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COMMUNICATION

Developing Hot Air-Assisted Radio Frequency Drying for In-shell Macadamia Nuts

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Abstract Dehydration reduces water activity and extends shelf life of perishable agricultural products. The purpose of this research was to study the application of radio frequency (RF) energy in dehydration of in-shell Macadamia nuts and shorten the lengthy process times needed in conventional hot air drying operations. A pilot scale 27.12-MHz and 6-kW RF system was used to determine the operational parameters, the drying curve, and the quality attributes of the processed nuts. The results showed that an electrode gap of 15.5 cm and a hot air temperature of 50 °C provided an acceptable heating rate and stable sample temperatures, and were used for further drying tests. The drying curves showed an exponential decay and required 750 and 360 min to achieve the final moisture content of 0.030 kg water/kg dry solid (3.0 % dry basis) in whole nuts in hot air drying and RF heating/hot air combined drying, respectively. The drying kinetics of the nuts were described well by the Page model for hot air drying, but a logarithmic model was more suited for RF/hot air drying. Peroxide value and free fatty acid increased with the drying time both for hot air and RF drying but remained within acceptable range required by the nut industry. The RF process shows potential to provide rapid, uniform, and quality-acceptable drying technology for the nut industry.

Keywords Macadamia nuts · Drying · Radio frequency · Drying kinetics · Quality

Introduction

Macadamia nuts (*Macadamia tetraphylla*) are one of the most valuable edible nuts in the world with a high monounsaturated fatty acid content that may lower the risk of heart disease (Grag et al. 2003; Borompichaichartkul et al. 2009). The top four producers in the world are Australia (40 %), the USA (24 %), South Africa (15 %), and South America (12 %) (AMS 2008; USDA-NASS 2011). Hawaii is the major producer of Macadamia nuts in the USA with an annual production of 18,200 metric tons in 2010 (USDA-NASS 2011). A major problem is nut loss caused by mold and germination during processing and storage caused by the high moisture content after harvest. Since freshly harvested Macadamia nuts have a moisture content of about 33 % dry basis (d.b.), hot air is typically used to reduce the kernel moisture content to 1.5 % d.b. for long-term storage in ambient environment. This drying process requires more than 1 month, including drying on-farm for 3–4 weeks and hot air drying in circulating bins for 6 days (Silva et al. 2006). It is desirable to develop a new drying process to

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shorten drying time and retain more nutrients in the processed nuts.

Dielectric drying using microwave (MW) or radio frequency (RF) energy has been proposed to improve conventional drying methods for preserving agricultural products. MW drying alone produces uneven heating, possible textural damage, and limited product penetration (Zhang et al. 2006). Drying methods combining MW with airflow drying (Feng and Tang 1998; Silva et al. 2006), vacuum drying (Clary et al. 2005; Cui et al. 2005), and freeze drying (Wang et al. 2005; Xu et al. 2005) have been studied to shorten drying time and improve product quality for a wide variety of dried products. Although significant progresses and beneficial evidences have been reported on MW-assisted or MW-enhanced combination drying methods, this technology is still limited to small-scale laboratory applications due to non-uniform heating, unstable temperature control, and possible product quality damage (Zhang et al. 2006).

RF drying has some advantages over MW drying, such as, better heating uniformity, greater penetration depth, and more stable product temperature (Marra et al. 2009; Wang et al. 2003a; 2011). With early applications for the post-bake drying of cookies and snack foods (Orfeuil 1987; Koral 2004), RF heating technology has been studied for thawing/tempering (Farag et al. 2010; 2011), disinfestation (Lagunas-Solar et al. 2007; Wang et al. 2007a, b), and pasteurization (Luechapattanaporn et al. 2005; Gao et al. 2011) of food and agricultural products. RF drying has also been applied to various paper, textiles, glass fibers and spools, water-based glues, pharmaceutical products, and plastics (Pound 1973; Barber 1983; Balakrishnan et al. 2004). In particular, RF drying of wood materials in combination with vacuum and other conventional drying methods has been extensively studied (Koumoutasakos et al. 2001; Dziak 2008; Li and Lee 2008; Lee et al. 2010). Several RF-assisted drying studies of foods and agricultural products have been conducted on alfalfa (Murphy et al. 1992), corn (Jumah 2005), and bean (Ptasznik et al. 1990) but not on nuts up to now. To make dielectric drying practical and acceptable by the nut industry, it is important to develop an RF drying process that ensures the desired heating uniformity with the needed drying rates without damaging nut quality.

The objectives of the current study were (1) to determine the suitable electrode gap and hot air temperature for RF drying to achieve acceptable heating rates and uniformity in Macadamia nuts, (2) to compare the drying curves of nuts when subjected to hot air only and RF heating, (3) to evaluate the suitability of the six commonly used kinetic models for both hot air and RF drying, and (4) to study the influence of hot air and RF drying time on the nut quality.

Materials and Methods

Materials and Moisture Measurement

In-shell Macadamia nuts were obtained from Island Princess Macadamia Nut Company in Hawaii, USA. After dehulling and pre-drying, the nut samples were shipped to Washington State University, Pullman, WA. To prevent moisture loss during shipping and storage, the nut samples were packed and vacuum-sealed into aluminum bags. Immediately after receiving, the packaged samples were placed under refrigeration (0–4 °C) until needed. The samples were then conditioned at room temperature overnight for drying tests.

