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Considerations in design of commercial radio frequency treatments for postharvest pest control in in-shell walnuts

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Abstract

Scaling-up radio frequency (RF) treatment protocols to control insect pests in in-shell walnuts is an essential step to transfer laboratory results to industrial applications. Practical considerations in this effort should include walnut orientation, differential heating between open and closed shell walnuts after bleaching, intermittent mixing to improve heating uniformity, nut quality after storage, and energy costs. A pilot-scale 27 MHz, 6 kW/12 kW RF system was used to determine the effect of process parameters on walnut temperature distribution. Temperatures of vertically oriented walnuts were 7.4 °C higher than those of horizontally oriented walnuts. The open shell walnuts heated much faster in RF systems than closed shell walnuts after 1.5 min of bleaching. Mixing the walnuts twice during 3 min of RF treatment improved the heating uniformity of final walnut temperatures by reducing non-uniformity of the electromagnetic field in the RF system. The accelerated shelf life tests at 35 °C for 10 and 20 days provided accurate simulations of actual storage at 4 °C for 1- and 2-year periods, respectively, based on similar peroxide and free fatty acid values. The energy costs of treating 4540 kg/h was only $0.23 cents/kg. This study should provide useful information for designing an industrial scale quarantine security process against insect pests in walnuts as an alternative to chemical fumigation.

Keywords: Heat treatment; Insect control; Phytosanitary; Quarantine; Radio frequency; Walnut

1. Introduction

Electromagnetic energy in a wide band of frequencies ranging from 3 MHz to 30 GHz has been investigated in laboratory research to control insects in agricultural products (Wang & Tang, 2001). The US Federal Communications Commission (FCC) allocates five frequencies for industrial, scientific and medical applications: 13.56, 27.12 and 40.68 MHz in the radio frequency (RF) range, and 915 and 2450 MHz in the microwave range. RF energy has been favored over microwave energy in many studies for pest control because of the larger penetration depths and possible differential heating of insects in commodities associated with RF energy (Frings, 1952; Headlee & Burdette, 1929; Nelson, 1996; Nelson & Payne, 1982; Wang, Tang, Cavalieri, & Davis, 2003; Wang, Tang, Johnson, et al., 2003). However, commercial processes based on RF energy have not yet been developed as post-harvest treatments against insects in nuts or dried fruits (Tang, Ikediala, Wang, Hansen, & Cavalieri, 2000).

Recently, the interest in studying RF treatments has increased because methyl bromide may be eliminated and banned in the near future for post-harvest phytosanitary treatments according to the Montreal protocol (Tang et al., 2000). Walnuts are routinely fumigated

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with methyl bromide for insect control prior to shipment. Several pilot-scale RF studies have been reported as a new means to rapidly deliver thermal energy to walnuts for insect control without significant quality degradation (Wang, Ikediala, et al., 2001; Wang, Tang, Johnson, Mitcham, et al., 2002). These protocols are developed based on thermal-death-time (TDT) curves determined for the three important insects infesting walnuts, such as codling moth (Wang, Ikediala, Tang, & Hansen, 2002), Indian meal moth (Johnson, Wang, & Tang, 2003) and navel orangeworm (Wang, Tang, Johnson, & Hansen, 2002). RF energy directly interacts with the kernel inside the shell resulting in a fast and linear ramp of the kernel temperature to a lethal level (53–55 °C) for insect pests (Wang, Tang, & Cavalieri, 2001). Laboratory and pilot-scale tests are essential to the development of treatment protocols because optimal information can be found easily using small-scale experiments. But, it is important to transfer pilot-scale or laboratory research results to large-scale industrial implementations. The factors influencing the commercial RF processes should be taken into account, including walnut orientation, differential heating between open and closed shell walnuts, actual post-storage, and energy costs.

Heating uniformity in the RF-treated walnuts is a major concern in developing a large-scale treatment. In-shell walnuts are non-isotropic materials due to the irregular shape of the shell and kernel. The variations in walnut temperature after RF heating are caused by the different properties and shape of individual walnuts and different positions of the walnuts in non-uniform RF fields. It is desirable to minimize the effect of walnut orientations and positions by mixing the walnuts during RF treatment.

In-shell walnuts are often bleached to lighten the shell color following the fumigation treatment. In the bleaching operation, 3% sodium hypochlorite solution is used for walnuts shipped within the US or export to Spain, and 6% hydrogen peroxide solution is used for export to Germany. Walnuts absorb these solutions during soaking that results in different moisture contents within the walnuts, depending on the condition of the walnut shells, i.e. open, closed, cracked, or infested. These walnuts must then be dried to assure they will not support mold growth. RF heating could rapidly dry these nuts, but this presents an additional source of variability in nut temperature. Moist materials in general have high dielectric loss factors, resulting in the potential of differential RF heating between walnuts with open and closed shells.

