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MATHEMATICAL MODELING OF MICROWAVE-ASSISTED HOT AIR DRYING FOR MACADAMIA NUTS

*Nattapol POOMSA-AD[1], Lamul WISET[2] and Wasan DUANGKHAMCHAN[3]

[1]*Thermal Processing Research Unit, Faculty of Engineering, Mahasarakham University, Kantarawichai, Maha Sarakham, 44150, Thailand*

[2]*Postharvest Technology and Agricultural Machinery Research Unit, Faculty of Engineering, Mahasarakham University, Kantarawichai, Maha Sarakham, 44150, Thailand*

[3]*Research unit of process and product development of functional foods, Department of Food Technology and Nutrition, Faculty of Technology, Mahasarakham University, Kamriang, Kantarawichai, Maha Sarakham 44150, Thailand*

Corresponding author: Wasan DUANGKHAMCHAN. E-mail: wasan.d@msu.ac.th

ABSTRACT

Drying behavior of food and agricultural products plays an important role in design and process optimization. The objective of this research was to study the drying kinetics of macadamia undergoing drying in a microwave-assisted hot air dryer. Unshelled macadamia with initial moisture content of 16-20% (wet basis) was dried until the final value of less than 4% (wet basis). The experiment was conducted under variations of hot air temperature (40, 50 and 60ºC) and microwave power, ranging from 300 to 600 W. The experimental data of the drying kinetics was fitted to various well-known theoretical models using nonlinear regression analysis. Furthermore, the appearance of dried macadamia and energy consumption were examined. Based on the coefficient of determination (R2), the root mean square error and chi-square, the Midilli model was most suitable for characterizing the drying behavior for the overall tested temperatures and microwave powers. The drying data also showed that among the operating factors tested, the microwave power was more dominant in reducing the moisture content of macadamia. The color of kernels dried using 300 W was most uniform at all tested temperatures. Regarding the energy consumption, the lowest value (0.17 kW-h) was found when drying was at 40ºC in combination with microwave power of 450 W. Even though the suitable model obtained in this work could be used to characterize the microwave-assisted hot air drying behavior of macadamia, physico-chemical property changes of macadamia should be taken into account in practical use.

Keywords: Macadamia; Microwave; Drying model

INTRODUCTION

Macadamia (*Macadamia tetraphylla*) is well known as an oil-rich nut, containing monounsaturated fatty acids which are proven as a reducer of cholesterol and triglyceride levels [1, 2]. The major fatty acids are palmitioleic (15-30%), oileic acid (40-65%), and palmitic acid (7-24%) [3]. The moisture content of freshly harvested macadamia nuts are in a range of 15-25% (wet basis, wb) [4] at which hydrolytic and oxidative rancidity occur due to reaction between free moisture and unsaturated fatty acids [2]. Rancidity or peroxide value (≤ 3.0 meq O_2/kg oil) is used as an index to characterize the acceptable quality of macadamia nuts in Australian Macadamia Society [2]. Therefore, the macadamia nuts have to be dried immediately after harvesting in order to lower their moisture content to an acceptable level (1.5%wb) [5].

In the industrial macadamia production, the in-shell nuts with moisture content of 20-30%db after recently harvested were dried using natural shade drying for 3-4 weeks to reach moisture of 10%db [1, 4]. The pre-dried nuts are then submitted to the next stage to be hot-air dried with temperature varied from 40°C to 60°C in various kinds of drying chamber. In this stage, it takes approximately 6 days to lower the moisture content to 1.5%wb at which the nuts can be stored up to 1 year without product deterioration [1, 4]. It can be revealed that the total drying cycle is very long while energy efficiency is low [6]. Microwave radiation is the one of alternative drying methods implemented to overcome these disadvantages due to its high energy efficiency and uniform heat distribution in the material [7-9]. In this method, the electromagnetic energy is directly transferred to the water molecules resulting in rapid evaporation from the interior towards the surface of material, and then removed by convective air current [10, 11]. However, as a result of low-temperature ambient air surrounding the product, volumetric microwave heating may promote a water film on its surface, resulting in electrical surface conduction and product damage [12]. The microwave heating is therefore combined with other techniques including hot air, infrared and vacuum in order to remove surface moisture [13]. Convective hot-air drying has been widely used as an association with microwave heating to enhance the drying rate and improve qualities of a final product [14].