The moisture content of shell, kernel, and whole nuts was determined by vacuum oven drying method. Ground nut samples (2–3 g) were put into aluminum dishes. Samples were placed in a vacuum oven (ADP-31, Yamato Scientific America, Inc., Santa Clara, CA, USA) at 100 °C and 21 kPa for 7 h according to a modified AOAC Official Method 925.40 (AOAC 2002). Samples were placed in desiccators with $CaSO_4$ and brought to room temperature before weighing. Each measurement was conducted in triplicate. Weight changes in samples were used to calculate the moisture content of the samples on a dry basis (d.b.). The initial moisture contents were 13.1 %, 4.7 %, and 10.6 % d.b. for shell, kernel and whole nuts, respectively.

Hot Air-Assisted RF Heating System

A 6-kW, 27-MHz free-running oscillator type pilot-scale RF system (COMBI 6-S, Strayfield International, Wokingham, UK) was used to dry the in-shell Macadamia nuts. This applicator system had two parallel plate electrodes in the applicator for RF heating. It also had a customized auxiliary hot air system consisting of a 5.6-kW electrical strip heater and a fan (Fig. 1). A detailed description of the RF and hot air systems can be found elsewhere (Wang et al. 2010). The nut samples were dehydrated under a stationary condition and in a plastic sample container (25.5 L×15.5 W×11.0 H, cubic meter) made of Teflon with perforated side and bottom walls (Fig. 2). Hot air was sent into the RF cavity through inlet holes in the bottom electrode. To improve heating uniformity and drying efficiency of nut samples, we added forced hot air at a velocity of 1 m/s inside the RF cavity, as measured by a rotating vane anemometer (LCA 6000, AIRFLOW Instrumentation, Buckingham-215 Shire, UK). To ensure repeatability of the experimental results and limit the influence of non-uniform electromagnetic fields on sample drying, the location of the plastic container was fixed on the bottom electrode during all experiments as indicated in Fig. 3.

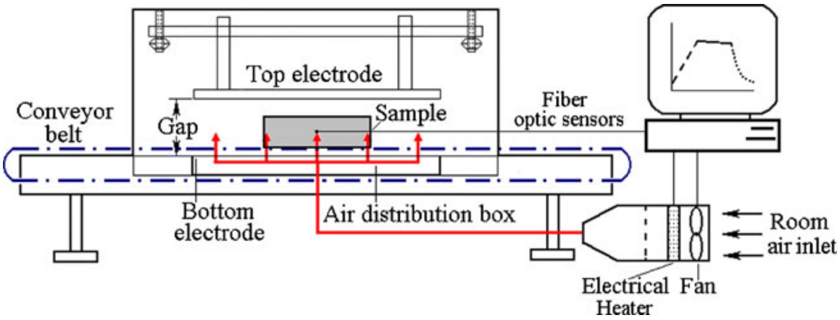

Fig. 1 Schematic diagram of the RF/hot air drying system showing the plate electrodes, conveyor belt, and the fiber optic temperature measurement (Wang et al. 2010)

Determining the Electrode Gap

Typically, the first step of experiments with a free-running oscillator style RF heating system is to determine the appropriate range of electrode gaps to deliver desired RF energy to a specific load. Since the control screen of the RF system displayed only the electrical current (*I*, ampere), the output RF power (*P*, kilowatt) was estimated using a correlation $(P = 5 \times I - 1.5)$ provided by the manufacturer (Jiao et al. 2012). Changing the electrode gap from 20 to 12 cm in the RF system adjusted the electric current, and thus the RF power. To determine the appropriate electrode gap, the plastic sample container filled with 2 kg of nut samples and without the nuts was placed between the two plate electrodes. The initial electrical current was recorded immediately after the RF power was turned on at room temperature (25 °C) without hot air heating. This procedure was repeated with decreasing electrode gap from 20 cm until the electrical current exceeded 0.55 A when the gap reached 12 cm. This experiment was repeated two times. Based on the measured electrical current, three electrode gaps were selected for further studies on improving heating rates and uniformity.

Electrode Gap and Hot Air Temperature Selection

Electrode gap and temperature of the auxiliary hot air are two important factors that influence the RF heating rate, uniformity, and drying efficiency of an RF drying system. Based on the previously selected three electrode gaps (14.5, 15.5, and 16.5 cm), three hot air temperatures (40, 50, and 60 °C) (Table 1) were chosen to measure the kernel temperatures during RF drying of in-shell nut samples. The plastic sample container was loaded with 2 kg of nuts and was placed on the bottom electrode plate (Fig. 3). Sample temperatures at seven representative locations (Fig. 2) in the container were measured using an eight-channel fiber optic temperature measurement system (UMI, FISO Technologies, Inc., Sainte-Foy, Quebec, Canada) having an accuracy of 0.5 °C. Probes connected with the seven channels were inserted into kernels through predrilled holes while the remaining channel was used to monitor the air temperature in the RF cavity. Temperatures were sampled every second and recorded every 2 min over 2 h, or until sample temperatures exceeded 90 °C. Average and standard deviation values in the temperature of the RF heated samples over the seven locations were compared to determine a suitable electrode gap and hot air temperature that yielded minimum sample temperature variations for further RF drying tests.