The lipid oxidation reaction should be determined to evaluate walnut quality following exposure to elevated temperatures. Buranasompob, Tang, Mao, and Swanson (2004) reported that heating shelled walnut kernels with 60 °C hot air for up to 10 min did not increase rancidity compared to untreated walnuts. Walnut quality after heating with RF energy to 55 °C and holding at that temperature for up to 10 min shows that the final peroxide values (PV) and free fatty acids (FA) after accelerated storage at 35 °C for up to 20 days simulating 2 years of storage at 4 °C remained below the industry standard values (PV < 1.0 meq/kg and FA < 0.6%) for good walnut quality (Wang, Tang, Johnson, Mitcham, et al., 2002). However, the effect of actual storage conditions on potential development of rancidity of RF-treated walnuts should also be evaluated.

The objectives of this study were (1) to determine the effect of walnut orientation on the final temperature distributions, (2) to explore differential heating between open and closed shell walnuts after bleaching, (3) to evaluate heating uniformity improvements using pulsed RF heating and intermittent mixing in RF-treated walnuts, (4) to determine any quality difference between actual stored walnuts and walnuts subjected to accelerated storage life tests, and (5) to estimate the energy costs for a large-scale treatment.

2. Materials and methods

2.1. Orientation and position effects

A 12 kW, 27 MHz pilot-scale RF system (Strayfield Fastran with E-200, Strayfield International Limited, Wokingham, UK) was used to heat in-shell walnuts in this study. A plastic container (40 × 27 × 12 cm) was placed between two parallel plate electrodes (104 cm × 80 cm), in which 4.5 kg of in-shell walnuts were heated (Fig. 1). The minimum and maximum gaps between the two electrodes were 200 and 400 mm, respectively. The actual gap (≈260 mm) between the electrodes was adjusted to obtain a heating rate of about 5–10 °C/min depending on the samples. After a predetermined heating time, the container was taken out of the RF system for temperature mapping using an infrared camera (Thermal CAM™ SC-3000, N. Billerica, MA) with an accuracy of ±2 °C. A thermal image was taken for the entire walnut surfaces in this container

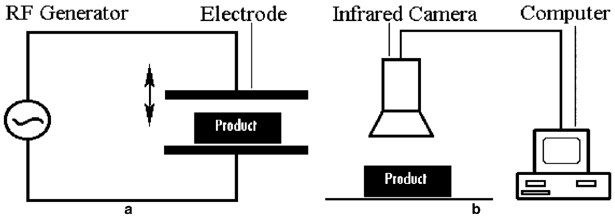

Fig. 1. Schematic view of the pilot-scale 27 MHz radio frequency (RF) system used to treat walnut sample (a) and the infrared imaging system to measure product surface temperature after RF treatment (b).

to evaluate the heating uniformity. Tests were also conducted to determine the effect of walnut orientation on heating uniformity. Four horizontally and four vertically oriented walnuts in a similar size were placed in the center of the container. Fiber-optic sensors (FOT-H, UMI, FISO Technologies Inc., Saint-Foy, Que., Canada) with an accuracy of ±0.5 °C measured the kernel temperatures of the eight walnuts.

2.2. Differential heating between open and closed shell walnuts

Kinetics for water absorption during bleaching operation was studied with open (infested) and closed (good) shell walnuts. Walnuts with closed and open shells were manually selected based on appearance. Changes of an individual walnut weight were recorded after soaking for 0, 2, 4 and 6 min in a water bath (Model ZD, Grant, Cambridge, UK) containing heated water at 35 °C or 50 °C. Before weighing each walnut, the free surface water was dried by paper towel. The average and standard deviation values of the increased moisture content were estimated from the initial moisture content and changes in the weights measured by an electronic balance. These tests were conducted in three replicates. FISO fiber-optic sensors inserted through pre-drilled holes (1.4 mm of diameter) in one open and five closed shell walnuts located in the container center were used to monitor the kernel temperatures during RF heating after 2-min soaking in tap water.

To further investigate possible differential heating in open and closed shell walnuts, in-shell walnuts were bleached in two different solutions: 3% sodium hypochlorite (NaClO) and 6% hydrogen peroxide (H_2O_2). Chorox bleach (about 6%) procured from a local grocery store was diluted to the required concentration of 3% sodium hypochlorite. The 6% hydrogen peroxide solution was diluted from 30% hydrogen peroxide solution. Sixty in-shell walnuts were agitated in either solution at 22 °C for 1.5 min. Surface free water on the shell was dried by paper towel.

