

Analysis of Changes in Moisture Content and L-Ascorbic Acid of Sweet Potatoes during Hot Air Drying

Takahiro ORIKASA*, Takeo SHIINA¹, Akio TAGAWA²

Abstract

Changes in moisture contents and L-ascorbic acid of sweet potatoes during hot air drying were investigated at temperatures of 30, 40, 50, and 60°C. The drying process was evaluated using measured moisture content data of the drying test. The measured data was fitted to a combination of the exponential drying model and an infinite plane sheet model for the diffusion equation. The empirical moisture content changes agreed well with the models. An Arrhenius-type equation was used to estimate the temperature dependency of the diffusion coefficient of sweet potatoes. Changes in the L-ascorbic acid content of sweet potatoes during hot air drying were analyzed using a first-order reaction rate equation to model changes in the decomposition of the L-ascorbic acid content. The activation energy required for the decomposition reaction during the hot air drying of sweet potatoes was estimated to be 48.8 kJ mol⁻¹.

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Key words : sweet potato, hot air drying, moisture content, L-ascorbic acid, Arrhenius-type equation

1. Introduction

The sweet potato (*Ipomoea batatas Lam.*) is an important agricultural product; it is one of the most efficient food crops in terms of caloric value per area cultivation and is relatively easy to grow, even in poor, dry soil (Antonio et al., 2008). The sweet potato greatly contributes to the nutritional needs of the human diet by providing at least 90% of daily dietary requirements, except protein and niacin (Bouwkamp, 1985), because the root portion of the plant is rich in not only β -carotene, food fiber, and potassium ions (Lin et al., 2005) but also carbohydrate and fat. Sweet potatoes must be consumed within a few weeks after they are harvested or must be dried to lower the moisture content for long-term storage (Diamante and Munro, 1991). Hot air drying has been used as a simple and common method for drying fruits and vegetables (Ogura, 1993; Leonid et al., 2006). Although some studies described the hot air drying characteris-

tics of other fruits and vegetables with high moisture contents, such as tomatoes (Doymaz, 2007), apples (Sjoholm and Gekas, 1995), kiwifruits (Orikasa et al., 2008), garden beets, and carrots (Pabis and Jaros, 2002), a suitable drying model for sweet potatoes has not yet been established.

The change in nutrient content during drying is an important factor in the production of high-quality dried products. The sweet potato is rich in L-ascorbic acid, a functional nutrient constituent. However, the amount of L-ascorbic acid in sweet potatoes decreases with drying time, and details concerning the changes in L-ascorbic acid of sweet potatoes during hot air drying have not yet been reported. The objectives of this study were as follows: (1) To investigate the hot air drying characteristics of sweet potatoes; (2) evaluate a suitable drying model for sweet potatoes using moisture content data; and (3) analyze changes in the L-ascorbic acid content of

¹ National Food Research Institute

² Graduate School of Horticulture, Chiba University

* Corresponding author (E-mail : orikasa@myu.ac.jp)

sweet potatoes during hot air drying.

2. Materials and methods

2.1. Materials

Sweet potatoes were purchased from a local market and stored in a refrigerator at 15°C until needed. The initial moisture content of the sweet potatoes, which was measured using a method that uses film with diatomite (Japan Food Research Laboratories, 1973), was 1.94 ± 0.09 on a dry basis (d.b., decimal) ($= 0.645 \pm 0.001$ on a wet basis) ($n = 10$). The experimental samples consisted of rectangular blocks of $50 \times 20 \times 10$ mm cut from the center of each sweet potato.

2.2. Hot air drying test

Drying tests [from the initial moisture content to 0.5 (d.b., decimal)] were carried out at temperatures of 30, 40, 50, and 60°C using a hot air drying chamber (WFO-700, EYELA, Japan). The air velocity during drying was 0.3 m s^{-1} , and the chamber volume was 700 L. The samples were weighed with a digital balance at 0.5-h intervals, and the moisture content was calculated (d.b., decimal). The moisture ratio, MR , of each sample was determined using the following equation:

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (1)$$

Orikasa et al. (2010) reported that equilibrium moisture contents of sweet potatoes during hot air drying at temperatures of 30, 40, 50, and 60°C were 0.115, 0.049, 0.038, and 0.029, respectively. These values were substituted in equation (1) to estimate the moisture ratio, MR , for this study. Drying tests at each predetermined temperature were repeated three times.

