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Storage stability of pistachios as influenced by radio frequency treatments for postharvest disinfestations

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ABSTRACT

There has been an increased interest in developing alternative physical methods for disinfesting postharvest nuts under growing international pressures to replace chemical fumigation due to its adverse effects on human health and environment. The present research explored the possibility of using radio frequency (RF) heating as a non-chemical treatment for disinfestations of pistachios. A pilot-scale, 27 MHz, 6 kW RF unit was used to study RF heating uniformity, develop a treatment protocol, and evaluate quality attributes and storage stability in treated samples. Only 5.6 and 5.5 min were needed to raise the centre temperature of 1.8 kg in-shell and 2.0 kg shelled pistachios to reach 55 °C using RF energy, respectively, compared to about 82 and 117 min when using hot air heating at 55 °C. RF heating uniformity in both types of pistachios was improved by adding forced hot air, sample movements on the conveyor and a single mixing in the middle of the treatment time. The final average temperatures on the surface and in the interior of both types of pistachio kernels exceeded 52 °C, following a holding step at 55 °C for 2 min using hot air. This provided a conservative and 100% mortality of fifth-instar Indianmeal moth (*Plodia interpunctella* [Hübner]). RF treated samples were not significantly different from control samples in weight loss, peroxide values, fatty acid values, fatty acid composition and kernel colour. RF treatments can, therefore, potentially provide an effective and rapid protocol against stored product pests in pistachios as an alternative to chemical fumigation.

Industrial relevance: A pilot-scale 6 kW RF system with conveyor belt was used to determine the heating uniformity and quality changes of pistachios. For a combination with hot air surface heating and mixing, an effective and continuous RF disinfestation method could be developed for pistachios. The RF heating technology has been successfully demonstrated for disinfesting walnuts in California, USA. We tried to expand the industrial applications of RF heating for disinfesting pistachios, to replace the chemical fumigation. This research may provide potential industrial applications of RF treatments for disinfestations based on fast and uniform heating.

1. Introduction

Pistachio (*Pistacia vera* L.) is one of the most important tree nuts. In-shell and shelled pistachio nuts mainly dried or roasted with salt are marketed extensively all over the world, especially for the shelled or ground pistachios to be used in food industry as an ingredient of pastries, sausages, ice creams, etc. (Tsantili et al., 2010). The world production of pistachios is around 1 million metric tons in 2012, which are mainly contributed by three world producers: Iran, USA and Turkey (FAOSTAT, 2014). Pistachio nuts are important sources of nutrients, since the kernels contain about 50% of lipids and 20% of proteins, and are also a good source of vitamins and antioxidant substances (Arcan & Yemenicioğlu, 2009; Arena, Campisi, Fallico, & Maccarone, 2007; Kornsteiner, Wagner, & Elmadfa, 2006). Due to its high nutritional value and split shell, the average export prices of raw and dried pistachio nuts in 2012 had exceeded 5000 dollars per ton in the international market (FAOSTAT, 2014). Therefore, the problems related to postharvest processing of pistachio nuts are becoming major concerns of the nut industry.

Following harvest and during production, storage, marketing and exporting of pistachio nuts, insect infestation by stored-product pests, such as Indianmeal moth (*Plodia interpunctella* [Hübner]), is most often responsible for consumer returns and complaints (Johnson, Wang, & Tang, 2003). This pest reduces nut quality through direct damage and by contaminating the product with webbing, cast skins and frass, as well as creation of favourable conditions for mould growth (Johnson, Vail, Brandl, Tebbets, & Valero, 2002). Chemical fumigation using methyl bromide (MeBr) and phosphine has been a common practice for controlling insects in dried fruit and tree nuts. However, their use will be phased out in developing countries by 2015 due to its negative impact on human health and the environment (USEPA. United

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States Environmental Protection Agency, 2001). Therefore, adoption strategies of developing post-harvest technologies are of great importance to control the target insects and maintain the environment and nutritional quality of pistachios.

There are a large number of suggested potential non-chemical alternatives to fumigation, including ionizing radiation, cold storage, controlled atmospheres and thermal treatments (Hoa, Clark, Waddell, & Woolf, 2006; Jiao et al., 2013; Mexis & Kontominas, 2009; Whiting, Jamieson, Spooner, & Lay-Yee, 1999). Unfortunately each of these methods has limitations in terms of efficiency or cost that prevents it from becoming a direct replacement for fumigation. For example, cold storage and controlled atmospheres require lengthy treatment times, and consumers in Japan and the EU countries that don't accept irradiated products. Conventional thermal treatments, such as hot air or steam are relatively easy to apply, leave no chemical residues, and may offer some fungicidal activity, but an inherent difficulty in using these methods is that slow heating rates may result in long treatment times and possible damage to product quality. Thus, it is desirable to develop effective, practical, economically viable and environmentally-friendly method for disinfesting pistachio nuts.