The targeted samples including three closed and three open shell walnuts were placed together in the same layer in the center of the container (28 cm × 18 cm × 7 cm) before RF treatment. The kernel temperatures of these six walnuts during RF heating in the pilot-scale 6 kW, 27 MHz RF system, (COMBI 6-S, Strayfield International Limited, Wokingham, UK) were measured using the fiber-optic temperature sensors through pre-drilled holes in the shell after bleaching. Finally, the surface temperatures of those walnuts were immediately measured after RF heating by the infrared camera. The positions of those treated walnuts were recorded by a digital camera with a resolution of 4.1 megapixels (Sony, Cyber Shot W4, Sony Electronics Inc., Tokyo, Japan).

2.3. Improving heating uniformity with mixing

The 12 kW, 27 MHz pilot-scale RF system was used to determine the heating uniformity of in-shell walnuts under pulsed RF energy and with two-intermittent mixings. One open shell walnut and seven closed shell walnuts were soaked in tap water for 2 min at 22 °C to simulate bleaching operation. Immediately after drying off the surface water with paper towel, they were placed in a single layer in the container for RF heating. The kernel temperatures of the samples were monitored by the FISO fiber-optic temperature system. The temperature–time history was recorded when the walnuts were subjected to pulsed RF heating (30 s on and off). For the mixing tests, the same plastic container (40 cm × 27 cm × 12 cm) was placed between two parallel plate electrodes (104 cm × 80 cm), in which 4.5 kg in-shell walnuts were heated. The gap between the electrodes was adjusted to provide a heating rate of about 10 °C/min with the RF power set at 4 kW with the actual gap of 240 mm. After 3 min of heating, the container was immediately taken out of the RF system for temperature measurement using the infrared camera. The walnut temperature distribution after 3-min RF heating with mixing of the nuts after 1 and 2-min heating was also tested under similar conditions as described above. In each of the thermal images, 45,056 individual temperature data were collected from the surface of the container and were used for statistical analyses.

2.4. Actual and accelerated storage life effects on walnut quality

Calculations for the accelerated storage simulation were based on the Q_{10} factor, which is commonly used in the food industry to quantify the rate of quality change (k) in storage as affected by an increase in temperature (T, °C). It is defined as the ratio of quality change rate at $T + 10$ °C to that at T (Taoukis, Labuza, & Sagus, 1997):

$$Q_{10} = \frac{k(T + 10\,^{\circ}\mathrm{C})}{k(T)} \tag{1}$$

Since storage life is inversely proportional to the rate of deterioration, Eq. (1) can also be written as

$$Q_{10} = \frac{\theta_s(T)}{\theta_s(T + 10\,^{\circ}\mathrm{C})} \tag{2}$$

where θ_s stands for the storage life of a product. In general we have:

$$Q_{(T_2-T_1)} = Q_{10}^{(T_2-T_1)/10} = \frac{\theta_s(T_1)}{\theta_s(T_2)} = \frac{k(T_2)}{k(T_1)} \tag{3}$$

The temperature difference for Q_{10} value between the accelerated storage-life study and the actual storage should be kept in a small range to avoid significant chemical or physical changes in quality at the two temperatures (Taoukis et al., 1997). Values of Q_{10} can be used to predict storage life at lower temperatures based on the storage life at higher temperatures. The Q_{10} values range from 1.5 to 2.0 for sensory quality loss, 1.5 to 3.0 for rancidity, 4 to 10 for browning reactions, and 20 to 40 for quality loss for some frozen fruits and vegetables (Labuza, 1982, 1984). A Q_{10} value of 3.4 was used in our previous studies (Wang, Tang, Johnson, Mitcham, et al., 2002) based on reported literature on lipid oxidation at 35 °C (Taoukis et al., 1997). With a Q_{10} value of 3.4, accelerated storage life tests of in-shell walnuts were performed in an incubator at 35 °C and 30% relative humidity (RH) for 10 and 20 days. These conditions should simulate approximately 1 and 2 year storage periods at 4 °C, respectively.

To compare the walnut quality difference between actual storage life at 4 °C (1 and 2 years) and accelerated storage life at 35 °C (10 and 20 days), untreated and RF-treated (55 °C + 5 min) walnuts were evaluated at the same time based on the PV and FA values of the kernels using methods Cd 8-53 and Ca 5a-40 of the American Oil Chemists Society (AOCS, 1998a, 1998b). Detailed measurement procedures and calculations of PV and FA values were described in Wang, Ikediala, et al. (2001). Mean values and standard deviations were calculated from three replicates of each treatment.