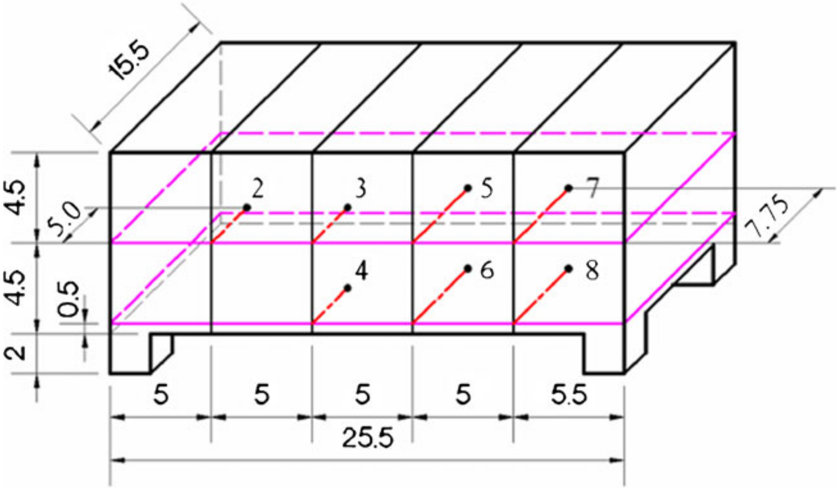

Fig. 2 The plastic container with seven fiber optic probe positions for sample temperature measurements (all dimensions are in centimeters)

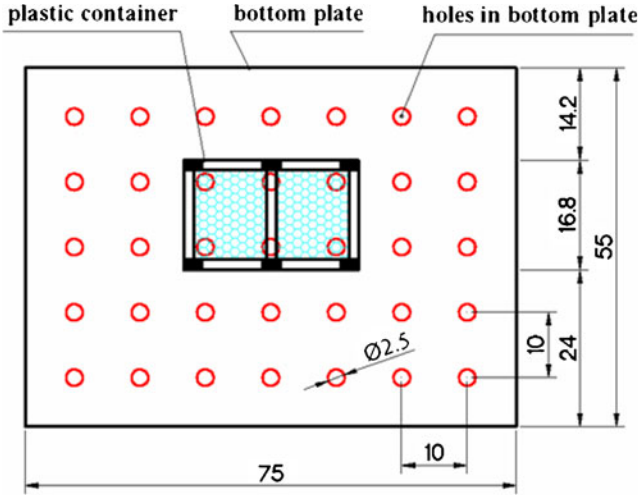

Fig. 3 Hot air inlet distributions on the bottom plate electrode and the location of the plastic container (all dimensions are in centimeters)

RF/Hot Air Drying

The plastic sample container loaded with 2 kg of raw nuts was placed on the bottom electrode plate for drying tests (Fig. 3). An optimal electrode gap (15.5 cm) and hot air temperature (50 °C) were selected based on the results of the experiments described above. Every 30 min, the container was taken out of the RF system, and the surface temperature and sample weight were measured. The surface nut temperature in the container was measured by an infrared camera (Thermal CAM^{TM} SC-3000, N. Billerica, MA) having an accuracy ±2 °C. For each of the thermal images, 45,056 individual temperature data were collected over product surface in the container and used for statistical analyses. The sample weight in the container was determined by a balance. Each measurement took about 1 min, and the sample was then placed back into the RF cavity for further heating under the same conditions. The RF/hot air drying test was completed when a final whole nut moisture content of 0.03 kg water/kg dry solid (3.0 % d.b.) and kernel moisture content of 0.015 kg water/kg dry solids were obtained. The test was replicated three times.

The highest air temperature (60 °C) used during heating uniformity tests was selected to compare hot air only drying with RF/hot air drying. The surface nut temperature and weight in the container were also measured every 30 min using the same method as described above. The hot air drying test was completed when a final moisture content of 0.01 kg water/kg dry solid was obtained for the nuts.

Drying Kinetics

To mathematically describe the drying characteristics of nuts under RF/hot air and hot air only, experimental data were fitted to various mathematical models developed for drying a variety of fruits and vegetables. Six common kinetic models are listed in Table 2 for comparison. Since these drying models are plotted in the form of moisture ratio (MR) versus time, MR is defined as:

$$\mathrm{MR} = \frac{X - X_e}{X_0 - X_e} \tag{1}$$

where X is the average sample moisture content (kilogram water/kilogram dry solid) at time t (minutes), X_e is the equilibrium sample moisture content, estimated to be 0.018± 0.001 kg water/kg dry solid by preliminary tests according to the methods used by Silva et al. (2006) and Lam et al. (2012), and X_0 is the initial sample moisture content (kilogram water/ kilogram dry solid). The experimental sets of (MR, t) were fitted to the six selected empirical models using the Statistical Package for the Social Sciences (SPSS) (version 16.0, SPSS, Inc.) nonlinear regression tool. The determination coefficient (R^2), residual sum-of-square (RSS), and standard error of estimate (SEE) were used as critical parameters to evaluate the fitness of each model. SEE was calculated as:

