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# Development of thermal treatment protocol for disinfesting chestnuts using radio frequency energy

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ABSTRACT

Methyl bromide fumigation, widely used for disinfesting chestnuts, will be banned in developing countries by 2015 under Montreal Protocol due to its adverse effects on human health and environment. The purpose of this research was to study possible applications of radio frequency (RF) heating for disinfestations of chestnuts to replace chemical fumigation. A 6 kW, 27 MHz free-running oscillator RF system was used to determine the effect of a developed RF treatment protocol on quality of chestnuts. The results showed that the heating time needed only 5.4 min to heat the 2.5 kg chestnuts from 20 °C to 55 °C using RF energy, and 170 min for chestnuts to reach 52.5 °C using hot air at 55 °C and 1.6 m/s. Based on the heating uniformity studies, a RF treatment protocol was finally developed to combine 0.6 kW RF powers with a forced hot air at 55 °C, movement of the conveyor, mixing twice, and holding at 55 °C hot air for 5 min, followed by forced room air cooling through single-layer samples. Quality of chestnuts was not affected by the RF treatments because no significant differences in moisture, protein, fat, soluble sugar, firmness, and color were observed between RF treatments and untreated controls after 8 days at 35 °C, simulating one year of storage at 4 °C. The RF treatments may provide a rapid and environmentally friendly method to replace chemical fumigation for disinfesting chestnuts.

## 1. Introduction

Since postharvest chestnuts contain high moisture content, rich carbohydrate, and low fat (Chenlo et al., 2009; Vasconcelos et al., 2010; Suárez et al., 2012), infestations with pests and diseases are the major problems in a chestnut storage (Chenlo et al., 2009; Antonio et al., 2011), resulting in high economic losses and short shelf-life. Methyl bromide fumigation has been widely used to disinfest agricultural products, such as chestnuts. However, this chemical fumigation is harmful not only to human health but also the environment. According to the Montreal Protocol, production and applications of methyl bromide will be banned in developing countries, such as in China, by 2015 (UNEP, 1992). It is urgent to develop non-chemical alternative methods to replace methyl bromide fumigation for disinfesting chestnuts.

Non-chemical methods include cold storage, controlled atmosphere, low pressure, irradiation, and thermal treatments for disinfesting agricultural commodities (Heather and Hallman, 2007). Cold storage, controlled atmosphere and low pressure treatments require lengthy exposures, and particular concerns on irradiation are the possibility of inspectors or consumers finding live insects in treated products. Thermal treatments, such as hot air and radio frequency (RF) treatments, have been mainly proposed as physical methods for disinfesting agricultural commodities since they are relatively easy to apply, leave no chemical residues, and may offer some fungicidal activity. A common difficulty with conventional heating methods is the slow rate of heat transfer, resulting in long treatment times (Hansen, 1992). In contrast, RF energy interacts directly with the entire volume of agricultural products and thus provides fast and volumetric heating (Tang et al., 2000). Although potential differential RF heating has been reported between insects and host dry products (Shrestha and Baik, 2013; Wang et al., 2013), there is a need to determine the RF heating uniformity in chestnuts before developing an effective treatment protocol.

Most work on the use of RF energy for disinfestation has focused on fresh fruit, such as cherries (Hansen et al., 2005), apples (Wang et al., 2006) and persimmons (Tiwari et al., 2008), and dry products, such as almonds (Gao et al., 2010), beans (Jiao et al., 2012), grain (Nelson, 1996), pecans (Nelson and Payne, 1882), and walnuts (Mitcham et al., 2004; Wang et al., 2007b). Lack of RF heating

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uniformity in fresh fruit often results in unacceptable product quality (Drake et al., 2005; Wang et al., 2006). But RF disinfestation treatment protocols have been developed for beans and walnuts after heating uniformity is improved with hot air surface heating, product movement on conveyors, and mixing (Wang et al., 2002, 2007a; Jiao et al., 2012). For example, treatments at 55 °C for 5 min result in complete control of fifth-instar navel orange worm in in-shell walnuts both with pilot- and industrial-scale RF systems without causing quality losses (Wang et al., 2002, 2007b). Chestnuts are different from fresh fruit and dry products since their kernel moisture contents are around 50% with different dielectric properties (Guo et al., 2011; Zhu et al., 2012). It is desirable to develop a RF treatment protocol for disinfesting chestnuts without affecting product quality.

The objectives of this research were (1) to compare the heating rates of chestnuts when subjected to hot air and RF heating, and determine an effective cooling method after heating, (2) to study the RF heating uniformity in chestnuts using additional hot air for surface heating, moving, and mixing, and (3) to determine moisture content, protein, fat, soluble sugar, firmness, and color of chestnuts after RF treatments and for an accelerated storage.