After determining the PV and FA values for accelerated and real storage life, an actual Q_{10} value was estimated according to the quality change rate k and derived from Eq. (3):

$$Q_{10} = \left[\frac{k(T_2)}{k(T_1)}\right]^{\frac{10}{T_2 - T_1}}, \tag{4}$$

where T_1 and T_2 are 4 °C and 35 °C, respectively. $k(T_1)$ and $k(T_2)$ were calculated as the average quality changes over a specific time at a given temperature. For example, k (35 °C) from the measured PV was calculated as PV at 35 °C for 20 days minus PV at 0 days and divided by 20 days.

2.5. Energy costs estimation

The rise in walnut temperature was assumed to be the result of only RF heating. The heat losses to the surrounding environment and re-circling of other forms of thermal energy were neglected because of short treatment time (5 min) and porous nature of walnut shell, which should act as a good insulation. The RF power absorbed by walnuts to raise the mean temperature can be expressed as

$$P = \frac{mC_p}{\eta}\Delta T \tag{5}$$

where C_p is the specific heat of walnut kernels (J kg^{-1} °C^{-1}), m is the total walnut mass treated in a unit time (kg/s); P is the power absorbed by the walnuts (W), ΔT is the temperature increase in the walnuts (°C). η is the energy efficiency, which was estimated to be 60% from preliminary experiments with the same system. The calculated power required for a period of time was used to determine the power output needed from the RF system and the energy costs at a given location (e.g. CA, USA) of a processing plant.

3. Results and discussion

3.1. Orientation and position effects

The effect of walnut orientation on average and standard deviation temperatures of walnuts during RF heating were investigated (Fig. 2). After 5 min of RF heating, the four vertically oriented walnuts had average and standard deviation temperatures of 61.3 °C and 1.9 °C, respectively, which were higher than those of the four horizontally oriented walnuts, 53.9 °C and 1.1 °C, respectively. The average temperature difference reached 7.4 °C. Vertically oriented walnuts perhaps provided preferred paths for RF energy as compared with horizontally oriented walnuts. Therefore, it is necessary to design a mixing or tumbling process to eliminate the non-uniform heating caused by different orientations of walnuts.

A typical walnut surface temperature distribution was obtained by thermal imaging after RF treatments (Fig. 3). There were two hot spots (about 70 °C) near the lower right corner and cold spots (about 28 °C) around the surrounding walls of the plastic container. Similar results were also reported elsewhere (Wang, Yue, Tang, & Chen, 2005). Excluding the boundary area of the container, the average, maximum difference and

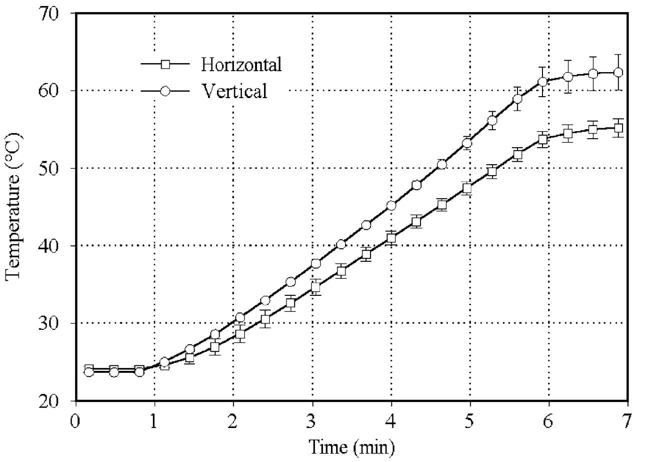

Fig. 2. Typical temperature–time history (average and standard deviation) of four horizontally and vertically oriented walnuts in the center of a single layer when subjected to RF heating.

