Change in dielectric properties of sweet potato during microwave drying

Dongyoung Lee¹ · Changyeun Mo² · Chang Joo Lee³ · Seung Hyun Lee¹

Received: 26 April 2018 / Revised: 13 November 2018 / Accepted: 27 November 2018 / Published online: 8 December 2018
© The Korean Society of Food Science and Technology 2018

Abstract Sweet potato slices and strips (thickness of 6 and 9 mm, respectively) as single layer were dried at different microwave power levels (90 W to 900 W) in order to determine the effect of microwave power and sample shape on drying characteristics. Dielectric properties of sweet potato slices were measured during microwave drying. Drying time for both samples was decreased with increase in microwave power, and drying time of strips was longer than slices in the microwave power range between 90 and 720 W. Page model was suitable for describing experimental drying data regardless of microwave power and shape of sweet potato samples. Dielectric properties of sweet potato slices were decreased with a decrease in moisture content. The change in dielectric properties of sweet potato slices could be predicted by Henderson and Pabis model and could be applied to estimate the change in moisture content of sweet potato during microwave drying.

Keywords Sweet potato · Microwave drying · Drying models · Dielectric properties

Introduction

Sweet potato is an important food crop containing high nutritional components such as β -carotene and polyphenols. Since sweet potato is rich in nutritional components, it has been widely used to produce diet food and dried sweet potato products have gained popularity with consumers as healthy food. However, sweet potato is easy to be perishable and damaged because it has high moisture content and relatively thin and delicate skin (Ahmed et al., 2010). Although a variety of preservation methods for minimizing damage of sweet potato during storage periods such as modified atmosphere packaging and edible coatings on its surface have been suggested by a number of researchers (Ehivet et al., 2011; Gorris and Peppelenbos, 1992), these methods are complicated or expensive to store sweet potato for a certain time.

Drying is known as the simplest and low-cost method to preserve agricultural products by removing moisture content in agricultural products and foods. Since dielectric heating such as radio frequency (RF) and microwave heating can be generated inside food materials by frictional energy resulting from dipolar relaxation and ionic conduction in the applied electric field, it can be employed to dehydrate water inside food materials within a short time (Wang et al., 2009). Microwave drying offers significantly increased drying rate and better quality of a dried product as compared with hot air drying (Yan et al., 2013). Therefore, continuous microwave drying system has been widely investigated and applied to dry large volumes of agricultural products in commercial food industry sites (Wang et al., 2011).

Dielectric properties [also known as permittivity (ϵ), DP] of agricultural products should be determined to understand the interaction between electromagnetic energy

✉ Seung Hyun Lee
seunglee2@cnu.ac.kr

¹ Department of Biosystems Machinery Engineering, College of Agricultural and Life Science, Chungnam National University, 99 Daehak-ro, Yuseong-gu, Daejeon 34134, Republic of Korea

² National Institute of Agricultural Sciences, Rural Development Administration, 310 Nonsaengmyeong-ro, Wansan-gu, Jeonju-si, Jeollabuk-do 54875, Republic of Korea

³ Department of Food Science and Biotechnology, College of Life Resource Science, Wonkwang University, 460 Iksandae-ro, Iksan, Jeonbuk 54538, Republic of Korea

from microwaves and agricultural product during microwave drying (Fasina et al., 2003). DP provides important information necessary for the design of microwave drying process. DP consist of two main parts; dielectric constant (ϵ' , real part) and dielectric loss factor (ϵ'' , imaginary part) which describe the ability of material to store energy and the ability of material to dissipate energy in response to an applied electric field, respectively (Sosa-Morales et al., 2010). In particular, DP of food and agricultural products are altered depending on frequency, temperature, and moisture content (Feng et al., 2002). Transmission line, free space, resonant cavity, parallel plate, and open-ended coaxial probe methods are employed to measure DP of dielectric materials. Among these methods, open-ended coaxial probe method is commonly used to measure DP of variety of agricultural products because it covers broad frequency band and is convenient to use. Furthermore, DP of target material can be easily measured by making close contact between the probe and the surface. By using an open-ended coaxial method, the variation of DP of grain, and red pepper was determined depending on change in moisture content (Guo and Zhu, 2014; Kim, 2002). Because DP of agricultural products is significantly changed by their moisture contents, the change in DP during microwave drying can be usefully employed to describe their drying characteristics. However, the research on the measurement of DP of agricultural products during microwave drying has been rarely attempted. The aim of this study was (a) to investigate the effect of microwave power and sample shape on the drying characteristics of sweet potato; (b) to evaluate the selected drying models for describing microwave drying process of sweet potato; and (c) to determine change in dielectric properties of sweet potato depending on moisture content during microwave drying.