Table 1 Nut temperatures during RF heating as influenced by electrode gaps and air temperatures

Number	Electrode gap (cm)	Air temperature (°C)	Average heating rate (°C/min) for the first 30 min	Sample temperature (°C, average ± SD) during RF heating between 30 and 120 min
1	14.5	40	1.7	76.1±6.9
2	14.5	50	2.0	88.1±7.4
3	14.5	60	2.4	92.4[a]±4.7
4	15.5	40	1.2	62.9±5.3
5	15.5	50	1.6	77.1±5.1
6	15.5	60	1.8	82.7±5.9
7	16.5	40	0.8	49.9±4.4
8	16.5	50	1.2	63.3±5.6
9	16.5	60	1.5	72.5±3.8

[a] Radio frequency system was turned off at 48 min when temperature was higher than 90 °C due to safety concerns

Table 2 Kinetic models from the literature (Yaldýz and Ertekýn 2001; Lahsasni et al. 2004; Srinivasakannan and Balasubramanian 2009; Mota et al. 2010; Guiné et al. 2011)

Models	Equations
Page	$MR = \exp(-kt^n)$
Modified Page	$MR = \exp(-(kt)^n)$
Newton	$MR = \exp(-kt)$
Henderson and Pabis	$MR = a\ \exp(-kt)$
Logarithmic	$MR = a\ \exp(-kt) + c$
Wang and Singh	$MR = 1 + a\,t + b\,t^2$

$$\mathrm{SEE} = \sqrt{\frac{\mathrm{RSS}}{\mathrm{df}}} \tag{2}$$

where df is the degree of freedom in the experiment.

Estimation of the Effective Moisture Diffusion Coefficient

Mass transfer due to moisture migration takes place through the product so as to reach moisture equilibrium between the product and the ambient environment. The mechanisms involved can be commonly expressed by Fick's second law of diffusion for drying porous materials during the falling rate period (Zopas and Maroulis 1996). For non-steady-state diffusion when the nuts are considered to be homogeneous spherical solids, the diffusion is expressed as follows (Crank 1970; Yang et al. 2001):

$$\frac{\partial X}{\partial t} = D_{\mathrm{eff}}\left[\frac{\partial^2 X}{\partial r^2} + \frac{2}{r}\frac{\partial X}{\partial r}\right] \tag{3}$$

where D_{eff} is effective moisture diffusion coefficient (square meter per minute), and r is the spherical radius (meter) of the material (Guiné et al. 2011).

Assuming uniform initial moisture content distribution, one-dimensional moisture diffusion, no shrinkage, negligible external resistance, and a constant effective moisture diffusion coefficient throughout the drying period, the analytical solution of Eq. (3) for the nut samples is derived as follows (Crank 1970):

$$\mathrm{MR} = \frac{\mathrm{X} - \mathrm{X_e}}{\mathrm{X_0} - \mathrm{X_e}} = \frac{6}{\pi^2}\sum_{\mathrm{n}=1}^{\infty}\frac{1}{\mathrm{n}^2}\exp\left(-\frac{\mathrm{n}^2\pi^2\mathrm{D_{eff}t}}{\mathrm{r}^2}\right) \tag{4}$$

where n is the number of terms of the Fourier series and r is the average radius of the nuts. The numerical solution–regression method proposed by Marinos-Kouris and Maroulis (1995) has usually been used to fit drying data to Fick's equation. In this study, D_{eff} was determined together with R^2, RSS, and SEE both for RF/hot air and hot air only drying by fitting the experimental data (MR, t) to numerical solutions of Eq. (4) using the SPSS nonlinear regression tool. Since the Macadamia nut shape is close to a sphere and an average nut diameter of 22.8 mm was obtained by measuring 100 nuts, the trial fit was conducted as n increased from 1 to 20 and the best fit was finally achieved when n was equal to 10 since the criterion of correlation coefficient was nearest 1.

Quality Evaluation

Since Macadamia nut kernels contain approximately 75 % fat (Wang et al. 2012), oxidation of unsaturated fatty acids is the primary reason for nut quality degradation. Consequently, the most important quality indexes of Macadamia nuts, peroxide value (PV) and free fatty acid (FFA), were evaluated after RF/hot air and hot air only drying treatments for 0, 120, 240, 360, and 540 min of drying. The methods Cd 8b-90 and Ca 5a-40 (AOCS 2002) were applied to determine the PV and FFA values, respectively. The experiment was performed in triplicate.

Statistical Analysis

Mean values and standard deviations were calculated from the replicates for each hot air only and RF/hot air treatment. The mean values were compared and separated at a significant level of P=0.05 with the least significant difference t test using the Excel variance procedure (Microsoft Office Excel 2003).