## 2. Materials and methods

### 2.1. Materials

In-shell chestnuts (*Castanea mollissima*) were purchased from a local wholesale market in Yangling, Shaanxi, China. The average initial moisture content and individual weight of tested chestnuts were 51.27 ± 1.19% on wet basis and 11.71 ± 0.91 g, respectively. The chestnuts were stored with mesh bags in a refrigerator (BD/BC-297KMQ, Midea Refrigeration Division, Hefei, China) at 3 ± 1 °C. They were taken out from the refrigerator 12 h before the experiment and kept at ambient room temperature (20 ± 1 °C) for equilibration.

### 2.2. Hot air-assisted RF heating system

A 6 kW, 27.12 MHz free-running oscillator RF system (SO6B, Strayfield International, Wokingham, UK) was used to heat chestnuts associated with a hot air system supplied by a 6 kW electric heater (Fig. 1). Moving the top electrode (40 cm × 83 cm) was used to change the electrode gap, and thus regulate RF power. Samples between electrodes were moved on a conveyor belt during RF heating to simulate continuous processes. The 2.5 kg in-shell chestnuts were placed in a plastic container (26 cm × 18 cm × 8 cm, HF-932, Zhejiang Howfun Company, Taizhou, China) made of polypropylene with perforated side and bottom walls, which allowed hot or room air to pass through the samples for heating or cooling. The hot air speed was from 1.1 to 1.6 m/s inside the RF cavity provided through an air distribution box under the bottom electrode and measured at 2 cm above the bottom electrode by an anemometer (DT-8880, China Everbest Machinery Industry Co., Ltd., Shenzhen, China).

### 2.3. Electrode gap selection

Different electrode gap in the RF system results in corresponding electric current and RF power. The electrical current ($I$, A) was displayed on the console of the RF system, and used to estimate the output power ($P$, kW) of the RF system with a relationship ($P = 5 \times I - 1.5$) provided by the manufacturer (Jiao et al., 2012). To determine the appropriate electrode gap, the plastic container filled with and without 2.5 kg of chestnuts was placed on the conveyor above the bottom electrode. After the RF power was turned on without hot air heating and movement, the electrical current was recorded when the electrode gap was reduced from 15 to 11 cm with a distance interval of 0.5 cm. Tests were repeated two times. Based on the electric current values, three electrode gaps were selected for further heating rate tests.

To determine the best one from the three electrode gaps for studying RF heating uniformity and treatment protocol, the sample temperature was measured at the central position of the container using a six-channel fiber-optic temperature sensor system (HQ-FTS-D120, Heqi Technologies Inc., Xian, China) with an accuracy of ±0.5 °C. The probe was inserted into chestnut kernels through predrilled holes. The temperature of samples was recorded every 1 s, until the temperature reached 55 °C, and then the RF power was turned off. The tests were replicated 2 times. The final gap was selected based on the suitable heating rate (6–8 °C/min) of chestnuts, and the most suitable gap was used for further tests.

### 2.4. Comparisons of temperature profiles of chestnuts

Based on the thermal death kinetics of storage insect pests, 100% inactivation could be reached when the final temperature and holding time might achieve 52 °C and 5 min, respectively (Wells and Payne, 1980; Johnson et al., 2010). Moreover, the best drying temperature of chestnuts was 60 °C for the highest amylose content, resistant starch, and swelling index (Correia and Beirão-da-Costa, 2012). Taking into consideration the non-uniformity of RF heating, the target sample temperature of 55 °C was selected to develop the treatment protocol.

The container with 2.5 kg samples was placed on the center of the RF bottom electrode for hot air and RF heating. The sample temperature at the geometric center of the container and the air temperature in the RF cavity were recorded every 60 s by the fiber-optic temperature sensor system during heating with a forced hot air at 55 °C and RF treatments. The measurement was stopped when the sample temperature reached 55 °C for RF heating or the sample temperature increase was below 0.5 °C for 30 min for hot air heating. Each test was repeated twice.

### 2.5. Determining the cooling methods and time

Rapid cooling is important to avoid quality degradation and improve processing efficiency. Chestnut samples preheated for 3 h with hot air at 55 °C were used to determine appropriate cooling methods. Chestnuts with 8 cm depth and a single layer in the plastic container were selected to determine the cooling method and time when subjected to natural and forced room air cooling. The forced room air was obtained by an electric fan (FT30-10A, Guangdong Midea Environment Appliances Manufacture Co., Ltd., Zhongshan, China). The air speeds at 2 cm above the sample surface were measured by the anemometer and were about 0.2 and 3.5 m/s for the natural and forced air cooling, respectively. Sample temperatures in the central position of the container were recorded every 60 s by the fiber-optic temperature sensor system during cooling, until the sample central temperature dropped to 30 °C. Two replicates were made for each experiment. The best cooling method with the shortest cooling time was selected and used for further RF treatment protocol development.