Materials and methods

Sample preparation

Sweet potatoes (beni-haruka cultivar) purchased from a local market (Noeun wholesale market, Daejeon, Republic of Korea) were stored at room temperature prior to drying experiment. Crumbly soil on the surface of sweet potato was removed and sweet potatoes were cut into two different shapes (slice and strip with thickness of approximately 6 and 9 mm, respectively) using a vegetable slicer. When slice and strip samples were prepared, the diameter of slices was not controlled and the length of strips was fixed to 8 cm. The initial moisture content of sweet potato samples was determined by convection drying at 105 °C for 24 h (AOAC, 1990). The initial moisture content of

sweet potato samples was 1.96 ± 0.03 kg water per kg dry matter.

Drying equipment and drying procedure

Domestic microwave oven (Mwx304sl, Whirlpool Co, Benton Harbor, MI, USA) with maximum output power of 900 W at 2450 MHz was used in this study. The dimension of inner microwave cavity was $240 \times 354 \times 358$ mm and a glass plate (315 mm in diameter) was located on turntable placed at the center of microwave cavity. The water evaporated from sweet potato samples during the drying process increased humidity in the enclosed microwave cavity, finally causing a decrease in drying rate. Hence, a small centrifugal fan was installed on the left upper side of microwave oven. The measured ventilation air speed at the outlet by a hygro-anemometer (HHC261, OMEGA Engineering, Inc., Stamford, CT, USA) was 2.8 m/s.

The average weight of sweet potato slices and strips used for microwave drying experiments was 114.10 ± 27.44 and 100.01 ± 0.21 g, respectively. Slices or strips were spread in a single layer on a circular mesh tray made of Teflon thread (thickness: 1 ± 0.2 mm) and stainless steel. The applied microwave power levels were from 90 to 900 W with an incremental interval of 90 W. During microwave drying, moisture losses of the samples were measured by a digital balance with 0.01 g precision (PAG2102C, OHAUS Co., Parsippany, NJ, USA). As the drying process progressed, the measurement interval time was 30 s until 2 min; afterwards, the interval was increased to 2 min. When the weight value of sweet potato samples was reached at a constant value, the drying experiment was stopped. All experiments were conducted in duplicate.

Mathematical modeling of microwave drying curves

Moisture content was calculated based on the weight values of a single layer at the drying time. The moisture ratio (MR) and drying rate of sweet potato slices and strips during microwave drying were calculated using following equations:

$$\text{Moisture ratio (MR)} = \frac{M - M_e}{M_o - M_e} \quad (1)$$

$$\text{Drying rate} = \frac{M_{t+dt} - M_t}{dt} \quad (2)$$

where, M , M_o , and M_e are the moisture content at any time, initial moisture content, equilibrium moisture content. M_t and M_{t+dt} are the moisture content at t and moisture content at $t + dt$ (kg water/kg dry matter), respectively, t is the drying time (min). For microwave drying, the equilibrium

moisture content can be assumed to be zero (Maskan, 2001).

Eight drying models that have been widely used for fitting of experimental drying characteristics of various agricultural materials (summarized in Table 1) were applied to select the model that best describe the drying curves of sweet potato slices and strips. The nonlinear regression analysis was performed using SPSS 24.0 software (SPSS Inc, Chicago, IL, USA). Non-linear regression analysis was performed to estimate the model parameters (such as k , n , a , b , c , g , and h). The best-fitted model expressed the microwave drying characteristics of sweet potato slices and strips was determined by the highest coefficient of correlation (R^2) value and the lowest root mean square error (RMSE) and chi-square (χ^2). The RMSE and χ^2 were calculated using the following equations:

$$\text{RMSE} = \left[\frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2 \right]^{1/2} \quad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{N - z} \quad (4)$$

where $MR_{exp,i}$ is the i th experimental moisture ratio, $MR_{pre,i}$ is the i th predicted moisture ratio, N is the number of observation, and z is the number of drying constants.