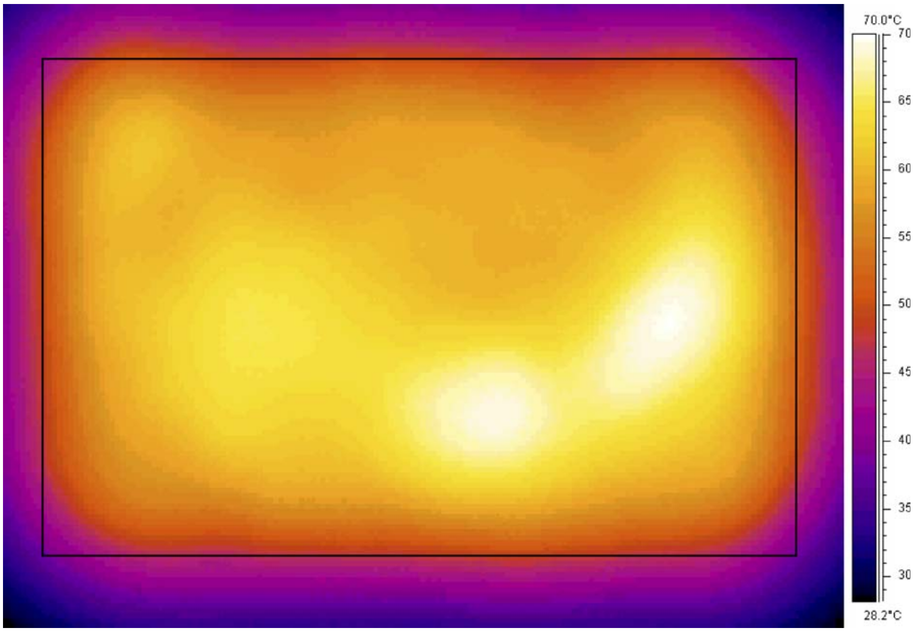

Fig. 3. Typical walnut surface temperature distribution after RF treatments obtained by thermal imaging within the boundary field used for statistical analyses.

standard deviation of the walnut temperatures over the central area (21.5 cm × 13.2 cm) were 62.8 °C, 13.3 °C and 3.0 °C, respectively. This suggested that the RF field was not uniform. Hot spot in the center and cold ones around four corners were observed in a water load in the same RF unit (Wang & Tang, 2003). A mixing process should help to reduce the effect of walnut positions on the non-uniformity.

3.2. *Differential heating between open and closed shell walnuts*

In open shell walnuts, the moisture gain increased sharply during the first 2 min of soaking in tap water, but slowly after 2 min, especially after 4 min of soaking (Fig. 4). The average moisture gain (28.1 ± 0.9%) at 50 °C was higher than that (20.6 ± 1.2%) at 35 °C after 4-min soaking. The moisture gain (1.8 ± 0.4%) in closed shell walnuts was very low, even after 6-min of soaking.

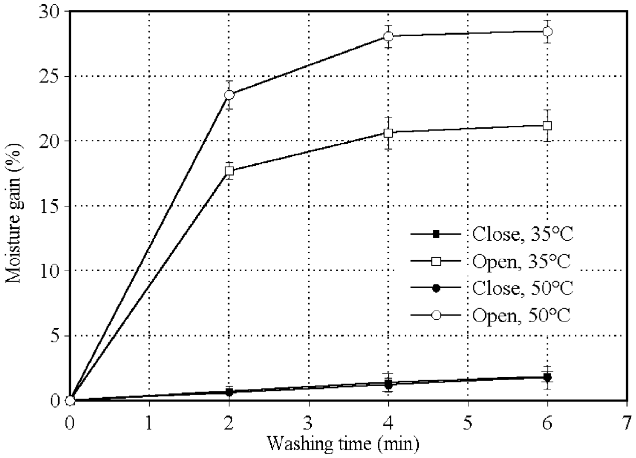

Fig. 4. Moisture gain (average and standard deviation over three replicates) of an individual open and closed shell walnuts when immersed in a water bath at 35 °C and 50 °C.

The temperature–time history for walnut kernels was monitored for one open and five closed shell walnuts during RF treatment after 2-min tap water soaking (Fig. 5). The open shell walnut heated much faster than the closed shell walnuts. The heating rate was about 49 °C/min for open shell walnuts versus 7.5 °C/min for closed shell walnuts. The temperature difference after 1.2 min of RF heating reached 44.1 °C, which would assure death of the insects in the open shell, infested walnuts. Mitcham et al. (2004) also observed that walnuts with higher moisture contents were heated faster than lower moisture content walnuts. Based on the actual heating rates reported by Mitcham et al. (2004), we estimated that the moisture contents for open and closed shell walnuts were around 14% and 5%, respectively. This agreed well with the data obtained in Fig. 4.

In our current studies when using an absolute moisture gain of 3% as a criterion to separate infested (open shell) walnuts from non-infested (closed shell) walnuts, only 75% of the walnuts were correctly categorized as infested. Some infested walnuts had completely sealed shells. There was a period before the shells had hardened when the nuts were vulnerable to insect attack. Regardless, the higher moisture content would assure complete disinfestation for about 75% of the infested walnuts due to extremely fast heating in the RF system.

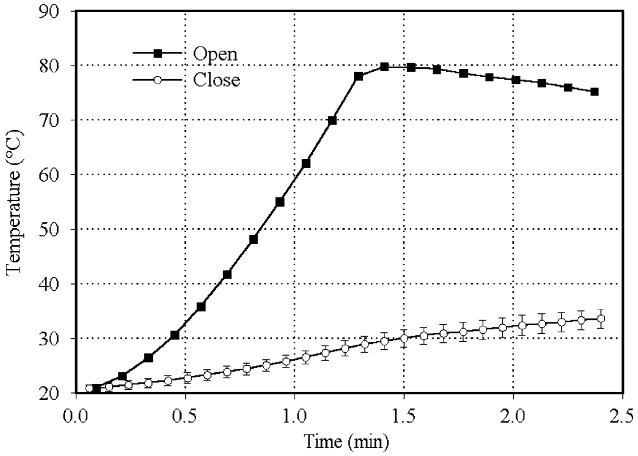

Fig. 5. Temperature–time history of walnut kernels for one open and five closed shell walnuts (average and standard deviation) during RF treatments after 2-min tap water soaking.