### 2.6. Heating uniformity tests

The heating uniformity is an important factor to develop a successful RF treatment protocol since it influences insect mortality and product quality. The RF heating uniformity depends on different treatment conditions, such as with or without forced hot air, with or without movement of samples on the conveyor belt, and with or without mixing. To obtain a treatment protocol and evaluate effects of RF treatments on sample quality, the optimized heating uniformity should be first determined. Full

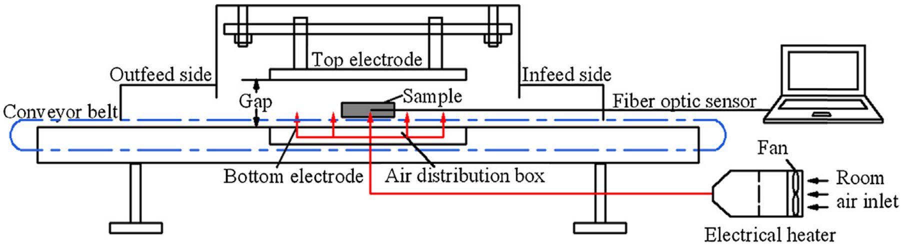

**Fig. 1.** Schematic view of the free-running oscillator 6 kW, 27.12 MHz RF system showing the plate electrodes, conveyor belt, the hot air system and the fiber optic sensors. Adapted from Wang et al., 2010.

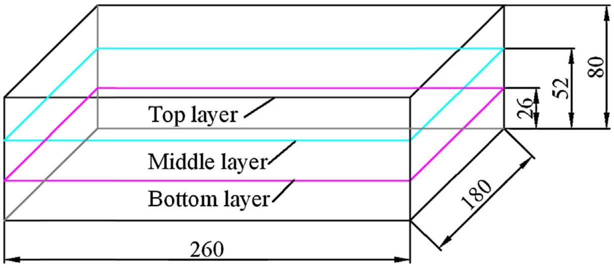

**Fig. 2.** Dimensions of the plastic container and three layers for temperature mapping using thermal imaging camera (all dimensions are in mm).

loads of chestnuts in the container were heated in the RF system to compare the sample temperature distribution. The container movement started from in-feed side to out-feed side of the RF system (Fig. 1). The forced hot air at 55 °C was provided through the air distribution box and the bottom electrode. A two-times mixing was carried out at intervals of 1.8 min during 5.4 min of the RF treatment time. Mixing was done outside the RF cavity by hand for about 20 s through putting the samples into a large container (35.5 cm × 27.5 cm × 10.5 cm), and then the samples were placed back again into the treatment container and finally the RF cavity for the remainder of the treatment time. The mixing process took <1 min. The chestnuts in the container were divided into three layers (Fig. 2) and separated by two thin gauzes (with mesh opening of 1 mm) to easily map the sample surface temperatures with a thermal imaging camera (DM63, Zhejiang Dali Technology Co., Ltd., Hangzhou, China) having an accuracy of ±2 °C. Before and immediately after RF treatments without mixing, the temperatures of the top layer were mapped first, followed by the middle and bottom layers. Each thermal image took <1 s. The surface temperature data in the treatment area were obtained and used for estimating the average and standard deviation temperatures. With mixing, six chestnuts were randomly selected both at middle and bottom layers for interior kernel temperature measurements using a thin Type-T thermocouple thermometer (TMQSS-020-6, Omega Engineering Ltd., CT, USA). Before inserting thermocouples, a hole was drilled for each chestnut. It took about 1 min to complete the kernel temperature measurements for the 6 chestnuts. The uniformity tests were conducted in triplicate.

Heating uniformity index (λ) was used for evaluating RF heating uniformity in almond (Gao et al., 2010), coffee bean (Pan et al., 2012), lentil (Jiao et al., 2012), and walnut (Wang et al., 2007a). It is defined as the ratio of the rise in standard deviation of sample temperature to the rise in average sample temperature during treatment and can be calculated by the following equation (Wang et al., 2008):

$$\lambda = \frac{\sqrt{\sigma^2 - \sigma_0^2}}{\mu - \mu_0} \qquad (1)$$

where $\mu_0$ and $\mu$ are initial and final mean chestnut temperatures (°C), $\sigma_0$ and $\sigma$ are initial and final standard deviations (°C) of chestnut temperatures over treatment time, respectively. The smaller λ values result in the increased heating uniformity.