Dielectric properties measurement system

The dielectric properties (ϵ , DP) of sweet potato were determined by open-ended coaxial-probe measurement system consisted of dielectric probe kit (85070E, Keysight Technologies Co., Santa Rosa, CA, USA) and vector network analyzer (VNA) (N9923A, Keysight Technologies Co, Santa Rosa, CA, USA). This method is generally well known for broadband measurements of liquid and semi-solid high-loss materials because air pocket that is problematic between the probe and the sample can be avoided

(Nelson, 2015). In this method, the VNA measures the reflection coefficient (S_{11}) of a dielectric sample in contact with the probe. The software (85070E software, Keysight Technologies Co, Santa Rosa, CA, USA) calculates dielectric constant (ϵ') and dielectric loss factor (ϵ'') of dielectric sample based on the measured reflection coefficient (S_{11}). DP was measured in frequency range between 500 and 3000 MHz at 101 frequency points. For DP measurement of sweet potato, the VNA was turned on for at least 1 h before calibration. Calibration was completed by using three stages (air, shorting block, water).

Dielectric properties measurement procedure

The variation in dielectric properties (DP) of sweet potato during microwave drying was measured using the similar protocol with microwave drying experiments. The initial DP of sweet potato was measured prior to microwave drying. One sweet potato slice with thickness in 6 mm was used for DP measurement during microwave drying and the average weight of slice samples used was 18.36 ± 2.48 g. The slice samples were dried at different microwave power levels (900, 630, 360, and 90 W). During microwave drying, the slice was taken out from the microwave oven for measuring its weight and DP values, and the interval of weight reading was 30 s; however, when the microwave power level of 90 W was applied for drying the slice sample, the interval for weight and DP measurements was increased to 5 min. DP measurement of the slice was performed on an aluminum plate in 10 mm thickness. Since moisture on the surface of food can affect a change in its dielectric properties during DP measurement, moisture which was partially generated on the surface of sweet potato slice during microwave drying was removed using a paper wipes prior to DP measurement.

Table 1 Drying models used for describing microwave-drying characteristic of sweet potato slices and strips

Model name	Model	References
Newton	$MR = \exp(-kt)$	O'Callaghan et al. (1971)
Page	$MR = \exp(-kt^n)$	Page (1949)
Henderson and Pabis	$MR = a \exp(-kt)$	Henderson and Pabis (1961)
Logarithmic	$MR = a \exp(-kt) + c$	Yağcıoğlu et al. (1999)
Modified Handerson and Pabis	$MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$	Karathanos (1999)
Two-term	$MR = a \exp(-kt) + b \exp(-k_0t)$	Henderson (1974)
Midilli et al.	$MR = a \exp(-kt) + bt$	Midilli et al. (2002)
Wang and Singh	$MR = 1 + at + b(t^2)$	Demirhan and Belma (2011)

Results and discussion

Microwave drying characteristics of sweet potato

The curves of moisture ratio versus time for a thin layer of sweet potato slices and strips are shown in Fig. 1A and B. Total drying time required to reach a final moisture content of sweet potato samples was varied depending on microwave power level and shape of samples. Regardless of the shape of samples, the moisture ratio decreased with an increase in drying time and drying time was shortened as microwave power increased. Microwave power level had a pronounced effect on shortening drying time. When the thin layer of potato slices having constant weight values and different thickness (4, 7, and 10 mm) were dried at constant microwave power level (160 W), the drying time of thicker slices was shorter than it of thinner slices (Wang et al., 2004). It would be that the drying rate was accelerated as the number and area of slices exposed to microwave was smaller. Although the average weight of thin layer of sweet potato slices was heavier than it of strips, the drying time of strips was little longer than it of slices at same microwave power intensity except for 810 and 900 W. It would be that microwave penetration was limited depending on thickness and the surfaces of strips were

more rapidly dried than the inside. The more rapidly dried surface than inside may lead to the case hardening. It could become a thermal barrier that prevents evaporation of moisture inside strip samples.