Due to complex phenomenon and several factors needed, the drying kinetics have been investigated using a mathematical model which serves as an effective tool to design and to optimize drying processes. Although many attempts have been made to mathematically investigate the drying kinetic of foods during microwave treatments such as garlic [15], wheat [16], macadamia nut [1], grape [13], cashew nut [11], papaya [17] and instant rice [10], the dependable models are still required to predict the drying behavior in the combined microwave and hot-air drying.

Due to several factors affecting the combined microwave and hot-air drying, variations of hot-air temperature and microwave intensity were chosen to investigate the drying kinetics and their models of unshelled macadamia in this work. In addition, the appearance of dried macadamia nuts and energy consumption were evaluated.

MATERIALS AND METHODS

Materials

The raw material used in this research was hulled in-shell macadamia nuts purchased from a local market. Prior to conducting experiment, an initial moisture content of the nuts was determined by the standard method [18]. The nuts were then stored in a fridge at 4-5°C until drying experiment started. Combined microwave and hot-air drying experiment

The prepared in-shell macadamia nuts of approximately 80 g were stabilized at the ambient condition for an hour before drying. They were then spread on a drying tray with distribution for which the samples could absorb the microwave energy uniformly. In order to investigate the effects of operating factors on the drying characteristics of the in-shell macadamia nuts, an experimental design was established using a full factorial plan with 2 factors and 3 levels. The variables studied in this work included microwave intensity (300, 450 and 600W) and hot-air temperature of 40, 50 and 60°C, while the air velocity was kept constant at 1.2 m/s. The dependent variable was the simplified moisture ratio (MR) expressed by MR = M/M0, where M is the moisture content at a certain drying time and M0 is the initial moisture content. Each experiment was conducted until the moisture content reached the steady state condition with triplication. All average values of moisture content were presented in wet basis. In addition, color of shelled macadamia nuts was visually inspected, and energy consumption for each condition were determined using a watt meter during drying period until the final moisture content reached 3%wb.

Mathematical modeling of drying curves

Combined microwave and hot-air drying curves were fitted with 10 different empirical and semi-empirical drying models (Table 1). Non-linear regression procedure was performed on all drying experiments to estimate the parameters from the MR values using a statistical software. The coefficient of determination (R2), the root mean square (RMSE), and the reduced chi-square (χ2) were used as the primary criterion for selecting the suitable choice to describe the combined microwave/hot-air drying behavior of the macadamia nuts.

Table 1 Mathematical models proposed by various authors [19]

Name	Model equation
(1) Newton	MR = exp(-kt)
(2) Page	MR = exp(-ktn)
(3) Modified Page	MR = exp(-(kt)n)
(4) Wang and Singh	MR = 1 + a·t + b·t2
(5) Henderson and Pabis	MR = a·exp(-kt)
(6) Logarithmic	MR = a·exp(-kt) + c
(7) Diffusion approach	MR = a·exp(-kt) + (1 – a)·exp(-kbt)
(8) Simplified Fick'sdiffusion	MR = a·exp(-c(t/L2))
(9) Modified Page II	MR = exp(-c(t/L2)n)
(10) Midilli	MR = a·exp(-k(tn)) + b·t

RESULTS AND DISCUSSION

The combined microwave and hot-air drying experiments were conducted with variations of microwave intensity and hot-air temperature. The initial moisture content was decreased until reaching the equilibrium value. The experimental moisture ratios were fitted to the proposed models depicted in Table 1. Tables 2 and 3 show the goodness-of-fit parameters obtained from various models at the selected conditions, fixed air temperature (60°C) and fixed microwave power (600W), respectively. Based on the criteria of the best fit for overall conditions, the Midilli equation seemed to be the suitable model the highest R2 and the lowest RMSE and χ2. Table 4 presents the model parame-ters obtained from the Midille equation.

Table 2 The goodness-of-fit parameters of models with variation of microwave power (W) at 60°C