### 2.7. *Treatment protocol development*

The target temperature in treated chestnuts was set at 55 °C and holding 5 min to achieve the complete kill of the target insects. Based on the above studies, a final treatment protocol was determined as follows. The suitable electrode gap (12 cm) was used for heating 2.5 kg chestnuts with 8 cm thickness in the RF system together with the movement at 9.2 m/h, hot air heating at 55 °C and a twice mixing. After 5.4 min of heating, the RF system was turned off and the chestnut samples were held in hot air for 5 min, followed by forced room air cooling for single-layer samples. The untreated samples were considered as controls. Each treatment was repeated three times. Both treated and control samples were used for quality evaluations.

### 2.8. *Quality evaluation of chestnuts*

Before and after RF treatments, the quality of chestnuts taken from each treatment was evaluated immediately and after accelerated shelf-life storage. Chestnuts were shelled before quality analysis. Moisture content, protein, fat, soluble sugar, firmness, and color were selected as major parameters to evaluate the chestnut quality. The accelerated shelf-life storage tests were conducted in an incubator (BSC-150, Shanghai Boxun Industry & Commerce Co., Ltd., Shanghai, China) at 35 ± 1 °C and 95 ± 1% RH for 4 and 8 days to simulate commercial storage at 4 °C for 0.5 and 1 year, respectively. The accelerated storage time at 35 °C was calculated based on a $Q_{10}$ value of 3.41 for nutrition loss (Taoukis et al., 1997).

Moisture content was detected by the vacuum oven drying method following the National Standard of China, GB5009.3-2010 (2010) issued by China State Bureau of Standards. Treated chestnuts were first sliced into 5 g samples with thickness of 5 mm, placed in aluminum dishes, and then dried in a vacuum oven (DZX-6020B, Nanrong Laboratory Equipment Co., Ltd., Shanghai, China) at 105 °C and 101.3 kPa until a constant weight of samples was attained. The samples were placed in desiccators with $CaSO_4$ and brought to room temperature before weighing.

The protein was detected using the Kjeldahl method following the National Standard of China, GB5009.5-2010 (2010). The percentages of nitrogen were transformed into protein content by multiplying by a conversion factor of 5.3 suggested elsewhere (Korel and Balaban, 2006; McCarthy and Meredith, 1988). The fat was determined by the Soxhlet extraction method following GB/T5009.6-2003 (2003) and measured by extracting a known weight of samples with petroleum ether. The soluble sugar of samples was determined by the Anthrone colorimetry method (Plummer, 1987) with minor modifications. The flesh of the chestnuts was extracted with 80% ethanol for 1 h at 70 °C in a water bath. Absorbance was read at 620 nm using a UV/Vis spectrophotometer

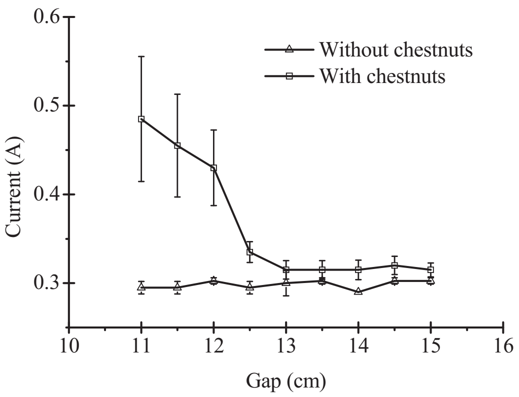

**Fig. 3.** Electric current of the radio frequency system as a function of electrode gap.

(UV2000, Unico Instrument Co., Ltd., Shanghai, China). The sugar content was calculated from a glucose standard curve.

Firmness of chestnuts was measured by a texture analyzer (TA-XT.PLUS/50, Stable Micro System Ltd., England), and determined as the maximum compression force (N) required to push a probe of 2 mm diameter to a depth of 10 mm at 2 mm/s test velocity. Readings were averaged for 6 replicates from each treatment. The force–time graphs were recorded by a computer and analyzed using the Exponent software (version 6.0.7.0, Stable Micro Systems Ltd., UK).