The drying rate of sweet potato slices and strips against moisture content at different microwave power levels are illustrated in Fig. 1C and D. At the same moisture content, the drying rate significantly increased with microwave power level. When higher microwave power level was applied for the drying, the mass transfer within slices and strips could be faster because more volumetric heating could be generated within the samples. The drying rate of both slices and strips was sharply increased at initial drying stage, and then almost constant drying rate period was observed until the moisture content (w.b) reached approximately 20%. Arian et al. (2012) also reported that after a short heating period the constant drying rate of carrots was observed for 3/5 of total drying time in intermittent microwave drying.

Evaluation of drying models

The moisture content data obtained from the drying experiments were applied for eight drying models as presented in Table 1 to predict microwave drying

Fig. 1 Moisture ratio (A 6 mm slices, B 9 mm strips) versus time and drying rate (C 6 mm slices, D 9 mm strips) of sweet potato samples

characteristics of sweet potato slices and strips. Regardless of microwave power level and shape of samples, R^2 and χ^2 values for eight models were all above 0.95 and below 0.007, respectively. All eight models were appropriate to describe experimental drying data for both shapes of sweet potato samples. The highest R^2 values (range from 0.9835 to 0.9998), and the lowest RMSE (range from 0.0049 to 0.0416) and χ^2 (range from 0 to 0.0017) values were obtained from Page model in all microwave power levels and both shapes of sweet potato samples. Page model was selected as the best model for describing microwave drying characteristics of sweet potato slices and strips. Although R^2 values from Newton model for both slices and strips were slightly lower than it from other models, Newton model could be suggested for convenient description of microwave drying characteristics of sweet potato slices and strips due to its simple form. The calculated coefficients and model indices (R^2 , RMSE, χ^2 , k , and n) of Page model for sweet potato slices and strips dried at different microwave power levels are listed in Table 2.

Dielectric properties

The measured dielectric properties (DP; both dielectric constant, ϵ' and dielectric loss factor, ϵ'') of sweet potato slices with thickness of 6 mm in frequency range between 500 MHz and 3000 MHz depending on moisture contents are presented in Fig. 2. The measured ϵ' and ϵ'' values of fresh sweet potato (initial $MC_{w,b}$: 66.2%) at 915 and 2450 MHz were $58.74(\pm 3.74)$ and $24.79 (\pm 4.24)$, and $53.13(\pm 3.64)$ and $18.35 (\pm 1.59)$, respectively. It was similar to the measured DP of sweet potatoes with 80% $MC_{w,b}$ (ϵ' : 55 and ϵ'' : 16, 915 MHz; ϵ' : 52 and ϵ'' : 14, 2450 MHz) reported by Nelson et al. (1994). The slight differences could be caused by moisture contents of used sweet potato samples. At same microwave frequency, DP (both ϵ' and ϵ'') of the sample were significantly decreased with a decrease in moisture content. Moisture content, which depends on the free and bound water contents, is a critical factor that has an influence on the DP of agricultural products (Guo and Zhu, 2014). In addition, as microwave frequency increased at the same moisture content, ϵ' values were linearly decreased; however, ϵ''

Table 2 The calculated coefficients of Page model for sweet potato slices and strips

