WFL Publisher
Science and Technology
Meri-Rastilantie 3 B, FI-00980
Helsinki, Finland
e-mail: info@world-food.net

Journal of Food, Agriculture & Environment Vol.12 (2): 114-117. 2014

www.world-food.net

Electric field enhancement of macadamia drying

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Received 30 January 2014, accepted 24 March 2014.

Abstract

Macadamia nut has high nutritional values leading to a high consumer demand. However, moisture reduction after harvest is still a problem. Conventional hot air drying has high energy consumption and long drying time. Prolonged exposure to oxygen and heat results in quality deterioration. The effects of hot air temperature and electric field intensity on the drying characteristic and quality were studied. The variations of hot air temperature and electric field intensity were ranging in 40-60°C and 50-150 kV/m. Drying air velocity was fixed at 1.0 m/s. Macadamia nuts in shell were dried from a moisture content of 28-30% dry basis down to 4-5% dry basis. The dry samples were analysed for colour and peroxide value. Energy consumption was also measured. The results showed that both high temperature and high electric field intensity dry the nuts faster. The macadamia nut colour after drying at 40, 50 and 60°C was significantly different ($p \leq 0.05$). High drying temperature results in lower brightness (L*) while redness (a*), yellowness (b*) and total colour difference (ΔE) are higher. Increasing electric field intensity leads to lower brightness. Drying at higher temperature results in higher peroxide value, but peroxide value is decreased by applying the electric field. Overall, the higher drying temperature and electric filed intensity lead to a higher drying rate. The combination of hot air and electric field also leads to lower specific energy consumption.

Key words: Macadamia, colour, electric field, peroxide value, specific energy consumption.

Introduction

Macadamia nuts have abundant monounsaturated fatty acids and no cholesterol [1]. Consequently, humans do not metabolize them into cholesterol and triglycerides, and they do not increase the risk of coronary heart disease [2].

Following harvest, nuts are husked, dried, cracked and roasted. Firstly, husks are removed as soon as possible to reduce the deterioration due to high moisture and ease drying in the next step. Then, nuts are spread on a wire mesh tray with one or two layers of kernels. To reduce moisture and develop the natural oil in the nut, they are ventilated by natural air circulation in the shade for at least 2 weeks, and then they are dried down to 1 or 2% dry basis at 40°C for 48 h [3]. This loosens the nut kernel in the shell, and they are ready to crack. Subsequently, roasting at a high temperature for a short time (typically at 125°C for 20-30 min) achieves the golden colour [4].

Recently, several researchers have studied the effect of drying methods on macadamia nut quality, browning of the nut kernel during drying and roasting [5], colour and rancidity of nut after hybrid drying [6] and sensory evaluation and rancidity using microwaves to augment hot air drying [7].

Because temperature affects the moisture, colour, reducing sugar, rancidity and texture of macadamia nut, Wall and Gentry [5] studied low temperature drying (e.g. 7 days at 30°C, followed by 7 days at 40°C and 3 days at 70°C) and roasting (e.g. 20 min at 125°C) have been studied. They found that low temperature drying of fresh kernels significantly dropped reducing sugars and lightness (L*) ($p \leq 0.001$), while the dried and roasted kernels had not differ in the reducing sugar and lightness [5].

Microwave assisted drying of bananas [8], pasta [9], Brazil nuts [10] and macadamia nuts [7] not only led to shorter drying time, but also had the overall sensory acceptance. Silva *et al.* [7] showed that microwave assisted hot air drying of macadamia nuts (entrance air temperature 58-62°C and set point temperature 64-68°C) had a minimal effect on peroxide value and free fatty acid levels. For a hybrid drying process [6], which used a heat pump at 40°C to lower the moisture down to intermediate levels (8.7 and 11% dry basis) followed by hot air drying at 50-70°C, it was reported that the higher hot air temperatures resulted in the higher peroxide values especially at 70°C and intermediate moisture content of 11% dry basis. Combinations of microwave or heat pump with hot air drying could accelerate the dehydration rate and reduce the drying time, but they require a high initial investment and have variable cost.