Model No.	Watt	R2	RMSE	χ2
(1)	300	0.8835	0.117984	0.014848
	450	0.9342	0.087526	0.008171
	600	0.9378	0.089821	0.008875
(2)	300	0.9897	0.034993	0.001399
	450	0.9891	0.035711	0.001457
	600	0.9958	0.023299	0.000663
(3)	300	0.9897	0.034993	0.001399
	450	0.9891	0.035711	0.001457
	600	0.9958	0.023299	0.000663
(4)	300	0.9727	0.057116	0.003728
	450	0.9672	0.061760	0.004359
	600	0.9732	0.058982	0.004252
(5)	300	0.9094	0.104052	0.012373
	450	0.9548	0.072506	0.006008
	600	0.9524	0.078592	0.007549
(6)	300	0.9760	0.053516	0.003525
	450	0.9677	0.061291	0.004623
	600	0.9660	0.066373	0.006057
(7)	300	0.9716	0.058207	0.004170
	450	0.9912	0.031921	0.001254
	600	0.9378	0.089821	0.011093
(8)	300	0.9094	0.104052	0.013325
	450	0.9548	0.072506	0.006470
	600	0.9524	0.078592	0.008493
(9)	300	0.9897	0.034993	0.001507
	450	0.8720	0.122064	0.018338
	600	0.9958	0.023299	0.000746
(10)	300	0.9937	0.027475	0.001007
	450	0.9936	0.027308	0.000994
	600	0.9971	0.019336	0.000587

Table 3 The goodness-of-fit parameters of models with variation of hot-air temperature (°C) at 600W

Model No.	Temp.	R2	RMSE	χ2
(1)	40	0.9487	0.079117	0.006829
	50	0.9480	0.078056	0.006770
	60	0.9378	0.089821	0.008875
(2)	40	0.9961	0.021721	0.000566
	50	0.9845	0.042652	0.002274
	60	0.9958	0.023299	0.000663
(3)	40	0.9961	0.021721	0.000566
	50	0.9845	0.042652	0.002274
	60	0.9958	0.023299	0.000663
(4)	40	0.9794	0.050175	0.003021
	50	0.9696	0.059749	0.004462
	60	0.9732	0.058982	0.004252
(5)	40	0.9630	0.067228	0.005424
	50	0.9596	0.068800	0.005917
	60	0.9524	0.078592	0.007549
(6)	40	0.9764	0.053721	0.003848
	50	0.9644	0.064581	0.005958
	60	0.9660	0.066373	0.006057
(7)	40	0.9487	0.079117	0.008346
	50	0.9588	0.069456	0.006892
	60	0.9378	0.089821	0.011093
(8)	40	0.9630	0.067228	0.006026
	50	0.9596	0.068800	0.006762
	60	0.9524	0.078592	0.008493
(9)	40	0.9961	0.021721	0.000629
	50	0.9845	0.042652	0.002652
	60	0.9958	0.023299	0.000746
(10)	40	0.9973	0.018133	0.000493
	50	0.9957	0.022480	0.000842
	60	0.9971	0.019336	0.000587

Table 4 The model parameters of Midilli equation.

Conditions		Model parameters $MR = a\cdot\exp(-k(t^n)) + b\cdot t$			
Temp.	Watt	a	b	k	n
40°C	300	1.009012	0.004564	0.029798	1.775348
	450	1.022703	0.003445	0.074669	1.539302
	600	1.012588	0.002310	0.105611	1.689659
50°C	300	1.016895	-0.07473	-0.03455	0.000018
	450	1.002626	0.004425	0.074720	1.524388
	600	1.007500	0.009845	0.120658	1.859556
60°C	300	0.949218	-0.00120	0.008320	2.244757
	450	0.996095	0.004203	0.036755	1.893223
	600	1.013347	0.002415	0.113833	1.851283

The selected combined microwave/hot-air drying model (Midilli equation) was subsequently used to describe the drying behavior of the in-shell macadamia nuts at all conditions. Figures 1 and 2 are instances of drying kinetics at fixed hot-air temperature (60°C) and at fixed microwave intensity (600W), respectively. These figures also show the consistency between the experimental moisture contents and those predicted by the Midilli equation. From these, the moisture contents of the in-shell macadamia nuts decreased exponentially with the extended drying time.

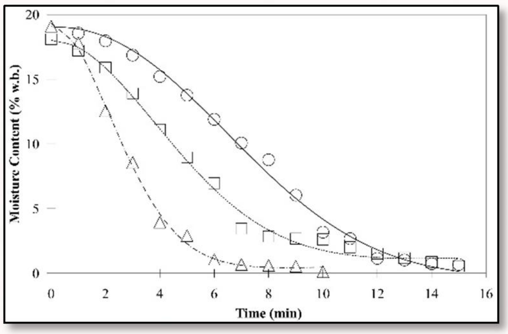

Fig. 1 Drying kinetic with variation of microwave power (circle-300W, rectangle-450W, and trian-gle-600W, lines-predicted moisture content); at 60ºC

Figure 1 shows the influence of microwave intensity on drying behavior of the in-shell macadamia nuts. At a certain drying time, the higher microwave power led to quicker moisture reduction, especially during the first period of drying. It could be explained that high microwave power resulted in high temperature gradient between interior and surface of the nuts, leading to high energy of water molecules for which it could overcome Van de Walls interaction. Water could therefore migrate more rapidly from inside towards the surface of the nuts.