Results and Discussions

Initial Current under Different Gap

Figure 4 shows the initial current with or without load (nuts) as a function of the electrode gap. Without any load, the initial RF current decreased slowly as the gap increased, and

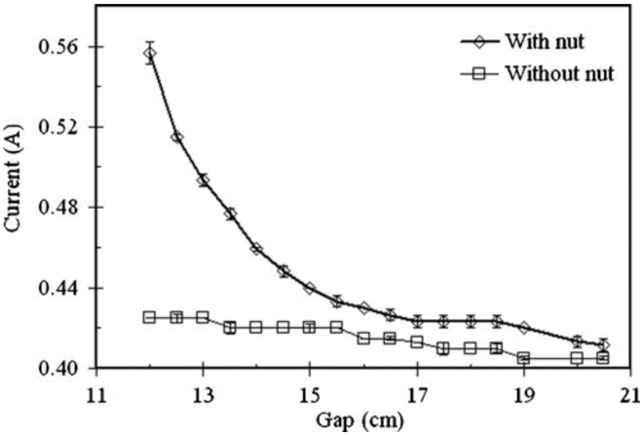

Fig. 4 Electric current of the radio frequency system as a function of electrode gap

generally was less than 0.425 A. With a load of nuts, this initial current was reduced dramatically as the gap increased from 12 to 15 cm but slowly when the gap was >15.5 cm, resulting in less than 0.75 kW of the RF output power according to the correlation reported in Jiao et al. (2012). Thus, three intermediate electrode gaps (14.5, 15.5, and 16.5 cm) were selected for further tests.

Selection of Electrode Gap and Hot Air Temperature for RF Drying

Figure 5 shows averages and standard deviations for nut sample temperatures over seven locations with electrode gaps of 16.5 cm (c), 15.5 cm (b), and 14.5 cm (a) when subjected to hot air (40, 50, and 60 °C) assisted RF heating. The average heating rate during the first 30 min of RF/hot air heating increased with decreasing electrode gap at the same air temperature and increasing air temperature at the same electrode gap (Table 1). Variation in nut temperatures increased with heating time (Fig. 5) and increasing electrode gap (Table 1). After an initial warm-up period of about 30 min, the sample temperature was maintained at a fairly constant value as the absorbed RF power was balanced by the latent heat of water evaporation. Except for the lowest sample temperature (resulting from an electrode gap of 16.5 cm and air temperature of 40 °C) and the highest sample temperature (resulting from an electrode gap of 14.5 cm and air temperature of 60 °C), the heating rate and the final mean sample temperature under all other

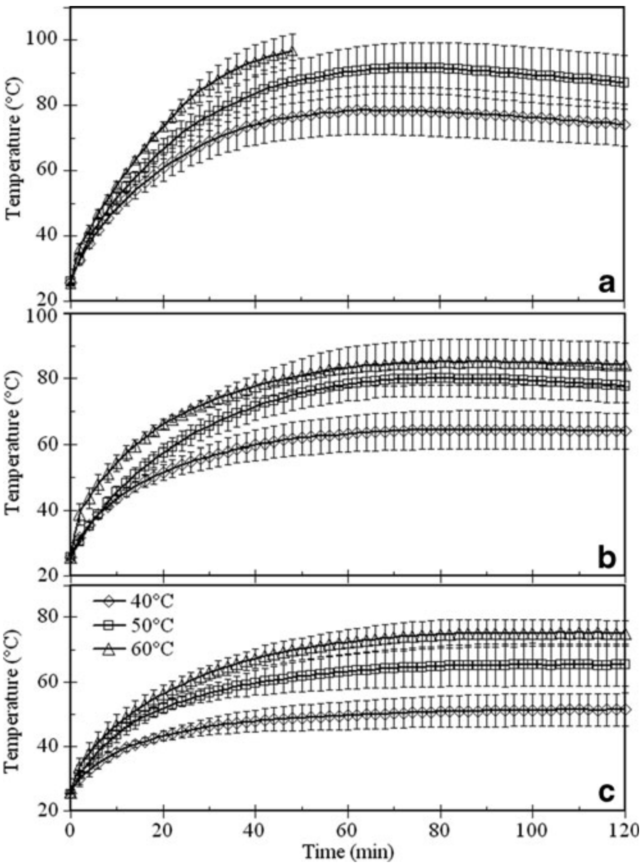

Fig. 5 Average and standard deviation values of nut temperatures over seven locations with electrode gaps of 14.5 cm (**a**), 15.5 cm (**b**), and 16.5 cm (**c**) and when subjected to hot air (40, 50, and 60 °C) assisted radio frequency drying