Chestnut kernel color was measured with a computer vision system (CVS), which included three parts: a lighting system, a Cannon EOS 600 Digital camera with 1800 megapixel resolution and EF-S 18–55 mm *f*/3.5–5.6 Zoom Lens, and a computer with image-processing software. Based on the measurement procedures suggested by Kong et al. (2007), color images of 10 chestnuts surfaces per treatment were captured by the camera, stored in the computer, and analyzed by Adobe Photoshop CS (Adobe Systems Inc., USA). The color values obtained from Photoshop (*L*, *a* and *b*) were converted to CIE LAB (*L**, *a** and *b**) values using the following formulas (Briones and Aguilera, 2005):

$$L^* = \frac{L}{2.5} \tag{2}$$

$$a^* = \frac{240}{255}a - 120 \tag{3}$$

$$b^* = \frac{240}{255}b - 120 \tag{4}$$

### 2.9. Statistical analysis

Mean values and standard deviations were calculated from the replicates for all treatments. All statistical analyses were performed at a 5% significance level with the least significant difference *t*-test using a Microsoft Excel variance procedure (Microsoft Office Excel, 2007).

## 3. Results and discussion

### 3.1. Electric current under different gap

Fig. 3 shows the relationship between the electric current and electrode gap when the plastic container filled with or without chestnuts was placed on the RF bottom electrode without movement and forced hot air. Without chestnuts, the electric current was almost constant, around 0.30 A, which was not affected by the electrode gap changes. With chestnuts, electric current decreased with increasing electrode gap from 11 cm to 13 cm and thereafter almost kept a constant around of 0.32 A. Correspondingly, the RF output power coupled to the samples increased from 0.1 to 0.9 kW when the electrode gap decreased from 15.0 to 11.0 cm. Similar trends were also observed by Wang et al. (2007a), Gao et al. (2010), and Jiao et al. (2012). Thus, three electrode gaps (11.5, 12.0, and 12.5 cm) were selected for further tests.

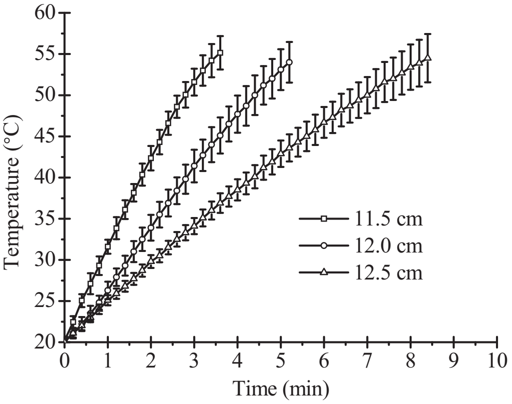

**Fig. 4.** Temperature–time histories of the RF heated chestnuts in the center of the 8-cm thick container as a function of the electrode gap.

### 3.2. Determination of electrode gap

Fig. 4 shows average and standard deviation for chestnut temperatures in the center of the container with electrode gaps of 11.5, 12.0, and 12.5 cm during RF heating. The chestnut temperatures increased almost linearly with the heating time under the three gaps. The heating rate increased with decreasing electrode gap or increasing RF output power. About 3.6, 5.4, and 8.4 min were needed to heat the 2.5 kg chestnuts from 20 °C to 55 °C for the gaps of 11.5, 12.0, and 12.5 cm, respectively. Shorter heating times corresponded to higher throughput, but heating uniformity could be negatively affected by rapid RF heating. To obtain a better balance between throughput and heating uniformity, the electrode gap of 12.0 cm was selected for chestnuts to achieve a suitable heating rate of 6.5 °C/min and used for further heating uniformity tests.

### 3.3. Heating and cooling profiles

Fig. 5 shows that heating rates and final temperatures of chestnut samples were influenced by the speed of hot air at 55 °C.

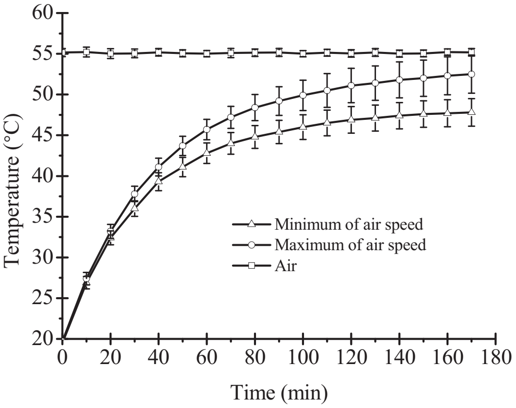

**Fig. 5.** Mean (±SD) temperatures of the chestnuts in the center of the 8 cm thick container when subjected to maximum (1.6 m/s) and minimum (1.1 m/s) speed of hot air heating.