2.3. L-Ascorbic acid content

L-ascorbic acid was measured according to the method of Nishiyama and Oota (2005). A reflection photometer (RQ-flex-plus, Merck, Japan) was used to measure the L-ascorbic acid content [mg/100 g fresh weight] in the sample material. The L-ascorbic acid

contents of the samples were measured at five or six moisture content levels from the initial moisture content to approximately 0.5 (d.b., decimal) at temperatures of 30, 40, 50, and 60°C. Total quantities of L-ascorbic acid in the test samples [mg] were calculated by multiplying the measured content [mg/100 g fresh weight] by the initial sample weight [g]. L-ascorbic acid contents were considerably different between samples. In this study, changes in L-ascorbic acid content were evaluated using the residual ratio of L-ascorbic acid content, which was defined as the value obtained by dividing the total quantity of L-ascorbic acid in a dried sample by the total quantity of L-ascorbic acid in the initial sample before drying. Measurements of each sample at each predetermined temperature were repeated three times.

2.4. Data analysis

Analysis of variance (ANOVA) was conducted using Microsoft Excel to determine the effect of variable data on drying parameters. The LSD multiple range test method at a significance level of 0.05 was used when a difference in means was detected. The parameters of equations (3), (4), and (5) were estimated by the nonlinear least squares method using Visual Basic for Applications (VBA) and Microsoft Excel.

3. Results and discussion

3.1. Hot air drying characteristics of sweet potatoes

In this study, the diffusion theory was used to model the drying of sweet potatoes. The solution of the diffusion equation is an infinite series (Crank, 1975), as shown in the following equation:

$$\frac{M - M_e}{M_0 - M_e} = \sum_{i=0}^{\infty} B_i \exp(-D\lambda_i^2 t) \quad (2)$$

The infinite series on the right side of equation (2) rapidly converges to the first term when the Fourier number ($F_0 = Dt/l^2$) becomes large, yielding equation (3):

$$\frac{M - M_e}{M_0 - M_e} = B_1 \exp(-D\lambda_1^2 t) = B_1 \exp(-k_2 t) \quad (3)$$

The relationship between the moisture ratio, MR , and drying time is plotted on a semilogarithmic scale. The parameter B_1 in equation (3) is the intercept on the MR axis (logarithmic axis). Figure 1 shows that a linear relationship is obtained for the first few hours of drying [from an approximate moisture content of 1.1 (d.b., decimal) to the final stage of drying], and the intercept, B_1 , is approximately 0.8. Using the measured moisture content, the parameter B_1 in equation (3) at the four predetermined temperatures was determined through the nonlinear least squares method (Deming method). The determined values for parameter B_1 were 0.87, 0.81, 0.85, and 0.86 at 30, 40, 50, and 60°C, respectively (RMS = $0.814 \times 10^{-3} \sim 2.364 \times 10^{-3}$). In contrast, B_1 in equation (3) during the first few hours [from initial moisture content to approximately 1.1 (d.b., decimal)] was estimated to be approximately 1.0. Substituting $B_1 = 1.0$ into equation (3) corresponds to the following exponential model [equation (4)]:

$$\frac{M - M_e}{M_0 - M_e} = \exp(-k_1 t) \quad (4)$$

Values for B_1 in equation (3) for a sphere model, an infinite plane sheet model, and an exponential model

are $6/\pi^2 = 0.61$, $8/\pi^2 = 0.81$, and 1.0, respectively (Tagawa et al., 2003). In this study, the exponential model as a drying model with moisture content ranging from the initial value to approximately 1.1 (d.b., decimal) and the infinite plane sheet model for the diffusion equation from approximately 1.1 (d.b., decimal) to the final stage of drying were used for the drying model of sweet potatoes during hot air drying.

3.2. Modeling the hot air drying process for sweet potatoes

The moisture content change in sweet potatoes ranging from the initial value to approximately 1.1 (d.b., decimal) was modeled with the exponential model [equation (4)] because the value of B_1 in equation (3) for this period was around 1.0. The parameter k_1 in equation (4) was determined by a least squares method using measured moisture content data. Table 1 shows the calculated values for parameter k_1 in equation (4) at the four predetermined temperatures. Figure 2 compares the measured and calculated results from equation (4). The solid lines in Fig. 2 represent the calculated results from equation (4). The measured results agree well with the calculated results [RMS = 0.005 – 0.030 (d.b., decimal)].