Novel thermal treatments, such as radio frequency (RF) energy, can directly interact with commodities to generate heat volumetrically, and significantly reduce heating time or increase the heating rate so as to avoid the quality loss caused by slow or overheating in conventional thermal treatments (Marra, Zhang, & Lyng, 2009). Many studies have explored the possibility of using RF energy to disinfest produce of insect pests (Frings, 1952; Hallman & Miller, 1994; Nelson & Payne, 1982). Recently, based on the thermal death kinetics of insect pests, RF treatments have been successfully used to control codling moth (Wang et al., 2001), navel orangeworm (Gao, Tang, Wang, Powers, & Wang, 2010; Wang, Monzon, Johnson, Mitcham, & Tang, 2007b) and coffee berry borer (Pan, Jiao, Gautz, Tu, & Wang, 2012) in in-shell walnuts, almonds, and coffee beans, respectively. Available research results demonstrate that the RF technology has great potential for disinfesting pistachios.

Heating uniformity in RF-treated samples is important to achieve effective treatments that ensure insect control and provide acceptable product quality. Factors resulting in non-uniform heating during RF treatments include non-uniform electromagnetic field distribution, variations of moisture content, and thermal and dielectric properties in products (Jiao, Johnson, Tang, & Wang, 2012). Many practical methods are used to improve the uniformity of RF heating in agricultural products, such as adding forced hot air for sample surface heating, sample movement, rotation or mixing of samples during RF heating and immersing products into water for fresh fruits (Birla, Wang, Tang, & Hallman, 2004; Tiwari, Wang, Birla, & Tang, 2008; Wang, Monzon, Johnson, Mitcham, & Tang, 2007a). Similar research is desirable to determine RF heating uniformity in developing postharvest treatment protocols for disinfesting pistachio nuts.

Since pistachio kernels contain substantial quantities of triacylglycerols and polyunsaturated fatty acids, and thus may be susceptible to oxidative and hydrolytic rancidity, commercially viable RF disinfestation treatments must retain pistachio quality during storage period. Temperatures experienced by pistachios during RF treatments may influence their marketability and storage stability. After hot air heating of walnut and almond kernels, Buranasompob, Tang, Mao, and Swanson (2003) observed that the oxidation and hydrolytic rancidity of nut kernels did not increase at 60 °C for up to 10 min, which might be due to possible inactivation of the lipoxygenase (LOX) enzymes by thermal treatments. In previous studies, Mitcham et al. (2004) reported that the final kernel temperatures around 75 °C for a short time did not alter walnut quality after RF treatments. Therefore, it's important to determine the quality of RF treated pistachio nuts during storage period under the improved heating uniformity.

The objectives of this study were (1) to investigate heating rates in in-shell and shelled pistachios when subjected to hot air and RF heating and develop an effective cooling method after heating, (2) to study the RF heating uniformity in pistachios using additional hot air surface heating, moving and mixing, (3) confirm the efficacy of the developed treatment protocol with infested pistachio nuts, and (4) to evaluate the effect of RF disinfestations on the storage stability of pistachios during accelerated shelf life tests.

2. Materials and methods

2.1. Materials

Raw and dried in-shell pistachios (*P. vera* L. Kerman variety) were purchased from Paramount Farming Company (Lost Hills, CA, USA). The average split ratio and moisture content of nuts were 85 ± 5% and 4.85 ± 0.28% wet basis (w.b.), respectively. They were cleaned manually to remove all foreign matters and broken or immature nuts. Whole kernels (shelled) were separated manually from cracked nuts. Then two types of pistachio samples were sealed into polyethylene bags at 4 ± 1 °C until testing. Before each test, samples were placed in an incubator (BSC-150, Boxun Industry & Commerce Co., Ltd., Shanghai, China) for 12 h at 25 ± 0.5 °C for equilibrium.