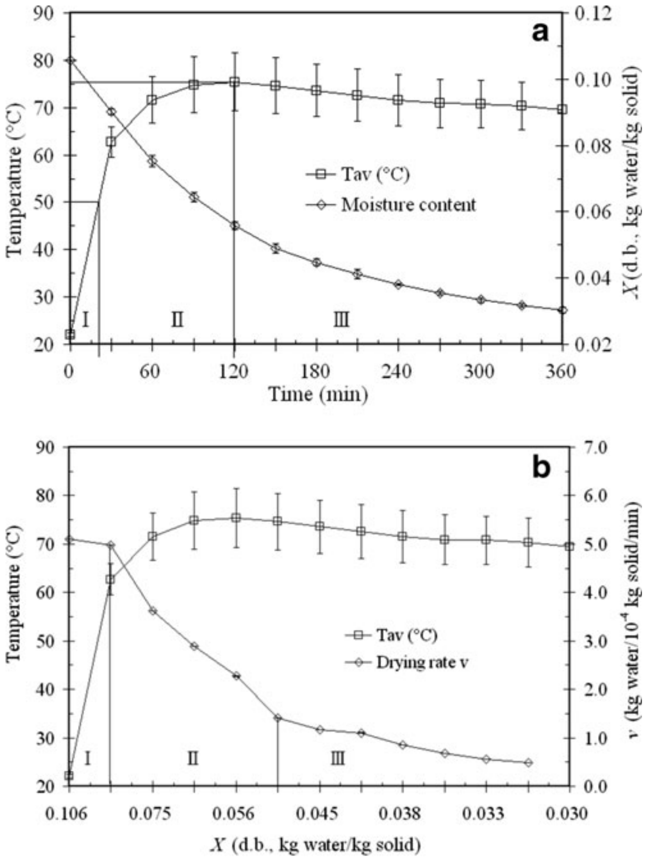

Fig. 6 Drying curve (**a**) and rate (**b**) at three stages (I, II and III) with average sample surface temperatures (T_{av}) measured by thermal imaging when subjected to hot air (50 °C) assisted radio frequency drying with an electrode gap of 15.5 cm

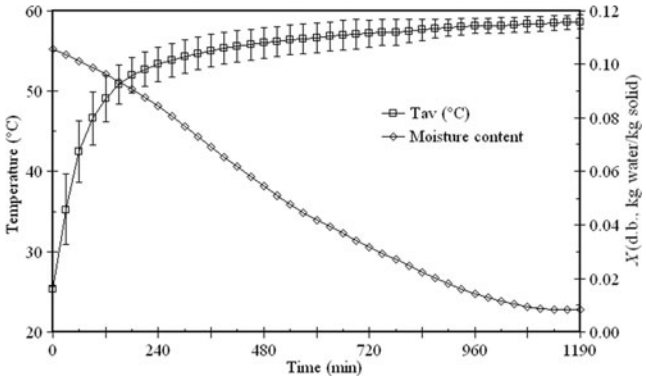

Fig. 7 Drying curve and average sample surface temperatures (T_{av}) measured by thermal imaging when subjected into hot air (60 °C) drying

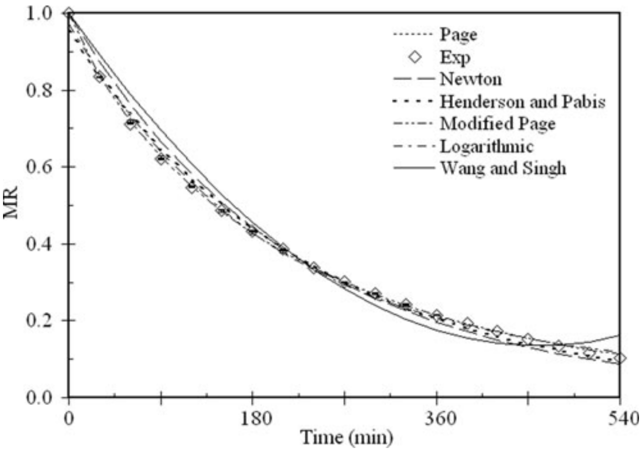

Fig. 8 Hot air drying kinetics of macadamia nuts at 60 °C fitted with six representative models against experimental values (*Exp*)

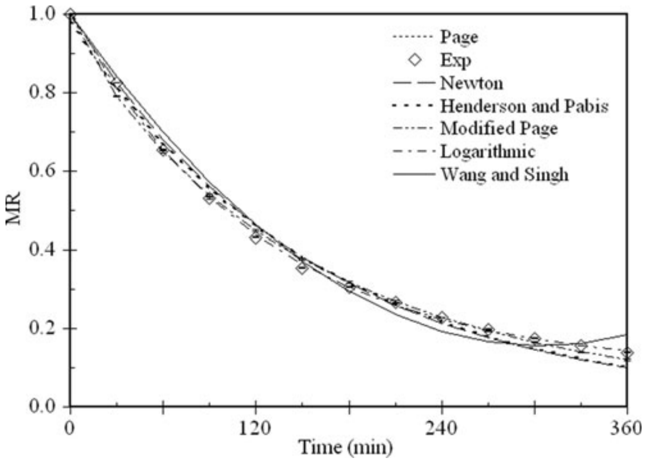

Fig. 9 Drying kinetics of macadamia nuts when subjected into hot air (50 °C) assisted radio frequency (gap of 15.5 cm) drying simulated by six representative models against experimental values (*Exp*)

treatment combinations would be acceptable for RF/hot air drying. To obtain the required drying rate and avoid nut quality degradation during and after drying, a process that combined an electrode gap of 15.5 cm with 50 °C air temperatures was selected for further drying tests.