The alternative combination of electric field with low temperature hot air drying has been shown to enhance the drying rate and qualities of several products, particularly heat sensitive products. Many agricultural products, for example potato tissue [11], carrot [12, 13], Japanese radish [14], spinach [15], red bell pepper [16], rough rice [17] and rapeseed [18] have been dehydrated by a high voltage electric field dryer. Macadamia nuts were chosen for this study because of their high sale price and heat sensitivity. The drying rate and the quality of nuts with different electric field intensities and hot air temperatures were assessed. The quality of the dried nuts was evaluated by moisture content, colour and peroxide value. In addition, the energy consumed by the combination system was compared to that for the hot air dryer without electric field.

Materials and Methods

Raw materials: Macadamia was harvested in Loei province in North East Thailand. After harvesting, the macadamia was dehusked. The nut was dried in its shell from 28-32% to 4-5% dry basis. The dried sample was stored at -20°C in a zip-lock packet for quality assessment. After that, the nut was shelled and ground to measure colour quality. The moisture content of ground nut was approximately 3% dry basis related to the 0.4-0.5 water activity. This stage shows the safe level from bacteria growth.

Experiments: A laboratory dryer at Mahasarakham University (Fig. 1), which can operate with hot air and hot air combined with high voltage electric field, was used. The drying chamber is a 0.4 m cube equipped with an axial fan and 2.0 kW electrical heaters. Air drawn in by the axial fan passes through the electrical heater, and is fed to the drying chamber. The air velocity was fixed at 1 m/s in all experiments. The hot air temperature was controlled with a PID temperature controller. The weight of sample was measured continuously by a digital balance fitted at the top of the drying chamber. The moist air is discharged to the atmosphere after passing through the drying chamber. Electric field is supplied from high voltage transformer with a voltage controller. The needle electrodes are placed at the top and the bottom of the sample screen separated by 100 mm. When transformer generates the electric field reach 160 kV/m, the system will be break down. The experiments were 3^2 factorial designs in CRD. The 9 treatments contained the three-level hot air temperature (40, 50 and 60°C) and the three-level electric field intensity (50, 100 and 150 kV/m). Three replicates were used for each experiment. Additionally, 3 treatments of hot air drying without electric field at 40, 50 and 60°C were used to compare with the 9 treatments of electric field and hot air temperature combination.

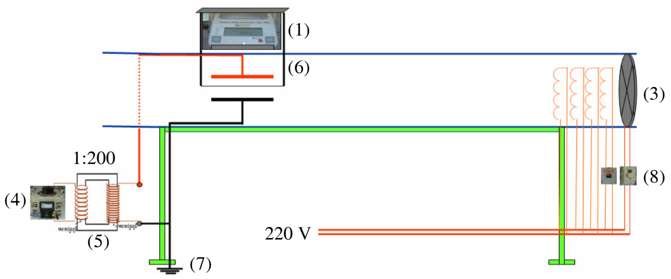

Figure 1. Schematic diagram of experimental test rig (1) digital balance; (2) electric heater; (3) axial fan; (4) variac transformer; (5) high voltage transformer; (6) electrodes; (7) ground; (8) temperature and fan speed controllers.

Moisture analysis: The dried sample was shelled, ground and placed in a vacuum oven at 70°C, 90 m bar for 24 h as suggested by Wall and Gentry [5]. Each drying condition was tested three times, and the moisture content based on dry weight was averaged. Water activity was measured using AquaLab water activity meter (AquaLink 3.0, Pullman, WA). The drying rate was calculated by following equation:

$$\text{Drying rate (DR)} = w_d \times dm/dt \quad (1)$$

where, DR is drying rate (g of water removal/ h), w_d is dry mass (g), dm/dt is slope of drying curve (Figs 2 and 3) at any time.