2.2. RF heating system and procedure

RF heating of pistachios was carried out using a 6 kW, 27.12 MHz pilot-scale RF system (SO6B, Strayfield International, Wokingham, U.K.) with a hot air system (6 kW) and a conveyor belt (Fig. 1). Moving the top electrode (40 cm × 83 cm) was used to change the electrode gap, thus regulating the RF power. A conveyor belt moved samples between electrodes started from in-feed side to out-feed side of the RF system to simulate continuous processes. The hot air speed was 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).

Pistachio samples were put in a plastic container (27 cm × 18 cm × 8 cm) with perforated side and bottom walls and then placed on the centre of the bottom electrode for RF or hot air heating. Based on the thermal death kinetics of Indianmeal moth, complete kill could be reached when the final temperature and holding time achieve 52 °C and 1 min, respectively (Johnson et al., 2003). Taking into consideration the non-uniformity of RF heating, the target sample temperature of 55 °C was used to develop the treatment protocol.

2.3. Determination of the electrode gap and cooling method

Different electrode gaps in the RF system result in corresponding RF power and heating rate. To determine the suitable gap for the desired heating rate 4–6 °C/min, about 1.8 kg of in-shell and 2.0 kg of shelled pistachios with 7 cm sample depth in the container described above were placed on the centre of the bottom electrode and subjected to RF heating without belt movement and hot air heating. The range of the electrode gap was selected from 10.5 to 12.0 cm and 9.5 to 11.0 cm with a 0.5 cm interval for in-shell and shelled samples, respectively.

Pistachio samples were also heated to about 55 °C by hot air, which were used to compare the temperature profiles with RF heating and select the best cooling methods. Since rapid cooling is important to avoid quality degradation and improve throughput of the industrial-scale treatments, in-shell and shelled samples both at 7 and 4 cm depths, and additional single layer held in the container were subjected to ambient natural and forced air for cooling tests. The forced air cooling was obtained using an electric fan. The air speeds at 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.

During the tests described above, the kernel temperature of a pistachio (in-shell and shelled) in the centre of the samples was measured using a fibre-optic temperature sensor system (HQ-FTS-D120, Heqi

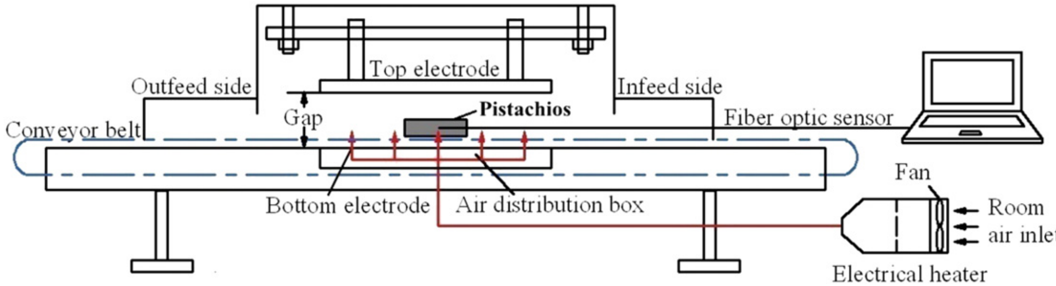

Fig. 1. Schematic view of the pilot-scale 6 kW, 27.12 MHz RF system showing the plate electrodes, conveyor belt, and the hot air system. Adapted from Wang, Tiwari, Jiao, Johnson, and Tang (2010).

Technologies Inc., Xian, China) with an accuracy of ±0.5 °C. The probe was inserted into pistachio kernel through a predrilled hole. The temperature of samples was measured and recorded every 1 s, until the temperature reached 55 °C and dropped to 30 °C during RF heating and cooling tests, respectively. Two replicates were made for each test. The most suitable gap and cooling method were selected based on the desired heating rate (4–6 °C/min) of samples and shortest cooling time, and used to further develop the RF treatment protocol.