Model name	Power (W)									
	900	810	730	630	540	450	360	270	180	90
<i>Page</i>										
6 mm slices										
R^2	0.9970 (0.002)	0.9967 (0.002)	0.9982 (0.002)	0.9950 (0.002)	0.9903 (0.005)	0.9973 (0.001)	0.9983 (0.001)	0.9990 (0.004)	0.9984 (0.002)	0.9986 (0.001)
RMSE	0.0213 (0.011)	0.0221 (0.009)	0.0161 (0.008)	0.0254 (0.009)	0.0342 (0.014)	0.0185 (0.002)	0.0146 (0.003)	0.0118 (0.009)	0.0132 (0.007)	0.0126 (0.003)
χ^2	0.0005 (0.000)	0.0005 (0.000)	0.0003 (0.000)	0.0006 (0.000)	0.0012 (0.001)	0.0003 (0.000)	0.0002 (0.000)	0.0001 (0.000)	0.0002 (0.000)	0.0002 (0.000)
k	0.0831 (0.007)	0.0743 (0.009)	0.0604 (0.021)	0.0888 (0.037)	0.0737 (0.029)	0.0744 (0.043)	0.0264 (0.001)	0.0171 (0.013)	0.0127 (0.004)	0.0047 (0.000)
n	1.6141 (0.130)	1.5628 (0.108)	1.5927 (0.160)	1.3499 (0.243)	1.2976 (0.214)	1.3297 (0.267)	1.4848 (0.020)	1.4429 (0.206)	1.2644 (0.092)	1.0704 (0.047)
9 mm strips										
R^2	0.9988 (0.002)	0.9987 (0.001)	0.9938 (0.003)	0.9835 (0.009)	0.9899 (0.005)	0.9981 (0.001)	0.9976 (0.000)	0.9964 (0.001)	0.9982 (0.001)	0.9998 (0.002)
RMSE	0.0132 (0.006)	0.0146 (0.005)	0.0266 (0.009)	0.0416 (0.018)	0.0326 (0.012)	0.014 (0.003)	0.0162 (0.001)	0.0201 (0.005)	0.0161 (0.002)	0.0049 (0.010)
χ^2	0.0002 (0.000)	0.0002 (0.000)	0.0007 (0.000)	0.0017 (0.001)	0.0011 (0.000)	0.0002 (0.000)	0.0003 (0.000)	0.0004 (0.000)	0.0003 (0.000)	0.0000 (0.000)
k	0.1309 (0.001)	0.0986 (0.027)	0.1117 (0.029)	0.1186 (0.022)	0.1015 (0.031)	0.0832 (0.015)	0.0408 (0.013)	0.0447 (0.015)	0.0165 (0.005)	0.0105 (0.005)
n	1.4488 (0.055)	1.5916 (0.158)	1.2801 (0.210)	1.1042 (0.212)	1.1103 (0.244)	1.0875 (0.193)	1.2408 (0.193)	1.0704 (0.232)	1.2814 (0.094)	0.9987 (0.093)

Fig. 2 Dielectric properties spectra of sweet potato slices affected by moisture content: **(A)** dielectric constant (ϵ') and **(B)** dielectric loss factor (ϵ'')

values were significantly decreased between 500 and 1000 MHz. It was owing to the wavelength of the measured frequency. The previous research on the DP measurement of dried apples reported that ϵ'' of dried apple drastically decreased when the frequency increased (Feng et al., 2002).

DP of sweet potato slices measured at 2450 MHz during microwave drying process applied with different microwave power levels (900, 630, 360, and 90 W) are shown in Fig. 3. In microwave drying process except for 90 W, the constant rate was not observed, and drying rate was significantly increased up to approximately 30% MC_{w.b} (30.39, 35.55, 32.38% at 900, 630 and 360 W,

Fig. 3 Change in dielectric properties (2450 MHz) and drying rate of sweet potato slices during microwave drying process. **(A)** 900 W, **(B)** 630 W, **(C)** 360 W, **(D)** 90 W (■: ϵ' , □: ϵ'' , —: predicted value, - -: drying rate)

Table 3 Model constants for the change in dielectric properties of sweet potato slices