The temperature–time history of walnut kernels was monitored for three-pairs of walnuts with closed (#1–3) and open (#4–6) shells during RF treatments after 1.5-min sodium hypochlorite bleaching (Fig. 6). The final temperatures of the six walnuts (#1–6) obtained by the fiber-optic sensors were 33.4, 39.2, 39.8, 43.1, 57.8, and 52.1 °C versus 36.4, 40.1, 41.3, 47.3, 60.9 and 54.5 °C obtained by the thermal image. The average difference between the two methods of temperature measurement was 2.5 °C. The temperatures of closed shell walnuts increased more slowly than the open ones, based both on the temperature–time history and the thermal image. The different heating rates of open walnuts were caused by the different water absorption conditions. One out of three open shell walnuts had similar temperature as those of the closed shell walnuts.

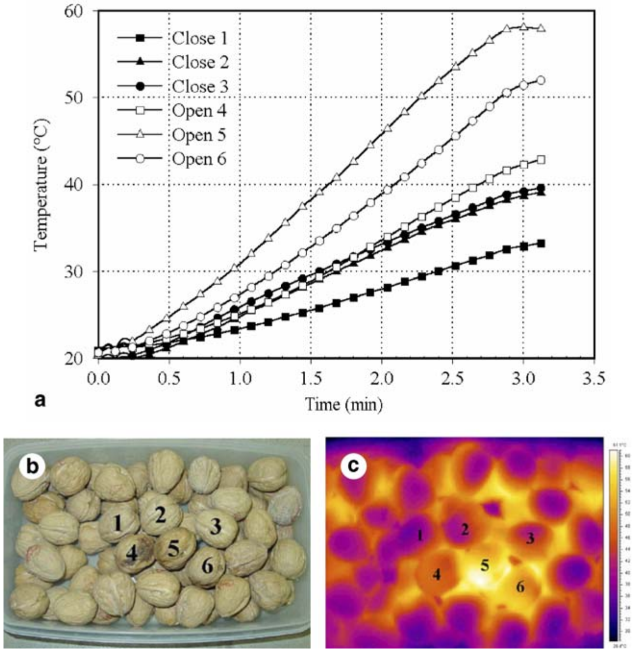

Fig. 6. Temperature–time history (a) and surface temperature distributions (c) of walnut kernels for three closed (#1–3) and three open (#4–6) shell walnuts (b) during RF treatments after 1.5-min sodium hypochlorite bleaching.

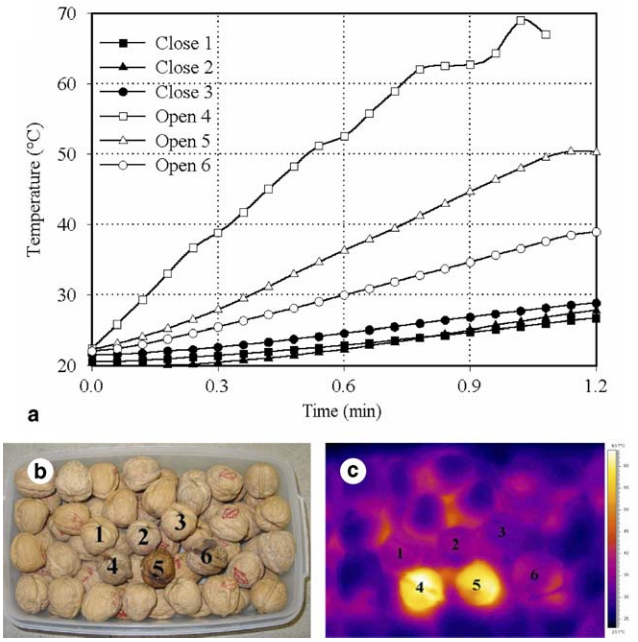

Fig. 7. Temperature–time history (a) and surface temperature distributions (c) of walnut kernels for three closed (#1–3) and three open (#4–6) shell walnuts (b) during RF treatments after 1.5-min hydrogen peroxide bleaching.