2.4. Heating uniformity tests

The heating uniformity is an important factor for a successful RF treatment protocol to completely control insects and ensure product quality. To optimize heating uniformity, full loads of in-shell and shelled pistachios were heated under five conditions: RF heating only, RF heating with forced hot air at 55 °C, RF heating with sample movement, RF heating with mixing, and RF heating with hot air, sample movement and mixing. Movement was achieved by the conveyor belt speed at 8.9 and 9.1 m/h (belt speed was calculated by dividing the electrode length by the resulting heating time) until the end of RF heating for in-shell and shelled samples, respectively. Mixing was conducted manually outside the RF cavity in the middle of the treatment time in a large plastic container (35.5 cm × 27.5 cm × 10.5 cm) made of polypropylene. After mixing for 20 s, the samples were returned to the treatment container and placed back into the RF system for the remainder of the treatment time. During above tests without mixing, two types of pistachios in the container were divided into two layers (Fig. 2) and separated by thin gauze (with mesh opening of 1 mm) to easily map the surface temperatures with a thermal imaging camera (DM63, Zhejiang Dali Technology Co., Ltd., Hangzhou, China). Immediately after the RF treatment was completed, the surface temperatures of the two layers were mapped sequentially within 10 s, and then ten pistachios (in-shell and shelled) were randomly selected both at top and bottom layers for kernel temperature measurements using a Type-T thermocouple thermometer (TMQSS-020-6, Omega Engineering Ltd., CT, USA). With mixing, only the top layer surface was mapped and other ten pistachios were randomly selected below the surface of container for interior kernel temperature measurements as described above. Each test was repeated twice for two types of pistachios. The average and standard deviation (SD) values of the surface and interior kernel temperatures for each replicate were used for evaluating the RF heating uniformity.

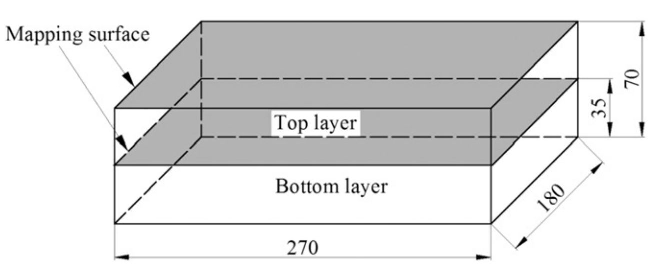

Fig. 2. Plastic container and two layers for surface temperature measurements (all dimensions are in mm).

To determine the optimal heating uniformity, a heating uniformity index (λ), was used to compare the difference of the above treatments. The λ value has been successfully used for evaluating RF heating uniformity in almond, coffee bean and chestnut (Gao et al., 2010; Hou, Ling, & Wang, 2014; Pan et al., 2012). 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, Yue, Tang, & Chen, 2005):

$$\lambda = \frac{\Delta\sigma}{\Delta\mu} \quad (1)$$

where $\Delta\sigma$ and $\Delta\mu$ are the rise in the standard deviation and mean values, respectively, from the initial to final nut temperatures (°C) over treatment time. The smaller λ values represent the better RF heating uniformity.

2.5. Treatment protocol development and efficacy confirmation

The optimal RF treatment protocol could be developed with previously determined suitable electrode gap, heating uniformity tests and cooling methods. To validate the final protocol, fifth-instar Indianmeal moth, the most heat resistant life stage (Johnson et al., 2003), was selected as the targeted insect for efficacy confirmation. Test insects were obtained from an Indianmeal moth laboratory colony originally from a grain packing house and reared at the Northwest A&F University, Yangling, China. The detail rearing conditions could be found in Johnson et al. (2003). One larva was placed into each in-shell pistachio through a 4 mm hole drilled in the kernel, and then the infested pistachio shell was sealed with scotch tape to prevent the insects escaping from the nut. Each container held 100 infested in-shell pistachios and enough uninfested pistachios to make a total of 1.8 kg (about 1400 nuts). This represented an artificial infestation level of 7%, well above the 2% actual level for insect damaged nuts (USDA-AMS, 2004) and the maximum acceptable rate (6%) based on the national standard of Iran (NSI, 1995). The confirmation tests included both three containers of infested pistachios used for RF treatments and unheated controls. Following RF treatments, the infested pistachios were removed for insect mortality evaluations according to the detailed procedures described in Wang et al. (2002).

2.6. Storage experiment and quality analyses

2.6.1. Storage conditions

Before and after RF treatments, the quality of pistachios was evaluated immediately and after accelerated shelf life storage. Due to its high split ratio, only in-shell pistachio was chosen for storage experiment. In-shell pistachios (160 g) were packed individually in brown paper bags and stored in the incubator set to 35 ± 0.5 °C with 30% relative humidity (RH) for 4 months to simulate commercial storage at 25 °C for 1 year. Longer storage was not considered, since after this period new nuts would be available. The storage time at 35 °C was calculated