**Table 1**
Comparisons of the temperature and heating uniformity index (mean ± SD over 3 replicates) of the chestnuts after RF heating with different conditions.

| Layers | RF | RF + hot air | RF + movement | RF + mixing | RF + hot air + movement + mixing | RF + hot air + movement + mixing + holding 5 min |
|---|---|---|---|---|---|---|
| *Temperature (°C)* | | | | | | |
| Top | 52.54 ± 1.89BC* | 53.58 ± 1.26bB | 50.14 ± 1.61 C | 51.49 ± 0.72bC | 55.85 ± 1.55bA | 53.37 ± 0.44BC |
| Middle | 53.59 ± 1.46AB | 55.21 ± 0.86aA | 53.04 ± 2.84AB | 53.03 ± 0.69aB | 56.42 ± 1.59aA | 54.75 ± 0.74AB |
| Bottom | 51.98 ± 2.51AB | 53.01 ± 1.12bAB | 49.45 ± 2.07B | 51.47 ± 1.22bAB | 55.27 ± 1.19bA | 53.20 ± 1.00A |
| *Heating uniformity index (λ)* | | | | | | |
| Top | 0.098 ± 0.002aA | 0.089 ± 0.002B | 0.089 ± 0.001aB | 0.080 ± 0.004aB | 0.065 ± 0.003aC | 0.057 ± 0.002aD |
| Middle | 0.090 ± 0.003bA | 0.081 ± 0.003A | 0.077 ± 0.003bA | 0.066 ± 0.008bAB | 0.042 ± 0.011bB | 0.034 ± 0.005cB |
| Bottom | 0.096 ± 0.007abA | 0.080 ± 0.003BC | 0.088 ± 0.005abB | 0.069 ± 0.007bC | 0.051 ± 0.010abCD | 0.040 ± 0.003bD |

[*] Means followed by different lowercase and uppercase letters are significantly different at $P = 0.05$ among layers and treatments, respectively, and no letters for insignificant difference at $P = 0.05$ level.

Increased air speed resulted in increasing heating rate and final temperature, which was probably caused by the increased surface heat convection. For example, it took about 170 and 150 min for the central sample temperatures to reach 47.7 °C and 52.5 °C when subject to hot air heating with minimum speed of 1.1 m/s and maximum speed of 1.6 m/s, respectively. This is in good agreement with the results obtained by Hwang et al. (2001). So hot air heating at the maximum speed was selected for further treatments.

Fig. 6 shows a comparison of temperature–time histories at the center of chestnuts when subjected to 55 °C forced hot air with the speed of 1.6 m/s and RF heating. The RF treatment resulted in the faster heating as compared to hot air heating. It took only 5.4 min for the center temperature of the RF heated chestnuts to achieve 55 °C, as compared to 170 min for hot air heating. The short RF heating time for chestnuts was probably caused by high power absorption as shown in Fig. 3, indicating the advantage of rapid RF heating as compared to conventional heating. The temperature–time histories in this study are similar to the results observed with almonds (Gao et al., 2010), coffee beans (Pan et al., 2012), and lentils (Wang et al., 2010).

Cooling temperature–time histories are shown in Fig. 7 for the sample center of chestnuts as influenced by the sample thickness and cooling methods. The cooling time decreased clearly when introducing forced air and reducing sample thickness since the surface heat transfer coefficient with forced convection was higher than that in natural convection and the thickness for heat conduction was reduced. For example, about 72 min was needed for the 8 cm deep chestnut samples to cool down from 52.5 to 30 °C in natural room air. This cooling time was reduced to 28 min when introducing forced room air. Since it took only 14 min to cool single layer samples to 30 °C with forced room air, this cooling method was used in the RF treatment protocol.

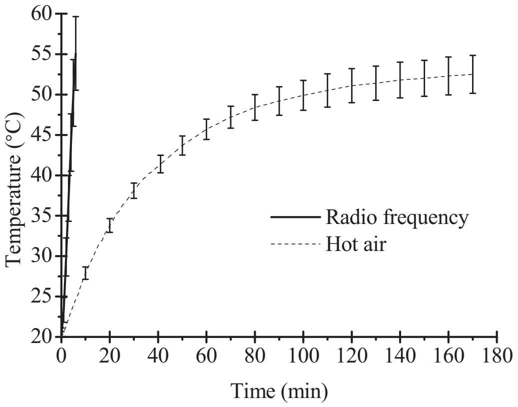

**Fig. 6.** Typical temperature–time histories of chestnuts when subject to hot air heating at 55 °C (1.6 m/s) and RF heating (electrode gap = 12 cm).

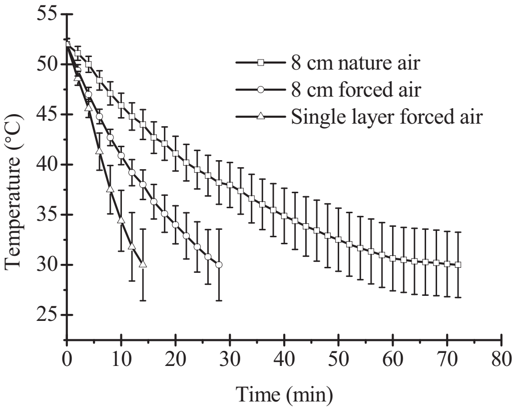

**Fig. 7.** Cooling curves of chestnuts in the sample center as a function of sample thickness with natural (0.2 m/s) and forced (3.5 m/s) room air cooling.