From approximately 1.1 (d.b., decimal) to the final stage of drying, an infinite plane sheet model was

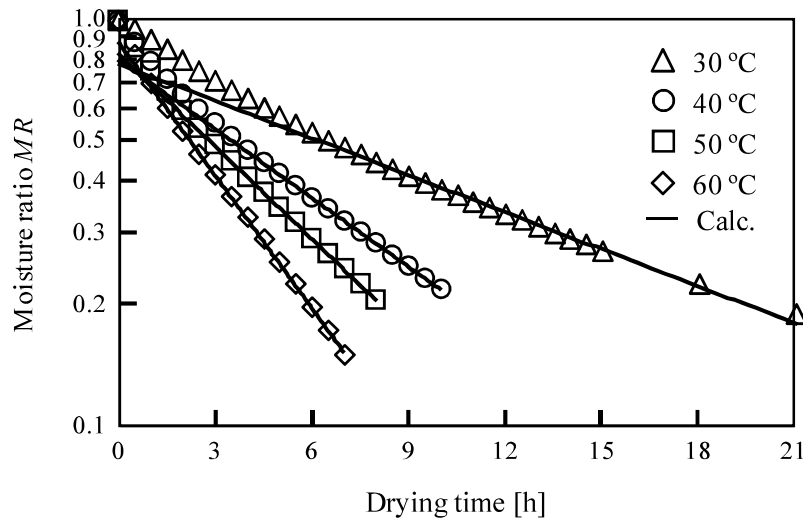


Fig. 1. Relationship between the moisture ratio MR and the drying time of sweet potato during hot air drying.

Table 1 Calculated values of parameter k_1 , k_2 and Me the root mean square error (RMS) for equation (3) and (4)

Temperature [°C]	Equation (3)		Equation (4)		
	k_1 [h ⁻¹]	RMS [decimal (d.b.)]	k_2 [h ⁻¹]	Me [decimal (d.b.)]	RMS [decimal (d.b.)]
30	0.11	0.005	0.07	0.111	0.020
40	0.20	0.021	0.13	0.030	0.011
50	0.26	0.020	0.16	0.023	0.014
60	0.32	0.030	0.22	0.018	0.016

used for the diffusion equation to predict the change in moisture content of the sweet potatoes. The solution to the diffusion equation for an infinite plane sheet model is given by equation (5) (Crank, 1975):

$$\frac{M - M_e}{M_0 - M_e} = \sum_{i=0}^{\infty} \frac{8}{(2i+1)^2 \pi^2} \exp\left\{-\frac{D(2i+1)^2 \pi^2 t}{4l^2}\right\} \quad (5)$$

$$= \sum_{i=0}^{\infty} \frac{8}{(2i+1)^2 \pi^2} \exp\{- (2i+1)^2 k_2 t\}$$

where k_2 is equal to $D\lambda_1^2 = (D\pi^2)/(4l^2)$ and $\lambda_1 l = \pi/2$. The parameters k_2 and Me in equation (5) were determined by a nonlinear least squares method (false position method) (Tagawa et al., 2003) using the measured moisture content data from the sweet potato samples. Table 1 shows the calculated values of parameters k_2 and Me for equation (5). Figure 2 shows the comparison between the measured and

calculated results from equation (5) for the sweet potatoes. The dashed lines in Fig. 2 represent the calculated results from equation (5). The measured results agree well with the calculated results [RMS = 0.011 – 0.020 (d.b., decimal)]. The results support the notion that the drying process for the sweet potato samples from approximately 1.1 (d.b., decimal) to the final stage of drying is in the second falling rate period and that the drying characteristic can be explained using the infinite plane sheet model. Hence, changes in the moisture content of the sweet potato samples during hot air drying were well estimated by a combination of an exponential model and an infinite plane sheet diffusion model.

The diffusion coefficient, D , has been extensively used to evaluate the fundamental parameters of the drying process (Wu et al., 2007). The diffusion

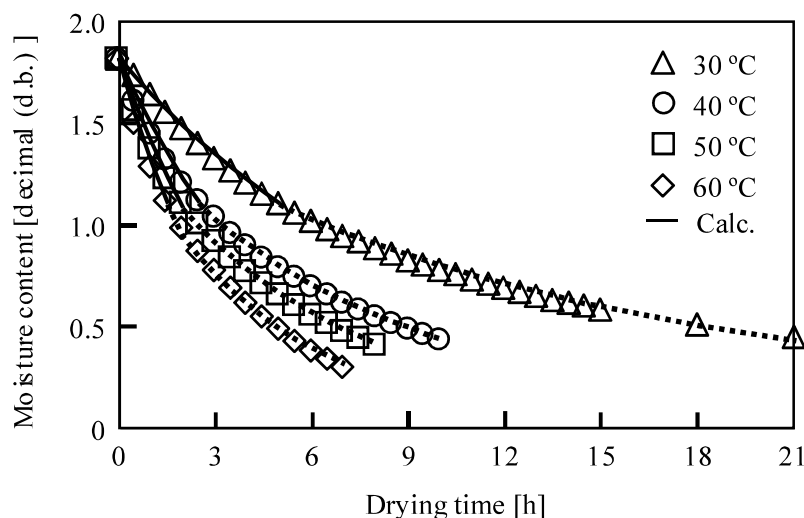


Fig. 2. Comparison of measured and calculated results from equations (3) and (4) for sweet potato.