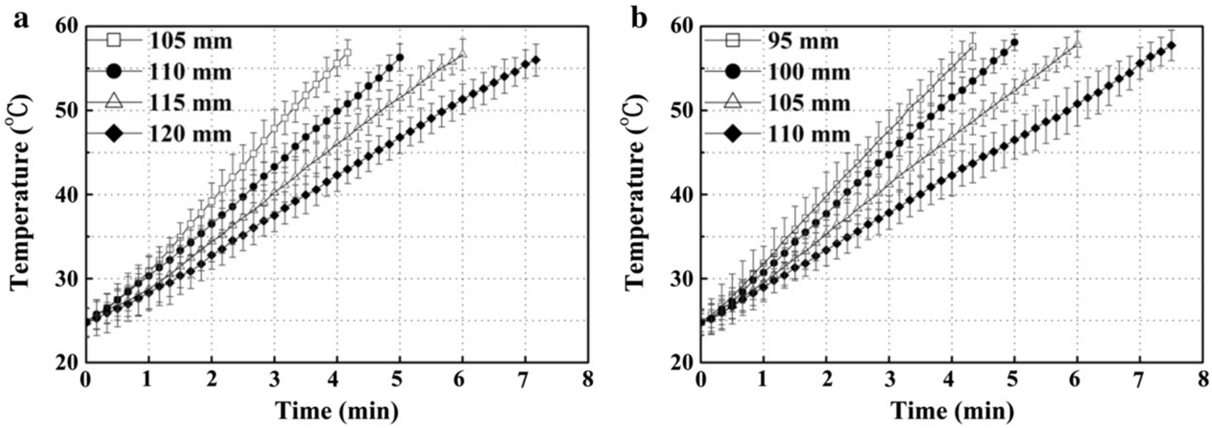

Fig. 3. Temperature–time histories of in-shell (a) and shelled (b) pistachios in the centre of the 7 cm thick sample with different electrode gaps.

based on a Q_{10} value of 3.4 for lipid oxidation (Taoukis, Labuza, & Saguy, 1997). Q_{10} was 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 *as follows*:

$$Q_{10} = \frac{k(T + 10^\circ \text{ C})}{k(T)} \quad (2)$$

The Q_{10} value of 3.4 for lipid oxidation was validated by real-time storage experiments (Wang et al., 2006). After each month of storage, samples were withdrawn from each treatment for quality analysis.

2.6.2. Moisture content and water activity

The moisture content (MC) of pistachios was determined according to the AOAC Official Method 925.40. About 2–3 g flour samples were placed in aluminium dishes and then dried in a vacuum oven (DZX-6020B, Nanrong Laboratory Equipment Co., Ltd., Shanghai, China) at 105 °C under pressure ≤ 100 mm Hg (13.3 kPa) until a constant weight of samples was attained. Observed loss in weight was reported as moisture content. About 5–6 g of in-shelled pistachios was placed into a sample cup and then in an Aqua Lab water activity meter (Model 4TE, Decagon Devices, Inc., Pullman, WA, USA) to measure water activity (Aw) under ambient temperature (25 °C). Before making any measurements, the instrument was calibrated following the instructions in the operation manual.

2.6.3. Oil extraction and chemical analysis

The oil was extracted from the pistachio kernels using a hydraulic press (T-50, Lefen, Dezhou, China) without additional heat treatment. The extracted oil was transferred into amber glass containers at 4 °C and all the quality analyses were performed within 3 h after pressing. Quality parameters were peroxide values (PVs) for assessing oxidative rancidity, free fatty acid (FFA) values for analysing hydrolytic rancidity, and fatty acid (FA) composition for analysing its stability and nutritional value. The PV and FFA were determined by official method Cd 8-53 and Ab 5-49 and recommended practices of the American Oil Chemists Society (AOAC, 1997) as follows:

$$\text{PV(meq/kg)} = \frac{(S - B) \times N \times 1000}{m} \quad (3)$$

where B is the volume (mL) of titrant for blank, S is the volume (mL) of titrant for sample, N is the normality of $Na_2S_2O_3$ solution (0.1 mol equi/L), and m is the weight (g) of oil sample.

$$\text{FFA(oleic acid g/100 g)} = \frac{V * N_1 * 28.2}{m} \quad (4)$$

where V is the titration of sample (mL), and N_1 is the normality of NaOH solution.

Fatty acid (FA) composition was determined by forming fatty acid methyl esters (FAME), and detailed measurement procedures can be found in Ling, Hou, Li, and Wang (2014).