Name of model	Microwave power (W)							
	900		630		360		90	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
Henderson								
<i>a</i>	57.0603	23.8393	58.5346	24.2347	44.9291	16.4358	52.7032	18.4408
<i>k</i>	0.7252	0.7187	0.6605	0.7100	0.3851	0.5010	0.0375	0.0340
R^2	0.9467	0.8469	0.9804	0.9504	0.9749	0.9846	0.9800	0.9596
<i>RMSE</i>	4.4402	3.4459	2.5411	1.7332	2.2253	0.6307	2.2984	1.1959
χ^2	19.7158	11.8741	6.4573	3.0040	4.9518	0.3977	5.2828	1.4301
Logarithmic								
<i>a</i>	58.7129	25.7498	59.1534	25.0407	44.2519	16.3247	50.8003	24.5836
<i>k</i>	0.6557	0.5773	0.6300	0.6304	0.4683	0.5268	0.0427	0.0188
<i>c</i>	− 2.1755	− 2.2640	− 0.9399	− 1.0756	2.2303	0.2396	2.6786	− 6.8785
R^2	0.9503	0.8644	0.9813	0.9576	0.9855	0.9858	0.9815	0.9802
<i>RMSE</i>	4.4958	3.4014	2.5748	1.6617	1.7435	0.6249	2.2691	0.8587
χ^2	20.2120	11.5697	6.6296	2.7612	3.0397	0.3905	5.1489	0.7373
Two term								
<i>a</i>	152.1651	76.2359	188.2582	73.7091	21.9392	7.7573	48.7800	38.8163
<i>k</i>	0.4908	0.4108	0.4760	0.4510	1.1878	0.9481	0.0341	0.0152
<i>b</i>	− 95.7200	− 52.6658	− 130.3273	− 49.7908	26.9798	9.1895	11.8266	− 21.1124
k_0	0.3943	0.3199	0.4159	0.3668	0.2370	0.3393	1.4159	0.0063
R^2	0.9545	0.8716	0.9836	0.9635	0.9932	0.9882	0.9973	0.9806
<i>RMSE</i>	4.5353	3.4883	2.5101	1.6053	1.2376	0.5874	0.8880	0.8737
χ^2	20.56871	12.1679	6.3007	2.5769	1.5317	0.3451	7.2812	0.7634
Modified Henderson and Pabis								
<i>a</i>	119.3034	183.0967	241.8113	54.5897	19.0746	7.7552	11.8923	50.8586
<i>k</i>	0.5072	1.7548	1.0515	0.4693	1.3416	0.9482	0.8526	0.0141
<i>b</i>	− 31.4254	− 82.4142	− 93.2855	− 15.3392	29.8630	4.5958	20.8355	− 16.5791
<i>g</i>	0.3729	2.3079	1.2944	0.3443	0.2620	0.3394	0.0333	0.0079
<i>c</i>	− 31.4321	− 82.1980	− 93.2662	− 15.3320	0.0097	4.5959	27.2184	− 16.5788
<i>h</i>	0.3748	2.2936	1.2891	0.3459	− 0.3133	0.3393	0.0336	0.0077
R^2	0.9544	0.9920	0.9912	0.9634	0.9942	0.9882	0.9967	0.9806
<i>RMSE</i>	26.5064	0.9869	4.0825	1.7618	1.5029	0.6310	1.1019	0.9253
χ^2	5.1484	0.9736	2.0205	3.1038	1.2259	0.3982	1.0497	0.8562

respectively). Falling rate period was observed after the maximum peak of drying rate. On the other hand, the drying rate at 90 W increased in the initial stages and then almost remained constant during drying process. Both ε' and ε'' of slices were decreased as microwave drying progressed. In all microwave drying experiments, the average ε' value decreased from 51.88 to 1.61, and the average ε'' value also decreased from 18.89 to 2.46. Both ε' and ε'' values constantly remained in falling rate period at 900, 630, 360 W. In case of microwave power of 90 W, both ε' and ε'' values linearly decreased at the constant rate period except for initial stage.

Predictive equations for DP of food materials are necessary to understand their heating pattern or sterilization temperatures during microwave heating process (Sipahioglu et al., 2003; Uan et al., 2004). Brinley et al. (2008) developed the empirical equations predicting DP of sweet potato purees affected by temperature and chemical composition. Fasina et al. (2003) also developed the equations for predicting DP of sweet potato purees as a function of temperature and frequencies. By measuring DP of a variety of fruit, the maturity, quality, and water activity of fruit could be determined and it was found that the moisture content of fruit was a critical factor affecting

DP of the fruit (Clerjon et al., 2003; Guo et al., 2007). However, no studies have been found to predict the change in DP of sweet potato during microwave drying as a function of moisture content using the drying model. The plot (Fig. 3) of changes in ϵ' and ϵ'' values of sweet potato slices are seemed to be similar to the drying curves of slices as shown in Fig. 1A and B. Therefore, aforementioned drying models as a function of moisture content (Table 1) were tested to determine the best model for describing the change in ϵ' and ϵ'' values of sweet potato during microwave drying.

