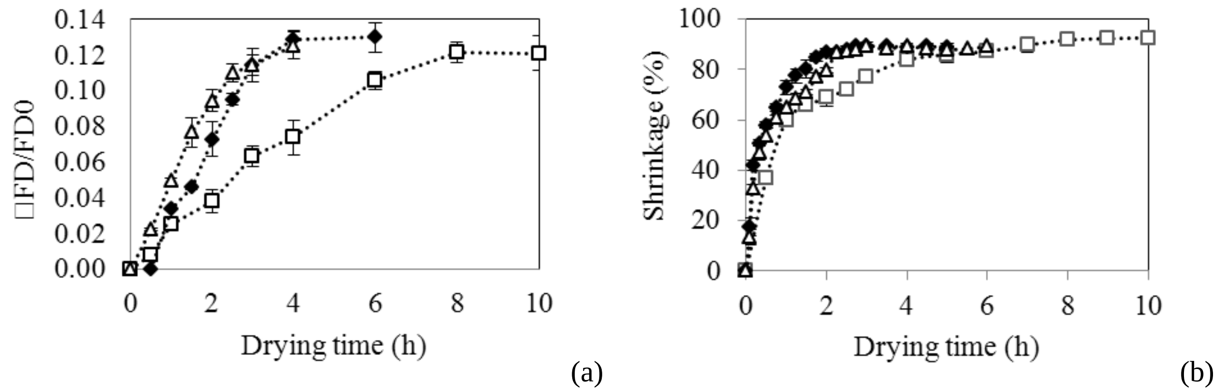

Fig. 4: $\triangle FD/FD_0$ (a) and % shrinkage of cabbage samples during drying: (□) hot air drying; (◆) vacuum drying; (△) low-pressure superheated steam drying at 60 °C.

The relationship between % shrinkage and $\triangle FD/FD_0$ is shown in Figure 5. $\triangle FD/FD_0$ increased with increasing shrinkage during drying. At prolonged drying time when the moisture content of the samples approached the equilibrium, no more water was removed from the plant cells. This led to a rather constant volume of the sample and hence reflected by the unchanged volumetric shrinkage values at approximately 89-91%. While the changes in volumetric shrinkage were no longer detected, the changes in $\triangle FD/FD_0$ still continued. Equation 3 was proposed to represent the relationship between $\triangle FD/FD_0$ and % shrinkage of cabbages undergoing hot air drying, vacuum drying and LPSSD:

$$\%\ \text{Shrinkage} = 20.22\ln(\Delta FD/FD_0)+128.01 \quad (3)$$

The high R^2 (0.912) values imply that $\triangle FD/FD_0$ was capable for monitoring volumetric change of cabbage sample during drying.

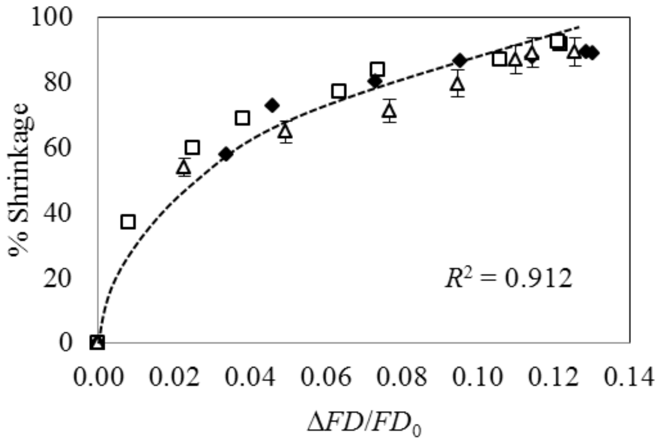

Fig. 5: Relationship between % shrinkage and $\triangle FD/FD_0$ during hot air drying (☐), vacuum drying (◆) and low-pressure superheated steam drying (△).

4. Conclusion

The effects of drying methods and conditions on the vegetable surface characteristics during drying were investigated. An image analysis technique, which could be used to quantitatively describe the surface characteristics of vegetable during drying, was developed in this study. The results showed that drying methods and conditions had a significant effect on the moisture content, % shrinkage as well as fractal dimension. It was found that the evolution of the normalized changes of fractal dimension ($\triangle FD/FD_0$) could relate well with the degree of shrinkage of product during drying.

5. Acknowledgments

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