Colour measurement: The colour of dried samples was measured with a Mini Scan XP plus (HunterLab 45°/0°, Reston, VA) colorimeter. Sets of 20 kernels were used to determine lightness (L*), redness (a*), yellowness (b*) and total colour difference (ΔE). The ΔE was calculated:

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad (2)$$

Peroxide value measurement: Macadamia nut oil was extracted from a 25 g ground sample using hexane by the Soxhlet method for 4 h. The oil was purified by evaporating the solvent at 45°C for 45 min with a rotary evaporator (RV 10 basic V, IKA, Malaysia). Peroxide values (PV) were measured in triplicate. The following procedure runs according to the AOCS method [20].

Determination of energy consumption: The energy consumption of the hot air dryer combined with electric field was monitored with a kWh meter. Specific energy consumption (SEC) was estimated as MJ per kg of water evaporated as follows:

$$\text{SEC (MJ/kg water removal)} = \text{Total energy use (kWh)} \times 3.6 \,/\, \text{Amount of water removal (kg)} \quad (3)$$

The figure of 3.6 in Equation (3) is the conversion factor to change kWh to MJ.

Statistical analysis: To test the significance of differences in parameters, hot air temperature and electric field intensity on the colour (L*, a* and b*) and peroxide value, all data were analysed by two-way ANOVA at the confidence level of 95%.

Results and Discussion

Effect of hot air temperature on moisture reduction and drying rate: Fig. 2 shows the reduction of moisture content for different hot air temperatures. The moisture content rapidly decreased in the first 10 hours and then gradually decreased to reach the equilibrium moisture content. In the same time, the drying rate was initially high and dropped in the later stages because a lot of free surface water was evaporated in the first 10 hours. After that, bound water was slowly moved to the surface and evaporated by hot air convection.

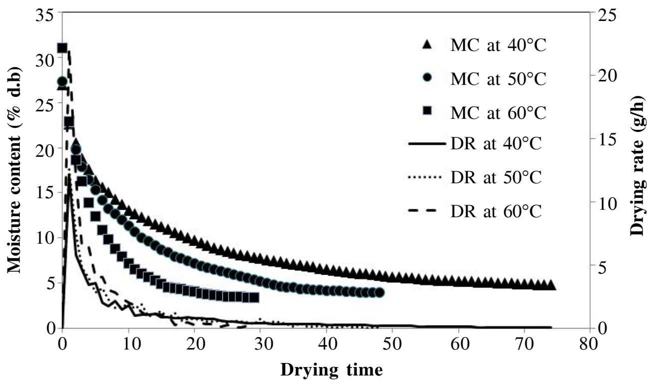

Figure 2. Moisture reduction and drying rate in different hot air temperatures.

In addition, higher air temperature resulted in a higher drying rate. Fig. 2 shows that 60°C air dried the macadamia fastest. The higher air temperature led to a higher temperature differential between the internal structure of the nuts, and the surface causing more moisture movement to surface by diffusion according to Fick's law [19].

Effect of electric field intensity on moisture reduction and drying rate: Fig. 3 illustrates the moisture reduction at a fixed 40°C air

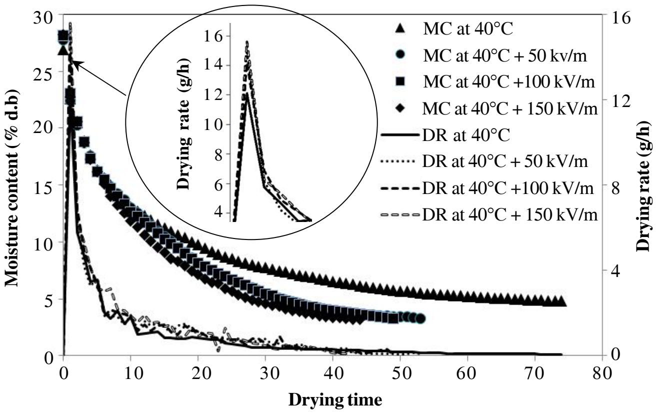

Figure 3. Moisture reduction and drying rate in different electric field intensities.

temperature with various electric field intensities. Results for other hot air temperatures (50°C and 60°C) showed similar behaviour. Fig. 3 shows that higher intensity electric field dried the nuts faster. The electric field increases turbulence of air above the surface of the nuts and reduces the thickness of the static boundary layer [17]. The thinner boundary layer allows higher convective heat transfer and higher moisture evaporation rate.