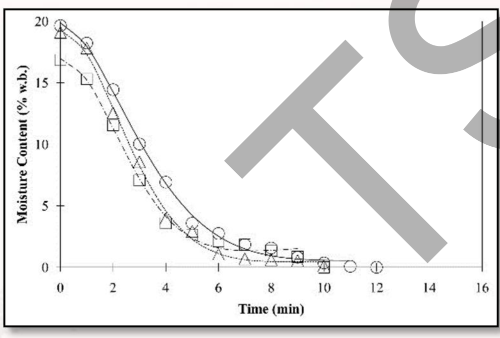

Fig. 2 Drying kinetic with variation of microwave power (circle-40ºC, triangle -50ºC, and rectan-gle-60ºC, lines-predicted moisture content); at 600W

The influence of hot-air temperature at a constant microwave (600W) is presented in figure 2. Similar trend in moisture content reduction with time was observed, exponentially decreasing with drying time. As normally observed in drying characteristics (ref.), the higher air temperature resulted in higher drying rate. When compared to figure 1, this figure also revealed that among the combined microwave/hot-air drying variables tested, the microwave intensity was more dominant in reducing the moisture content of the in-shell macadamia nuts.

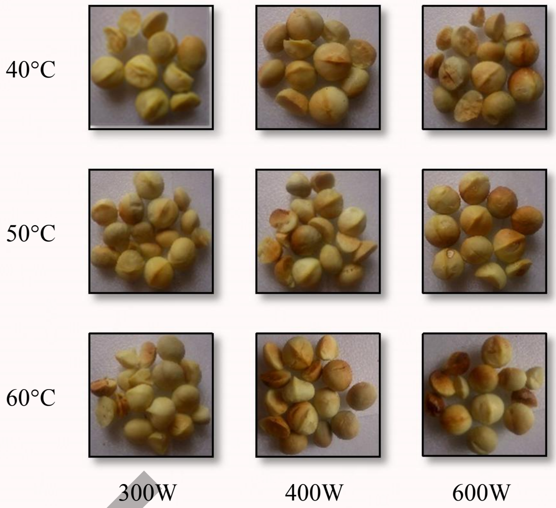

Fig. 3 Appearance of shelled macadamia nuts dried by various conditions

After drying, the nut samples were shelled in order to examine the effects of microwave power and hot-air temperature on their appearance. Figure 3 shows the shelled macadamia nuts dried under all conditions with the same final MC of approximately 3%wb. It could be observed from this figure that the dried macadamia nuts were darker with increasing microwave power at the same air temperature, while difference in color could be observed obviously when air temperature was varied. In addition, burnt spots could be found on surface of the nuts when using 600W. Therefore, even though the high microwave power led to high drying rate, quality aspects could be taken into consideration when process optimization is needed.

Table 5 Comparison of energy consumption (kW·h)

Temperature (°C)	Microwave power (W)	Drying time (min)	kW·h
40	300	11.00	0.22
	450	8.34	0.17
	600	5.15	0.15
50	300	10.31	0.52
	450	8.13	0.41
	600	4.51	0.27
60	300	10.07	0.70
	450	7.50	0.53
	600	4.21	0.34

Table 5 presents the energy consumption at all drying conditions. It could be found from this table that the increase in air temperature utilized more energy when compared to that in microwave power. The explanation could be that increasing microwave power resulted in faster moisture reduction, meaning shorter drying time. The lowest energy consumption of 0.17 kW-h was found when drying at hot-air temperature of 40°C and 450-W microwave power.

CONCLUSSION

In order to describe the drying behavior of in-shell macadamia nuts dried by the microwave-assisted hot-air method, 10 various drying models proposed in the literature were fitted with experimental data at different microwave powers and air temperatures. The Midilli model was mostly consistent with the experimental results, based on the highest R2 and lowest RMSE and χ2. This model could characterize the exponential decrease in moisture ratio, as normally observed in drying behavior of agricultural and food products. The experimental results also showed the influences of microwave intensity and hot-air temperature. Among them, the microwave power was more dominant in reducing the moisture content. In addition, the intensity of microwave affected the appearance of unshelled nuts, darker with increasing power. According to the energy consumption, the lowest value was found when drying below 40°C and 450W. It could be also found that the increasing hot air temperature did not affect the drying rate obviously, while energy utilization was high when compared to that used to increase the microwave power. However, this work focused only on drying characteristic and appearance of the dried shelled macadamia nuts. The quality aspects should be taken into consideration when optimization is needed for further study.