Drying Curves of RF and Hot Air Treatments

Figures 6 and 7 show the moisture content and nut surface temperatures as a function of drying time for the RF/hot air drying and hot air drying alone. For RF/hot air drying, the sample weight or moisture content was sharply reduced during the first 150 min of drying time and slowed thereafter (Fig. 6a). This drying curve exhibited a typical exponential decay, indicating an internal mass transfer inside the nut samples during RF/hot air drying (Tulasidas et al. 1993; Feng et al. 2001). After drying for 360 min, the target moisture of 0.03 kg water/kg dry solid in whole nuts was achieved. The average sample surface temperature increased quickly during the first 30 min and was maintained between 69.5 and 75.4 °C, about 20–25 °C above the hot air temperature during the remainder of the drying process. For hot air drying, however, the drying rate was much slower than in RF/hot air drying, resulting in a longer drying time (750 min) to reach the target moisture content of 0.03 kg water/kg dry solid for whole nuts and 0.015 kg water/kg dry solid for kernels. The sample surface temperature gradually increased with drying time but was always below the hot air set point (60 °C). The drying curve exhibited a typical profile for traditional hot air drying, similar to that observed in industrial silo drying of Macadamia nuts (Borompichaichartkul et al. 2009).

The drying profile could be divided into three stages (Fig. 6a): stage I occurring from 0 to 30 min when nut temperatures were below air temperatures; stage II occurring from 30 to 150 min when nut temperatures reached their maximum level, and stage III occurring from 150 to 360 min when nut temperatures were maintained stable. These three stages could also be clarified by the changes of the drying rate v (Fig. 6b). To clearly explain the drying process, the heat generating RF energy absorbed by the nuts could be defined as (Nelson 1996; Wang et al. 2001):

$$P = 2\pi f \varepsilon_0 \varepsilon'' E^2 \tag{5}$$

where P is the energy conversion per unit volume (watts per cubic meter); E is the electric field strength in the material (volts per meter); f is the frequency of electromagnetic waves in Hz (1/second); ε_0 is the permittivity of free space or vacuum (8.854×10^{-12}F/m); ε'' is the relative dielectric loss factor of the nuts. Eq. (5) illustrates that the RF energy absorbed in dielectric

Table 3 Kinetic models for hot air drying of nuts

Model	R^2	RSS	SEE	k	n	a	b	c
Newton	0.9908	0.0111	0.0248	0.2708±0.0053				
Page	0.9997	0.0004	0.0049	0.3292±0.0031	0.8615±0.0063			
Modified Page	0.9997	0.0004	0.0049	0.2753±0.0012	0.8615±0.0063			
Henderson and Pabis	0.9953	0.0057	0.0183	0.2557±0.0052		0.9510±0.0119		
Logarithmic	0.9976	0.0029	0.0131	0.3008±0.0119		0.9133±0.0122		0.0580±0.0125
Wang and Singh	0.9736	0.0318	0.0433			−0.2255±0.0075	0.0147±0.0111	

Table 4 Kinetic models for RF/hot air drying of nuts

Models	R^2	RSS	SEE	k	N	a	b	c
Page	0.9967	0.0030	0.0165	0.4335±0.0135	0.8853±0.0264			
Modified Page	0.9967	0.0030	0.0165	0.389±0.0067	0.8853±0.0264			
Newton	0.9913	0.0079	0.0257	0.3855±0.0093				
Henderson and Pabis	0.9898	0.0092	0.0289	0.3754±0.0121		0.9771±0.0188		
Logarithmic	0.9994	0.0005	0.0067	0.4895±0.0113		0.9131±0.0074		0.0950±0.0069
Wang and Singh	0.9876	0.0112	0.0319			−0.3342±0.0032	0.0331±0.0021	

materials is linearly proportional to the frequency, the relative dielectric loss factor, and the square of the electric field (Metaxas and Meredith 1983; Orsat 1999; Wang et al. 2003b; 2010).

For treated nut samples, the total absorbed energy consists of three components of energy exchanges as expressed in Eq. (6):

$$P_{net} = P_{RF} + P_{air} - P_{vapor} \tag{6}$$

where P_{net} is the net energy accumulated in the nut sample responsible for changes in the sample temperature (watts per kilogram solid), P_{RF} is the energy input due to RF heating (watts per kilogram solid), P_{air} is the energy exchange due to the hot air heating (watts per kilogram solid), and P_{vapor} is the energy loss due to moisture evaporation (watts per kilogram solid).

At stage I, since nut sample temperatures were lower than air temperatures and the energy loss from water evaporation was still low as drying began, the net energy from both the RF and hot air heating made nut sample temperatures increase quickly, resulting in large heating rates. RF heating contributed the greatest energy due to the high loss factor of high moisture nut samples (Wang et al. 2003a; 2012). At stage II, since sample temperatures exceeded air temperatures, hot air served as a medium to carry vapor away from the nut surface and lower sample surface temperatures. RF energy was the only source of heating, in addition to providing the energy for water vaporization and heat loss to the surrounding air, resulting in slower heating rates. At stage III, the sample temperature remained almost stable ($P_{\mathrm{net}}\approx 0$) since input RF energy was balanced by heat loss from water evaporation and exchanges with hot air. A similar progression was also observed in RF drying of in-shell almonds (Gao et al. 2011). The drying rate slowed steadily due to the continuous moisture loss in nut samples. The RF/hot air drying rate was faster when compared to hot air drying alone, since a positive temperature gradient remained due to RF heating and thus the vapor pressure gradient from the sample center towards the surface sped up the drying process (Feng and Tang 1998; Feng et al. 2001).