The drying time was shortest with a 150 kV/m field. At lower intensity fields, the drying times were longer by factors of 1.1 at 100 kV/m, 1.2 at 50 kV/m and 1.7 with no field. Thus, both hotter air and higher intensity field increased moisture reduction and drying rate. However, hot air was evidently more effective than electric field.

Colour quality of macadamia: The gold colour is an indicator of macadamia quality and impacts the sale price. Consumers are generally dissatisfied, when either the inside or the outside of the nuts is brown. The combined electric field with hot air dryer leads to a shorter drying time, and it would reduce the browning reaction due to heat treatment. The effects of hot air temperature and electric field intensity on nut colour are shown in Table 1. The columns in Table 1 are lightness (L*), redness (a*), yellowness (b*) and overall colour change (ΔE*).

In case of hot air drying without electric field (0 kV/m), increased temperatures led to the decreased L*and increased a* and b* clearly. Consequently, ΔE* (calculated from L*, a*and b*) also increased with temperature. For combination of temperature and intensity, the ANOVA analysis in Table 3 shows the significant effects of each parameter and interaction between both parameters. The effect of temperature on L*, a* and b* was the similar trend with case of 0 kV/m. The electric field intensity significantly affected on L*, a* and b* ($p \leq 0.05$). It had the positive effect on lightness (L*) at low temperature (40°C), but negative effect at high temperature (60°C). At the same time, the redness (a*) was increased with intensity at low temperature, but had no significant difference at high temperature, because drying time at low temperature is longer than that in high temperature evidently (Table 4). Therefore, the possible main factors of effects of temperature and intensity on the nut colour may be considered from drying time. The satisfied colour of macadamia nut, L* and a* were considered as the main factors due to consumer demand. They should be closed to the commercial L* and a*, which was applied at 40°C hot air temperature without electric field as shown in Table 1 (40°C; 0 kV/m). From 12 tested treatments, it can be noted that

Table 1. Colour of dried macadamia at various air temperatures and electric fields.

Colour	Hot air temperature (°C)	Electric field intensity (kV/m)			
		0	50	100	150
L*	40	66.0±0.6^{aA}	64.2±0.8^{bB}	62.0±0.3^{bC}	60.2±0.1^{bD}
	50	61.1±0.9^{bB}	65.5±0.4^{aA}	66.1±0.2^{aA}	65.8±0.2^{aA}
	60	59.7±0.8^{cA}	56.4±0.4^{cC}	57.4±0.1^{cB}	60.1±0.1^{bA}
a*	40	4.0±0.4^{bC}	5.0±0.1^{cB}	5.0±0.1^{cB}	6.2±0.0^{bA}
	50	3.5±0.5^{bC}	5.7±0.3^{bA}	5.7±0.0^{bA}	4.6±0.0^{cB}
	60	8.2±0.3^{aA}	7.9±0.1^{aB}	7.6±0.4^{aC}	7.8±0.1^{aBC}
b*	40	26.4±0.6^{bC}	26.8±0.4^{bC}	27.6±0.2^{bB}	29.3±0.8^{bA}
	50	24.5±1.1^{cD}	25.9±0.1^{cC}	26.9±0.1^{cB}	29.0±0.1^{cA}
	60	32.3±0.5^{aA}	29.9±0.4^{aC}	30.4±0.1^{aB}	32.2±0.1^{aA}
ΔE*	40	4.4±0.7	6.4±0.7	8.6±0.3	11.2±0.1
	50	8.5±0.8	5.4±0.4	5.4±0.1	6.3±0.2
	60	13.9±0.8	15.3±0.3	14.4±0.1	13.4±0.1

Values are the mean ± standard deviation. Different superscripts (a, b and c) in the same column imply that the values are significant different ($p \leq 0.05$).Different superscripts (A, B and C) in the same row imply that the values are significant different ($p \leq 0.05$).

Table 2. Peroxide values of macadamia undergoing the different drying conditions.