The solid line represents data calculated using equation (3)

The dashed line represents data calculated using equation (4)

coefficient, D , was estimated using the assumption that the half-thickness, l (l = half-thickness for an infinite plane = 3.5 mm from the previous measurement), is constant within the examined range. The calculated D values were 0.95×10^{-10} , 1.73×10^{-10} , 2.23×10^{-10} , and $3.09 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$ for the drying temperatures of 30, 40, 50, and 60°C , respectively.

The temperature dependency of the diffusion coefficient, D , is expressed by the following Arrhenius-type equation (Pinaga et al., 1984):

$$D = D_0 \exp\left(-\frac{E}{RT}\right) \quad (6)$$

The parameters D_0 and E in equation (6) were determined by a least squares method using the estimated diffusion coefficient, D , for the hot air drying of sweet potatoes. The calculated constants were $D_0 = 3.17 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ and $E = 31.8 \text{ kJ mol}^{-1}$. Figure 3 shows the relationship between the diffusion coefficients and the reciprocal of absolute temperature for sweet potatoes. The calculations from equation (6) agree well with the diffusion coefficient values. The results confirmed that an Arrhenius-type equation is useful for describing the relationship between the diffusion coefficient, D , and the absolute temperature, T , for sweet potatoes.

3.3. Residual ratio of L-ascorbic acid content

The residual ratio of L-ascorbic acid content decreased as drying time increased. Hosaka (1972) demonstrates that the decomposition reaction for L-ascorbic acid may be represented by a first-order reaction. Therefore, the measured residual ratio during drying was applied to the first-order reaction rate equation, as follows:

$$\frac{dx}{dt} = k'(1-x) \quad (7)$$

Equation (7) can be solved under the initial condition of $x = 0$ to $t = 0$; thus, equation (8) is given as follows:

$$\ln \frac{1}{1-x} = k't \quad (8)$$

A least squares method was applied to equation (8) with a measured residual ratio. The estimated decomposition rate coefficient, k' , was 0.020, 0.038, 0.071, and 0.111 h^{-1} at 30, 40, 50, and 60°C , respectively. The values for k' increased as drying temperature increased. The temperature dependency of k' was examined using the following equation:

$$k' = d \cdot \exp\left(-\frac{E}{RT}\right) \quad (9)$$

The constant, d , and the activation energy, E , in

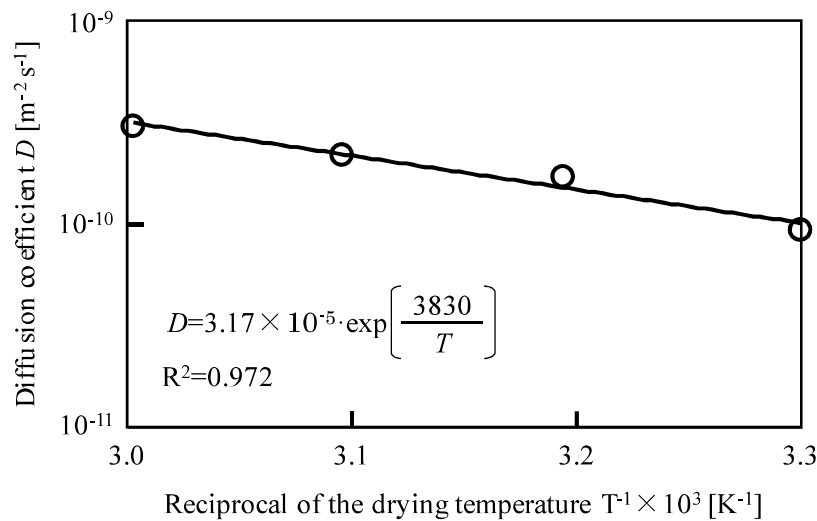


Fig. 3. Arrhenius relationship for the diffusion coefficients of moisture in sweet potato.

equation (9) were determined by a least squares method using the decomposition rate coefficient, k' . The calculated d and E values were $5.22 \times 10^6 \text{ h}^{-1}$ and 48.8 kJ mol^{-1} , respectively. Figure 4 shows the Arrhenius relationship for the decomposition rate coefficient, k' . Figure 4 confirms that an Arrhenius-type equation [equation (9)] was applicable to the relationship between the decomposition rate coefficient, k' , and the drying temperature, T , for the hot air drying of sweet potatoes. These experimental results could contribute the production of high quality dried sweet potato and to the development of drying theory for sweet potato.