Table 5 Effective moisture diffusion coefficient (D_{eff}) for Fick's diffusion model when subjected to hot air and RF/hot air drying

Drying method	T_{air} (°C)	Gap (cm)	$D_{\mathrm{eff}}\times 10^8$ (m^2/min)	R^2	RSS	SEE
Hot air	60	–	3.40±0.18	0.9676	0.0510	0.0532
RF/hot air	50	15.5	4.77±0.37	0.9475	0.0473	0.0628

Drying Kinetics of Nuts

Hot Air Drying

Figure 8 shows the experimental moisture ratio versus the drying time of Macadamia nuts in hot air drying at 60 °C, together with the fitted curves from the six kinetic models listed in Table 2. The results of these models are presented in Table 3, which include the estimated values and standard deviations of the model parameters with correlation coefficient (R^2) residual sum-of-square (RSS) and standard error of estimate (SEE). The data fitted the best with both Page and modified Page models. In both cases, the values for R^2, RSS, and SEE were of 0.9997, 0.0004, and 0.0049, respectively. This is in good agreement with the fitted kinetic models obtained for convective drying of pumpkin (Guiné et al. 2011). On the other hand, the model with the worst fit was that of Wang and Singh, with R^2 of 0.9736. Thus, the Page and modified Page models are listed below as those that best describe the drying kinetics of nuts under hot air

Table 6 Peroxide value and free fatty acid (mean ± SD over three replicates) of nuts as influenced by drying time when subjected to hot air and RF/hot air drying

Time (min)	Hot air		RF/hot air	
	PV (meq/kg oil)	FFA (oleic, %)	PV (meq/kg oil)	FFA (oleic, %)
0	0.12±0.02a	0.19±0.01a	0.12±0.02a	0.19±0.01a
120	0.42±0.03b	0.25±0.01b	0.41±0.02b	0.25±0.02b
240	0.52±0.03c	0.28±0.01bA	0.49±0.03b	0.26±0.02cB
360	0.66±0.03d	0.31±0.01bA	0.57±0.04c	0.27±0.01cB
540	0.72±0.03d	0.33±0.01b	–	–

Different lower and upper case letters indicate that means are significantly different among drying time and treatments, respectively, at P=0.05

drying at 60 °C:

$$\text{Page} \quad MR = \exp\left(-0.3292t^{0.8615}\right) \qquad (7)$$

$$\text{Modified Page} \quad MR = \exp\left(-(0.2753t)^{0.8615}\right) \qquad (8)$$

RF Drying

The moisture ratio versus drying time obtained from RF/hot air drying were also fitted with the six kinetic models (Fig. 9). The results of these models are presented in Table 4 and show that the best model was logarithmic, with R^2, RSS, and SEE values of 0.9994, 0.0005, and 0.0067, respectively. The worst model was also that of Wang and Singh, with R^2 of 0.9736. The logarithmic model for RF/hot air combined drying is listed below:

$$MR = 0.9131 \times \exp(-0.4895t) + 0.095 \qquad (9)$$

Moisture Diffusion Coefficients

Table 5 lists the values for moisture diffusion coefficient (D_{eff}), R^2, RSS, and SEE for both hot air and RF/hot air drying. The results showed that Fick's model used for diffusion fitted well to the experimental data. The estimated D_{eff} was in good agreement with that obtained in other studies on Macadamia nuts and pumpkins (Silva et al. 2006; Guiné et al. 2011). The D_{eff} of hot air drying was smaller than that of RF/hot air drying, and, as expected, agrees with the relative drying rates of nuts dried with hot air (Fig. 7) compared to RF/hot air drying (Fig. 6) because D_{eff} indicates the rate of water migration inside the material.

Quality Change of Nuts during Drying

Table 6 summarizes the results of nut quality evaluations during the entire drying time after hot air and RF/hot air treatments. Mean PV and FFA values increased with the drying time for both treated nuts, resulting in product quality degradation probably caused by nut oil oxidation at long exposure time and high temperatures. When compared to the control (0 min), both hot air and RF/hot air treatments did significantly ($P<0.05$) affect the PV and FFA values of nuts immediately after treatment ($P<0.05$). The PV and FFA values of hot air dried nuts were higher than those of RF/hot air at each drying period, but only FFA values at drying times of 240 and 360 min were significantly different ($P<0.05$). Similar quality results were found for walnuts and almonds after hot air and RF/hot air treatments (Buranasompob et al. 2003; Wang et al. 2007a, b; Gao et al. 2010; 2011). The final PV and FFA values both after hot air and RF/hot air drying were much lower than those required by Brazilian legislation (PV<10 meq/kg and FFA<1.5 %, ANVISA 1999) and remained within the acceptable range used by the Southern African Macadamia Growers Association (PV<3 meq/kg and FFA<0.5 %, SAMGA 2011).

Conclusions

This study demonstrated that RF/hot air treatments could shorten drying of Macadamia nuts by half when compared to hot air drying alone. Among the six drying kinetic models selected, the Page or modified Page models provided the best fit for hot air drying data, but the logarithmic model best described the nut drying kinetic models of RF/hot air drying. The results of quality studies showed that while overall quality was reduced for both hot air and RF/hot air drying, it remained within limits acceptable to the nut industry. Further studies on the effect of RF/hot air drying on nut quality during extended storage are needed. Shorter drying times for Macadamia nuts could reduce energy usage and the need for lengthy product storage, increasing overall product profitability.

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