The temperature–time history of walnut kernels was monitored for three open and three closed shell walnuts during RF treatments after 1.5-min hydrogen peroxide bleaching (Fig. 7). The open shell walnuts had faster heating rates than the closed shell walnuts. The final temperature of open shell walnuts (#4, 5 and 6) reached 67.0, 50.4 and 38.7 °C measured by the fiber-optic sensors while the closed shell walnuts (#1–3) reached only 26.7–28.8 °C. The thermal imaging data confirmed the above observation. Bleaching with 6% hydrogen peroxide solution resulted in much faster heating in open shell walnuts compared to bleaching with 3% sodium hypochlorite solution. A major reason for this difference was the much higher ionic conductivity in the 6% hydrogen peroxide solution. In RF heating, ionic conduction played a more dominated role than polarization of water molecular (Tang, Feng, & Lau, 2002; Wang, Tang, Johnson, et al., 2003).

3.3. Heating uniformity improvements

Fig. 8 shows a typical temperature–time history of one open shell walnut and average with standard deviation of seven closed shell walnut kernels in the center of the container when subjected to pulsed RF heating.

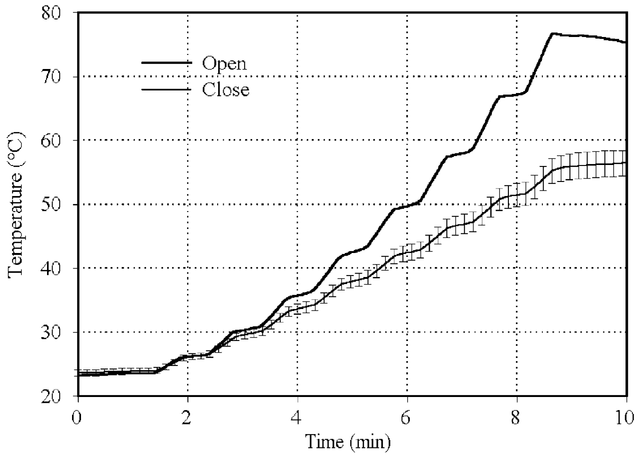

Fig. 8. Typical temperature–time history of one open shell walnut after soaking and average and standard deviation variations of seven closed shell walnuts in the center of a container when subjected to pulsed RF heating (30 s on and 30 s off of power).

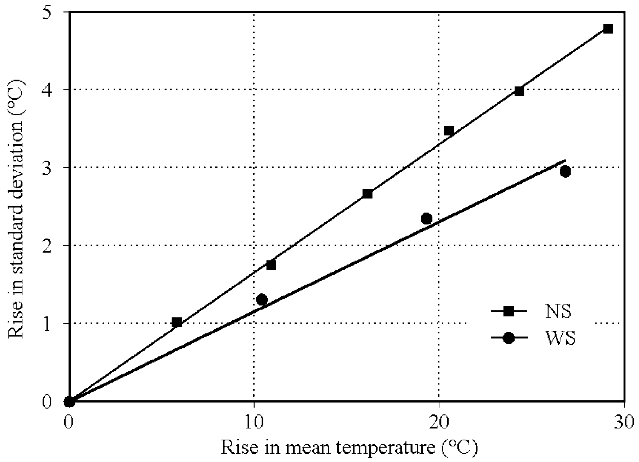

Fig. 9. Relationship between the rise in standard deviation and the rise in mean of walnut kernel temperatures with (WS) and without (NS) mixing.

There was a clear step in the temperature increase corresponding to each 30 s power on and off cycle for all walnuts. After 2.7 min pulsed RF heating, the open shell walnut kernel temperature remained to be higher than the other seven closed shell walnuts and the temperature difference among them gradually increased. The effect of pulsed heating on heating uniformity was negligible due to small heat conduction during the short period of RF treatments.

After sorting and removing open shell walnuts, the heating non-uniformity of walnuts over different positions and orientations still existed in RF heating. Fig. 9 shows the relationship between the rise in standard deviation and the rise in mean of walnut temperature with and without mixing during 3 min RF heating. The heating uniformity of the walnuts was greatly improved with two-intermittent mixings because the ratio of the rise in standard deviation to the rise in mean temperature was reduced from 0.165 to 0.115 for operations with mixing. The standard deviations of walnut temperatures were significantly reduced from 4.8 °C without mixing to 3.0 °C for walnuts mixed two times during RF heating. The average kernel temperatures in 3-min RF heating were 47.6 and 45.6 °C, respectively, for RF heating without and with two-time intermittent mixings. The slight mean temperature reduction was probably caused by the heat loss during mixings. Use of forced hot air should help to minimize the mean temperature reduction and the extreme temperature differences among the treated walnuts during the mixing process. The optimum number of mixings can be determined based on the required insect control level, walnut quality and operation costs (Wang et al., 2005). The maximum temperature difference among the RF-treated walnut kernels might be controlled within 10 °C at the final stage while the average kernel temperature was around 55 °C. This temperature distribution could completely kill insect pests in walnuts without quality damage (Mitcham et al., 2004; Wang, Tang, Johnson, Mitcham, et al., 2002).