4. Conclusions

Drying characteristics of sweet potato samples after hot air drying were investigated. The predicted drying model of the samples was also considered, and changes in L-ascorbic acid content of the samples during hot air drying were examined. The conclusions are summarized as follows:

- 1) Moisture content changes in the sweet potato samples during hot air drying were predicted by a combination of an exponential drying model and an infinite plane sheet model for the diffusion equation.
- 2) The diffusion coefficient, D , was related to the drying temperature by an Arrhenius-type

equation, and the activation energy for moisture diffusion was estimated to be 31.8 kJ mol^{-1} .

- 3) The decomposition rate coefficient, k' , for L-ascorbic acid content depended on the drying temperature. The activation energy for the decomposition of L-ascorbic acid was estimated to be 48.8 kJ mol^{-1} using an Arrhenius-type equation.

Nomenclature

B	shape factor (decimal)
d	parameter of equation (9)
D	diffusion coefficient [$\text{m}^2 \text{ s}^{-1}$]
D_0	constant equivalent to the diffusivity at infinitely high temperature [$\text{m}^2 \text{ s}^{-1}$]
E	activation energy [kJ mol^{-1}]
k_1	drying constant of first falling rate period [h^{-1}]
k_2	drying constant of second falling rate period [h^{-1}]
k'	decomposition rate coefficient for the L-ascorbic acid content [h^{-1}]
l	characteristic length [m]
M	moisture content (d.b. decimal)
Me	equilibrium moisture content (d.b. decimal)
M_0	initial moisture content (d.b. decimal)
MR	moisture ratio (decimal)
R	universal gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$)
RMS	root mean square

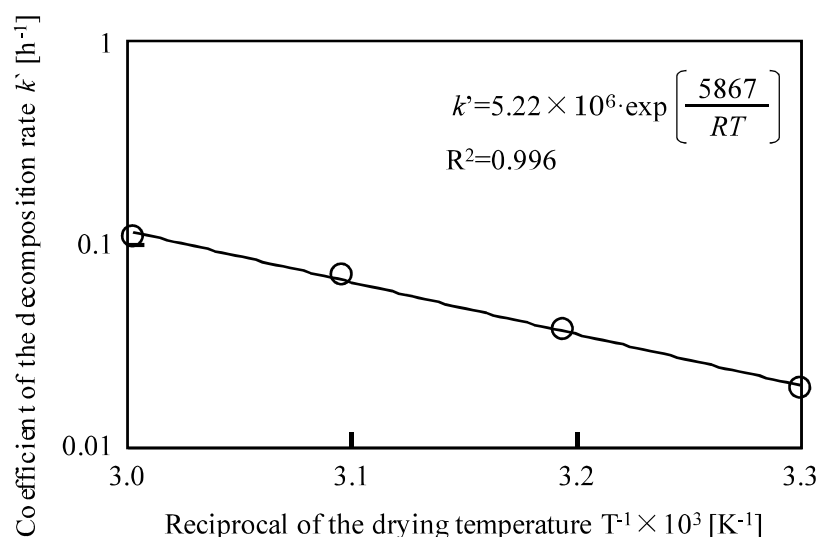


Fig. 4. Arrhenius relationship for the decomposition rate coefficient k' of ascorbic acid in sweet potato.

T	absolute temperature [K]
t	drying time [h]
x	residual ratio of L-ascorbic acid decreased after t h (decimal)
λ	characteristic value [m^{-1}]

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サツマイモの熱風乾燥における含水率およびL-アスコルビン酸の変動解析

折笠 貴寛*・椎名 武夫¹・田川 彰男²

要 旨

30, 40, 50および60°Cの温度条件下において, サツマイモの熱風乾燥を行い, サツマイモ乾燥試料の含水率変化およびL-アスコルビン酸変化について調査した。含水率変化は指数モデルおよび拡散方程式の無限平板モデルにより解析され, 両モデルより得られた計算値と測定値は良く一致した。含水率モデルより得られた拡散係数には, アレニウス型の温度依存性が認められた。熱風乾燥過程におけるL-アスコルビン酸変化は1次反応に従うことが示され, サツマイモの熱風乾燥過程におけるL-アスコルビン酸分解の活性化エネルギーは48.8 kJ mol⁻¹と算定された。

キーワード：サツマイモ, 熱風乾燥, 含水率, L-アスコルビン酸, アレニウス式

¹ 独立行政法人農業・食品産業技術総合研究機構 食品総合研究所

² 千葉大学大学院園芸学研究科