### 3.4. Heating uniformity in RF treated chestnuts

The initial sample temperature distribution was relatively uniform with 20 ± 0.1 °C before RF treatments. Table 1 summarizes a detailed comparison of the temperature distribution and heating uniformity index values of chestnuts on top, middle and bottom layers after RF heating under different conditions. The highest surface temperatures were observed in the middle layer, which was located at the geometric center of the container, and followed by the top and bottom layers. The relatively lower average temperatures of the samples at the top and bottom layers were probably caused by heat loss to ambient air. Adding forced hot air could help to raise the average temperatures of chestnut samples, especially in bottom layers, where the hot air was introduced. The average sample temperatures dropped about 2 °C for the three layers during 5 min holding (Table 1). In general, hot air, movement, mixing and holding all improved the RF heating uniformity in chestnut samples as shown by gradual reductions in the uniformity index value. Mixing was the better method to improve heating uniformity as compared to hot air and movement based on the reduced uniformity index

**Table 2**
Moisture contents (mean ± SD, % w.b.) of the chestnut kernels and shells before and after radio frequency (RF) treatments.

| Samples | 0 day | 4 days | 8 days |
|---|---|---|---|
| *Kernel* | | | |
| Control | 51.27 ± 1.19A* | 45.24 ± 1.07B | 40.63 ± 0.37bC |
| RF treated | 49.70 ± 0.79A | 45.18 ± 0.39B | 43.29 ± 0.16aC |
| *Shell* | | | |
| Control | 36.74 ± 0.82aA | 25.68 ± 0.68B | 16.11 ± 0.18 C |
| RF treated | 26.90 ± 0.22bA | 23.29 ± 0.33B | 15.67 ± 0.20 C |

[*] Different lower and upper case letters indicate that means are significantly different at $P = 0.05$ among treatments and storage time, respectively, and no letters for insignificant difference at $P = 0.05$ level.

**Table 3**
Storage quality characteristics (mean ± SD over 6 replicates) of chestnut kernels before and after radio frequency (RF) treatments.

| Quality parameters | Storage time (days) at 35 °C, 95% RH[a] | | | |
|---|---|---|---|---|
| | | 0 | 4 | 8 |
| Protein (%) | Control | 2.20 ± 0.18B[*] | 2.58 ± 0.68AB | 2.80 ± 0.39bA |
| | RF | 2.34 ± 0.42 C | 2.62 ± 0.22B | 3.49 ± 0.03aA |
| Fat (%) | Control | 5.94 ± 0.08A | 5.63 ± 0.01aB | 4.15 ± 0.05bC |
| | RF | 5.36 ± 0.29A | 4.87 ± 0.19bB | 4.33 ± 0.09aC |
| Soluble sugar (%) | Control | 10.07 ± 0.87B | 11.44 ± 0.41A | 10.84 ± 0.11AB |
| | RF | 9.96 ± 0.37A | 10.88 ± 0.61A | 10.22 ± 0.41A |
| Firmness (N) | Control | 27.11 ± 4.27 | 24.30 ± 5.14 | 23.95 ± 4.38 |
| | RF | 25.12 ± 3.87 | 24.24 ± 3.87 | 22.91 ± 5.34 |
| *Color* | | | | |
| $L^*$ | Control | 78.25 ± 3.68A | 77.83 ± 3.29A | 76.02 ± 4.86aA |
| | RF | 75.28 ± 2.90A | 72.59 ± 4.31B | 69.70 ± 2.44bB |
| $a^*$ | Control | 1.21 ± 1.83B | 2.85 ± 2.57AB | 4.34 ± 1.94A |
| | RF | 2.95 ± 2.19A | 3.29 ± 1.55A | 3.60 ± 1.05A |
| $b^*$ | Control | 57.89 ± 2.77A | 57.23 ± 1.88aA | 55.89 ± 4.21aA |
| | RF | 55.19 ± 2.93A | 52.18 ± 2.96bAB | 49.31 ± 3.66bB |

[a] 4 and 8 days at 35 °C to simulate 0.5- and 1-year storage at 4 °C, respectively.