3.4. Storage life effects on walnut quality

A comparison of the quality characteristics based on the PV and FA values in pressed walnut oil between walnuts from the accelerated storage life and the actual storage tests after RF treatments are summarized in Table 1. The RF treatments did not significantly affect the PV and FA values during the accelerated storage at

Table 1
Storage quality characteristics of in-shell walnuts treated by radio frequency (RF) energy with three replicates

Treatments	Peroxide value (meq/kg)		Fatty acid (%)	
	Control	RF + 5 min	Control	RF + 5 min
0 days	0.01 ± 0.01	0.05 ± 0.05	0.10 ± 0.01	0.08 ± 0.02
10 days at 35 °C	0.28 ± 0.11	0.12 ± 0.01	0.15 ± 0.01	0.16 ± 0.04
1 year at 4 °C	0.09 ± 0.01	0.11 ± 0.09	0.13 ± 0.00	0.13 ± 0.03
20 days at 35 °C	0.64 ± 0.16	0.37 ± 0.16	0.21 ± 0.01	0.22 ± 0.06
2 years at 4 °C	0.39 ± 0.02	0.30 ± 0.04	0.08 ± 0.01	0.09 ± 0.02

Table 2
Actual Q_{10} value for accelerated storage quality with peroxide value (PV) and fatty acid (FA) of in-shell walnuts treated by radio frequency (RF) energy

Storage conditions used for calculation	Q_{10} value			
	PV for control	PV for RF + 5 min	FA for control	FA for RF + 5 min
10 days at 35 °C versus 1 year at 4 °C	4.72	3.29	3.35	3.43
20 days at 35 °C versus 2 years at 4 °C	3.76	3.42	4.48	4.36
Mean	4.24	3.36	3.92	3.89

35 °C for up to 20 days and the actual storage at 4 °C for up to 2 years. The mean PV values of RF-treated walnuts decreased from 0.28 and 0.64 for controls to 0.12 and 0.37 meq/kg, respectively, at the accelerated storage for 10 and 20 days. This might be due to possible inactivation of the lipoxygenase enzymes by short heat treatments (Buranasompob et al., 2004). The values of PV and FA from accelerated storage tests were slightly higher than those from actual storage tests both for control and RF-treated walnuts.

Q_{10} values were estimated from experimental data (Table 1) using Eq. (4). These values summarized in Table 2 were calculated from measured PV or FA changes between 0 and 10 days at 35 °C versus 0 and 1 year at 4 °C as well as between 0 and 20 days at 35 °C versus 0 and 2 years at 4 °C. In all cases, the calculated Q_{10} value was not far from 3.4 selected from literature for lipid oxidation and used in our previous study. The Q_{10} values over all the tests were 3.85. That is, the accelerated shelf life test conditions calculated by the Q_{10} value slightly overestimated those for actual storage tests and would provide more conservative assessments for walnut quality after RF treatments.

3.5. Energy costs estimation

The temperature in the walnuts increases linearly with RF heating time if the coupled power remains constant. The complete control of fifth-instar navel orangeworms in walnuts required a final temperature of 55 °C and maintained at that temperature for at least 5 min (Wang, Tang, Johnson, Mitcham, et al., 2002). The mean temperature rise was 35 °C for each treatment. With the specific heat for whole walnuts of $C_p = 1.4$ kJ/kg °C (Wang, Ikediala, et al., 2001) and a handling rate of 4540 kg walnuts/h (1.26 kg/s), the total actual power estimated from Eq. (5) was 103 kW. One industrial RF machine with 110 kW is needed to meet the treatment requirements. Estimating the cost of electricity at $0.1/kW h in California in 2004, the total cost was $10.3/h and $0.23 cents/kg of walnuts. If the possible heat loss, low energy efficiency and other factors were taken into account, the doubled operation costs were still minimal compared to capital costs ($190,000–$380,000 per 100 kW RF unit depending on user's special requirements).

4. Conclusions

Practical considerations, including walnut orientation effects, differential heating between open and closed shell walnuts after bleaching, nut mixing for heating uniformity, actual post-storage quality, and energy costs, have been taken into account for industrial implementation. The mixing process was useful to reduce walnut temperature variations caused by walnut orientation and position in a non-uniform RF field. The accelerated storage life test is a conservative method to predict post-storage quality of RF-treated walnuts. Further research is needed to conduct large-scale tests with a commercial partner to develop a technically and economically effective process.

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