Rancidity	Hot air temperature (°C)	Electric field intensity (kV/m)			
		0	50	100	150
Peroxide value	40	0.76±0.0^{cA}	0.57±0.11^{cC}	0.66±0.01^{cB}	0.31±0.01^{bD}
	50	0.84±0.01^{bA}	0.66±0.00^{bC}	0.75±0.01^{bB}	0.31±0.02^{bD}
	60	0.93±0.01^{aA}	0.83±0.01^{aC}	0.86±0.00^{aB}	0.35±0.00^{aD}

Values are the mean ± standard deviation. Different superscripts (a, b and c) in the same column imply that the values are significant different ($p \leq 0.05$). Different superscripts (A, B and C) in the same row imply that the values are significant different ($p \leq 0.05$).

Table 3. ANOVA analysis of significance of independent variables.

Parameters	L*	a*	b*	PV
Hot air temperature (t)	**	**	**	**
Electric field intensity (e)	**	**	**	**
t*e	**	**	**	**

** Significant effect on dependent variables at $p \leq 0.05$.

Table 4. Drying time, electricity use and specific energy consumption (SEC).

Hot air temperature (°C)	Electric field intensity (kV/m)	Drying time (h)	Electricity use (kW-h)	SEC (MJ/kg water evaporated)
40	0	74	7.80	454
	50	53	7.60	399
	100	49	7.25	377
	150	44	6.85	344
50	0	48	6.91	402
	50	41	6.75	323
	100	35	6.34	316
	150	31	6.20	332
60	0	29	6.45	308
	50	24	5.82	277
	100	21	5.43	267
	150	16	5.25	252

satisfactory nut colour was obtained with 50°C hot air and up to 100 kV/m electric field.

Rancidity: This test uses the peroxide value to quantify the rancidity due to lipid oxidation. Table 2 shows the peroxide values of dried macadamia nuts at various electric field intensities and hot air temperatures. These peroxide values were statistically analysed at 95% confidence level. Increasing air temperature increased the peroxide value whilst electric field intensity had the opposite effect. The peroxide value decreased remarkably when applied the higher intensity. Especially, the peroxide value at 150 kV/m was approximately reduced more than twice compared to untreated electrical field. Table 3 shows that both temperature and intensity had significant difference in peroxide value. Besides, both variables had significant interaction with each other. It seems that the electric field had major change in peroxide value.

High temperature is major factor accelerating lipid oxidation. On the contrary, the electric field intensity not only affects the thin boundary layer of air around the macadamia, but also can deactivate the lipid oxidation. The temperature and electric field increase leading to shorter drying time. The shorter contact time between the macadamia and the air reflected in the lower peroxide value. To minimize lipid oxidation (or to maximize the unsaturated lipid content in macadamia nut), the drying should use mild temperatures (40-60°C) and be assisted by electric field to help the shortest possible time.

Energy consumption: Table 4 shows the drying time and specific energy consumption (SEC) at different temperatures and intensities. The SEC decreased with both elevated temperature and electric field intensity. Absolutely, the total energy use should be increased, when the temperature and field intensity increased. However, the temperature and intensity levels result in the lower drying time. Totally, the SEC became lower. This indicated that the drying time is the main factor for energy saving. Optimizing temperature level and field intensity are key energy saving factors. To minimize the SEC, the optimum conditions are hot air at 60°C with 150 kV/m electric field.

Conclusions

The electric field enhancement of macadamia convective hot air drying can be summarized as follows. Electric field could assist to increase drying rate and reduce the drying time (reduce the contact time between the macadamia and the air). The nut kernel became lighter and more red by using higher temperature and intensity. The rancidity was higher, when temperature increased and intensity decreased. In addition, drying time was also main factor, which affected directly the energy consumption. To balance quality based on colour and rancidity against energy consumption, drying should use hot air at 50°C with electric field of 50-100 kV/m. These conditions lead to moderate energy consumption but produce good quality product.

Acknowledgements

We are thankful to the Faculty of Engineering of Mahasarakham University for the financial support with thermal research unit.

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