[*] Different lower and upper case letters indicate that means are significantly different at $P = 0.05$ among treatments and storage time, respectively, and no letters for insignificant difference at $P = 0.05$ level.

value. The manual mixings could be designed as mechanical tumbling between two industrial RF systems (Wang et al., 2007a,b). Therefore, the optimal heating uniformity was obtained for RF treatments with hot air heating, movement, mixing and holding, which were used for the final treatment protocol (Table 1). The heating uniformity index values in this study were similar to those found for almonds (Gao et al., 2010), but slightly larger than those observed for coffee beans (Pan et al., 2012), lentils (Jiao et al., 2012), and smaller than those obtained for walnuts (Wang et al., 2007a). After achieving the required RF heating uniformity, the added treatment steps should be possibly reduced for obtaining the increased throughput and decreased process cost.

### 3.5. Chestnut quality with RF treatment protocol and storage

Table 2 shows moisture contents in the chestnut kernels and shells before and after RF treatments during accelerated shelf-life storage. The storage time and RF treatment reduced moisture contents of chestnut kernels and shells, but a significant difference ($P < 0.05$) was only observed for storage time both in chestnut kernels and shells. Furthermore, the moisture content of chestnut shells was significantly reduced just after RF treatment ($P < 0.05$). The control chestnut kernels lost about 10.64% w.b. of moisture content after 8 days of accelerated shelf-life storage, while RF treatment chestnut kernels lost about 6.41% w.b. after the same period. Less moisture losses in RF treated kernels during storage were probably caused by shell texture changes due to RF heating, resulting in preventing moisture diffusion through the shell. The changes of moisture content in control chestnuts during storage were similar to those of chestnuts during storage for 350 days at 2–4 °C reported by Chenlo et al. (2009).

Table 3 summarizes the quality results of control and RF treated chestnuts during the accelerated shelf-life storage. There was no significant difference between control and RF treated chestnuts for all the quality attributes at 0 day of storage ($P > 0.05$). The protein and the color $a^*$ values in control and RF treated chestnuts increased with increasing storage time but all other quality parameters showed a decreasing trend during the storage. But the significant increase and decrease ($P < 0.05$) with storage time was only observed for proteins in RF treated samples and fats in both control and RF treated samples, respectively. The increasing trend for proteins could be caused by decreasing moisture content with storage time but decreasing trend for fats was probably caused by increasing decompositions during the storage (Xu et al., 2008). Since the chestnut sweetness was a major parameter for sensory analysis, the results showed that the quality of RF treated chestnuts was acceptable even after storage for 8 days at 35 °C or 1 year at 4 °C based on the minimally required sugar content of 90 g/kg (Künsch et al., 2001). The similar trend during storage was reported for protein values in gamma irradiation treated chestnuts (Fernandes et al., 2011), fat values in electron-beam radiation treated chestnuts (Carocho et al., 2012), soluble sugar contents in cold stored chestnuts (Chenlo et al., 2010; Vasconcelos et al., 2010), firmness in gamma irradiated chestnuts (Carocho et al., 2012; Antonio et al., 2013), and color in gamma irradiated chestnuts or with cold storage (Chenlo et al., 2009; Antonio et al., 2013).

Pilot-scale tests are usually conducted in laboratories with relatively small samples (e.g. 2.5 kg in this study) to determine different combinations of treatment conditions. Optimal treatment parameters are then selected to ensure that all temperatures are as uniform as possible throughout the load of RF treated samples based on the acceptable product quality while ensuring quarantine security against the target pest. With the solid results from this study, it is effective and reasonable to scale up from pilot-scale (6 kW unit) to industrial-scale applications (e.g. 80–100 kW unit). Developing disinfestation process for walnuts demonstrates that scaling up from a pilot-scale protocol (Wang et al., 2002) to an industrial RF process (25 kW) for treating 1561.7 kg/h is feasible (Wang et al., 2007a,b).

## 4. Conclusions

The appropriate gap of electrode (12 cm) was selected based on suitable heating rate. RF treatments clearly increased heating rate in chestnut samples as compared to hot air heating. The RF heating uniformity was improved by forced hot air at 55 °C, movement, and twice mixing of the samples due to the reduced heating uniformity index. Based on temperature and time requirements of insect control, a RF treatment protocol was developed with RF heating to 55 °C, forced hot air, movement and twice mixing, then holding for 5 min in hot air, followed by forced room air cooling in a single layer for chestnuts. Chestnut quality was not affected significantly by the RF treatments because quality parameters (moisture, protein, fat, soluble sugar, firmness, and color) of treated chestnuts were similar to those of controls. Therefore, RF treatments should provide a practical, effective and environmentally friendly method for disinfestations of post-harvest chestnuts. Further research is needed to conduct efficacy tests and scale up the treatment protocol for commercial applications.

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