In this study, Page model could best describe microwave drying characteristics of sweet potato slices and strips. Therefore, Page model was tested to predict the change in DP of sweet potato slices; however, contrary to expectation, the model was not suitable because of low R^2 values (range between 0.7453 and 0.8707) and high RMSE (range from 3.7972 to 6.9981) and χ^2 (range between 14.4186 and 48.9743) values. Since low R^2 and high RMSE and χ^2 values were estimated from Page model, other drying models were also applied to determine the best model for describing the change in DP of sweet potato slices during microwave drying. The correlation coefficient and results of statistical analyses for variation in DP of the slices from different drying models are summarized in Table 3. R^2 values of ϵ' were generally higher than ϵ'' at all microwave power levels. Although the regularity of the relationship between permittivity and moisture content of agricultural product at different frequencies was evident, it was complicated to predict the dielectric loss factor behavior (ϵ'') than the dielectric constant (Nelson, 1991). Modified Henderson and Pabis model, which is the simplest of the four models, was selected as a suitable model for describing the change of DP. The predicted value of DP was plotted in Fig. 3. The change in DP of sweet potato slice during microwave drying procedure could be predicted by the drying model and could be used for deducing the change in moisture content during microwave drying.

Microwave drying characteristics of sweet potato slices and strips were investigated in this study. The drying time varied depending on the microwave power levels and shape of samples. The drying time of strips was shorter than it of slices. Under all drying conditions, a constant drying rate was found and the highest drying rate was obtained during the initial drying stage. The tested eight drying models were all suitable for clearly describing the drying curves of sweet potato slices and strips with coefficients of determination (R^2) greater than 0.95. The best model for describing drying characteristics of sweet potato slices and strips was Page model. Dielectric constant (ϵ') and dielectric loss factor (ϵ'') of sweet potato slices were decreased with decrease in moisture content of sweet potato and microwave frequency. Modified Henderson and

Pabis model was appropriate to predict the change in dielectric properties of sweet potato slice during microwave drying. Further study will be conducted to determine the suitability of the prediction of moisture content using dielectric properties.

Acknowledgements This work was carried out with the support of the “Cooperative Research Program for Agriculture Science and Technology Development (Project No. PJ10224701)” Rural Development Administration, Republic of Korea.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

References

- Ahmed M, Akter MS, Eun JB. Peeling, drying temperatures, and sulphite-treatment affect physicochemical properties and nutritional quality of sweet potato flour. *Food Chem.* 121(1): 112–118 (2010)
- AOAC. Official Method of Analysis. Association of Official Analytical Chemists (No. 934. 06), Arlington, VA (1990)
- Arikan MF, Ayhan Z, Soysal Y, Esturk, O. Drying characteristics and quality parameters of microwave-dried grated carrots. *Food Bioprocess Technol.* 5(8): 3217–3229 (2012)
- Brinley TA, Truong VD, Coronel P, Simunovic J, Sandeep KP. Dielectric properties of sweet potato purees at 915 MHz as affected by temperature and chemical composition. *Int. J. Food Prop.* 11(1): 158–172 (2008)
- Clerjon S, Daudin JD, Damez JL. Water activity and dielectric properties of gels in the frequency range 200 MHz–6 GHz. *Food Chem.* 82(1): 87–97 (2003)
- Demirhan E, Belma Ö. Thin-layer drying characteristics and modeling of celery leaves undergoing microwave treatment. *Chem. Eng. Commun.* 198(7): 957–975 (2011)
- Ehivet, FE, Min B, Park MK, Oh JH. Characterization and antimicrobial activity of sweet potato starch-based edible film containing origanum (*Thymus capitatus*) oil. *J. Food Sci.* 76(1): 178–184 (2011)
- Fasina OO, Farkas BE, Fleming HP. Thermal and dielectric properties of sweet potato puree. *Int. J. Food Prop.* 6(3): 461–472 (2003)
- Feng H, Tang J, Cavalieri RP. Dielectric properties of dehydrated apples as affected by moisture and temperature. *Trans. ASAE.* 45(1): 129–135 (2002)
- Gorris LGM, Peppelenbos HW. Modified atmosphere and vacuum packaging to extend the shelf life of respiring food products. *Horttechnology.* 2(3): 303–309 (1992)
- Guo W, Zhu X. Dielectric properties of red pepper powder related to radiofrequency and microwave drying. *Food Bioprocess Technol.* 7(12): 3591–3601 (2014)
- Guo WC, Nelson SO, Trabelsi S, Kays SJ. 10–1800-MHz dielectric properties of fresh apples during storage. *J. Food Eng.* 83(4): 562–569 (2007)
- Henderson SM, Pabis S. Grain drying theory I: temperature effect on drying coefficient. *J. Agric. Res. Eng.* 6: 169–174 (1961)
- Henderson SM. Progress in developing the thin layer drying equation. *Trans. ASAE.* 17(6): 1167–1168 (1974)
- Karathanos VT. Determination of water content of dried fruits by drying kinetics. *J. Food Eng.* 39(4): 337–344 (1999)