REFERENCES

[1] Silva, F.A., Marsaioli Jr., A., Maximo, G.J., Silva, M.A.A.P. and Gonçalves, L.A.G. Microwave assisted drying of macadamia nuts. Journal of Food Engineering 77: 550-558 (2006)

[2] Phatanayindee, S., Borompichaichartkul, C., Srzednicki, G., Craske, J. and Wootton, M. Changes of chemical and physical quality attributes of macadamia nuts during hybrid drying and processing. Drying Technology 30: 1870-1880 (2012)

[3] Kaijser, A., Dutta, P. and Savage, G. Oxidative stability and lipid composition of macadamia nuts grown in New Zealand. Food Chemistry 71: 67-70 (2000)

[4] Wang, Y., Zhang, L., Gao, M., Tang, J. and Wang, S. Temperature- and moisture-dependent dielectric properties of macadamia nut kernels. Food Bioprocess Technology 6: 2165-2176 (2013)

[5] Wall, M.M. and Gentry, T.S. Carbohydrate composition and color development during drying and roasting of macadamia nuts (*Macadamia integrifolia*). LWT-Food Science and Technology 40(4): 587-593 (2007)

[6] Mayor, L. and Sereno, A.M. Modeling shrinkage during convective drying of food materials: a review. Journal of Food Engineering 61(3): 373-386 (2004)

[7] Berteli, M.N. and Marsaioli, A. Evaluation of short cut pasta air dehydration assisted by microwaves as compared to the conventional drying process. Journal of Food Engineering 68(2): 175-183 (2005)

[8] Abbasi Souraki, B. and Mowla, D. Experimental and theoretical investigation of drying behavior of garlic in an inert medium fluidized bed assisted by microwave. Journal of Food Engineering 88: 438-449 (2008)

[9] Chandrasekaran, S., Ramanathan, S. and Basak, T. Microwave food processing – A review. Food Research International 52: 243-261 (2013)

[10] Jiao, A., Xu, X. and Jin, Z. Modelling of dehydration-rehydration of instant rice in combined microwave-hot air drying. Food and Bioproducts Processing 92: 259-265 (2014)

[11] Tirawanichakul, S., Saenaratana, N., Boon-yakiat, P. and Tirawanichakul, Y. Microwave and hot air drying of cashew nut: drying kinetics and quality aspects. Proceeding of IEEE Colloquium on Humanities, Science and Engineering Research, Penang, pp. 825-830 (2011)

[12] Zhang, H. and Datta, A.K. Electromagnetics of microwave heating: magnitude and uniformity of energy absorption in an oven, in Handbook of microwave technology for food applications, editors Datta, A.K., Anantheswaran RC, New York: Marcel Dekker Inc. pp. 33-67 (2001)

[13] Bingol, G., Pan, Z., Roberts, J.S., Devres, Y.O. and Balaban, M.O. Mathematical modeling of microwave-assisted convective heating and drying of grapes. International Journal of Agricultural and Biological Engineering 1(2): 46-54 (2008)

[14] Torringa, E., Esveld, E., Scheewe, I., Berg, R. and Bartels, P. Osmotic dehydration as a pre-treatment before combined microwave-hot-air drying of mushrooms. Journal of Food Engineering 49(2): 185-191 (2001)

[15] Sharma, G.P. and Parsad, S. Optimization of process parameters for microwave drying of garlic cloves. Journal of Food Engineering 75: 441-446 (2002)

[16] Walde, S.G., Balaswamy, K., Velu, V. and Roa, D.G. Microwave drying and grinding characteristics of wheat (*Triticum aestivum*). Journal of Food Engineering 55: 271-276 (2002)

[17] Yousefi, A., Niakousari, M. and Moradi, M. Microwave assisted hot air drying of papaya (*Carica papapy* L.) pretreated in osmotic solution. African Journal of Agricultural Research 8(25): 3229-3235 (2013)

[18] AOAC-Official Methods of Analysis of Association of Official Analytical Chemist's (1997. Helrich, K. (Ed.), Arlington

[19] Toğrul, H. Simple modeling of infrared drying of fresh apple slices. Journal of Food Engineering 71: 311-323 (2005)