- Kim KB. Measurement of dielectric properties of cereal grains by nondestructive microwave measurement technique. *J. Korean Soc. Nondestruct. Test.* 22(4): 369–376 (2002)
- Maskan M. Drying, shrinkage and rehydration characteristics of kiwifruits during hot air and microwave drying. *J. Food Eng.* 48(2): 177–182 (2001)
- Midilli A, Kucuk H, Yapar Z. A new model for single-layer drying. *Dry. Technol.* 20(7): 1503–1513 (2002)
- Nelson SO. Dielectric properties of agricultural products-measurements and applications. *IEEE Trans. Electr. Insul.* 26(5): 845–869 (1991)
- Nelson S, Forbus W, Lawrence K. Permittivities of fresh fruits and vegetables at 0.2 to 20 GHz. *J. Microw. Power EE.* 29(2): 81–93 (1994)
- Nelson S. *Dielectric Properties of Agricultural Materials and Their Applications*. Elsevier, Boston, MA (2015)
- O'Callaghan JR, Menzies DJ, Bailey PH. Digital simulation of agricultural dryer performance. *J. Agric. Eng. Res.* 16(3): 223–244 (1971)
- Page GE. Factors influencing the maximum rates of air drying shelled corn in thin layers. M.S. thesis, Department of Mechanical Engineering, Purdue University, Purdue, USA (1949)
- Sipahioglu O, Barringer SA, Taub I, Prakash A. Modeling the dielectric properties of ham as a function of temperature and composition. *J. Food Sci.* 68(3): 904–909 (2003)
- Sosa-Morales ME, Valerio-Junco L, López-Malo A, García HS. Dielectric properties of foods: reported data in the 21st century and their potential applications. *LWT-Food Sci. Technol.* 43(8): 1169–1179 (2010)
- Uan DG, Cheng M, Wang Y, Tang J. Dielectric properties of mashed potatoes relevant to microwave and radio-frequency pasteurization and sterilization processes. *J. Food Sci.* 69(1): 30–37 (2004)
- Wang J, Tang J, Wang Y, Swanson B. Dielectric properties of egg whites and whole eggs as influenced by thermal treatments. *LWT Food Sci. Technol.* 42(7): 1204–1212 (2009)
- Wang J, Xiong YS, Yu Y. Microwave drying characteristics of potato and the effect of different microwave powers on the dried quality of potato. *Eur. Food Res. Technol.* 219(5): 500–506 (2004)
- Wang Y, Li Y, Wang S, Zhang L, Gao M, Tang J. Review of dielectric drying of foods and agricultural products. *Int. J. Agric. Biol. Eng.* 4(1): 1–19 (2011)
- Yağcıoğlu A, Değirmencioğlu A, Çağatay F. Drying characteristics of laurel leaves under different drying conditions. In: 7th Int Congress on Agricultural Mechanization and Enerdy, pp. 565–569 (1999)
- Yan WQ, Zhang M, Huang LL, Mujumdar AS, Tang J. Influence of microwave drying method on the characteristics of the sweet potato dices. *J. Food Process. Preserv.* 37(5): 662–669 (2013)