2.6.4. Colour analysis

Surface colour of pistachio kernels was measured using a computer vision system (CVS), composed of a lighting system, a Cannon EOS 600 Digital camera with a 1800 megapixel resolution and an 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 Hou et al. (2014) and to reduce the data variability caused by kernel membrane, ground kernel and halves-kernel were placed in a plastic Petri dish (8 cm diameter) for measurement ground-state and inner kernel (cotyledons) colour (Bellomo & Fallico, 2007; Hojjati, Calín-Sánchez, Razavi, & Carbonell-Barrachina, 2013). Colour images of ground-state (20 g) and half-kernel cotyledon (n = 35) surface per treatment were captured and stored in the computer, then analysed by Adobe Photoshop CS3 (Adobe Systems Inc., USA). The reported colour values are the average values of ground-state and 35 half-kernel surface. Finally, the colour values obtained from Photoshop (L, a, b) were converted to CIE LAB (L^*, a^* and b^*) values using the following formulas (Briones & Aguilera, 2005):

$$L* = \frac{L}{2.5} \quad (5)$$

$$a* = \frac{240}{255} a - 120 \quad (6)$$

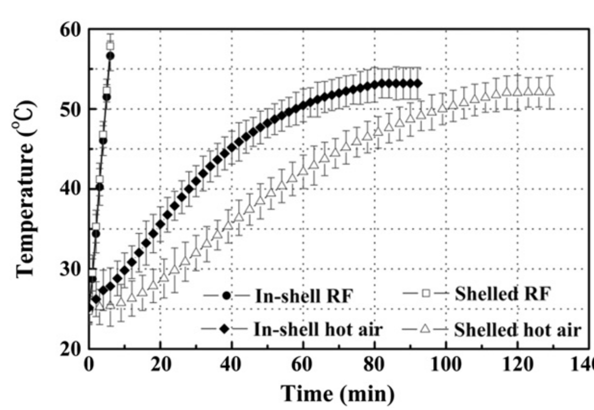

Fig. 4. Typical temperature–time histories of in-shell and shelled pistachios when subject to hot air heating at 55 °C compared with RF heating.

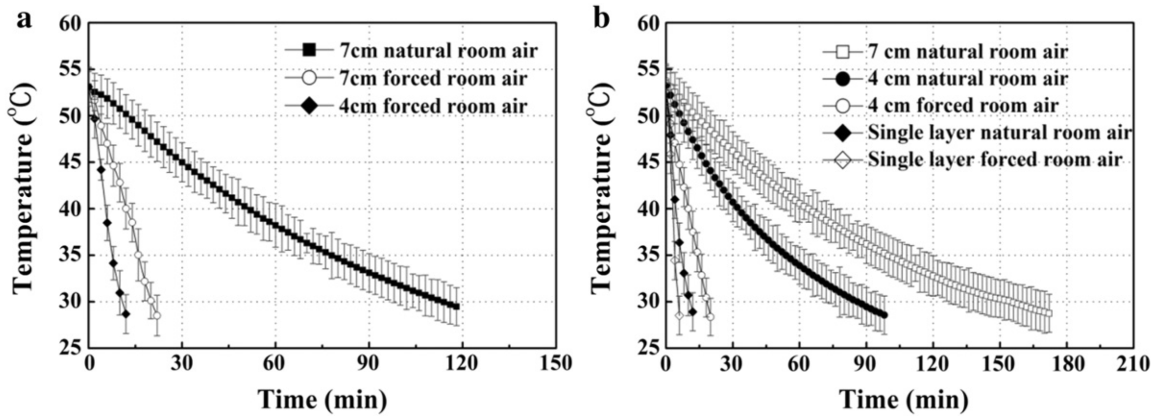

Fig. 5. Cooling curves of in-shell (a) and shelled (b) pistachios in the sample centre as a function of sample thickness with ambient nature or forced air cooling.

$$b* = \frac{240}{255}b - 120. \quad (7)$$

2.7. Statistical analysis

Results were expressed as means ± standard deviations (SDs) for moisture, Aw, FA composition, PV, FFA and colour values were calculated over three replicates. Differences were estimated by the analysis of variance (ANOVA) followed by Tukey's test and considered significantly at $p \leq 0.05$. All statistical analyses were performed using the statistical software SPSS 16.0 version (SPSS Inc., Chicago, IL, USA).

3. Results and discussion

3.1. Heating and cooling profiles

Fig. 3 shows the temperatures at the centre of 7 cm deep in-shell (a) and shelled (b) pistachio samples during RF heating using four different electrode gaps. The pistachio sample temperatures increased almost linearly with the heating time under the four electrode gaps. The heating rate increased with decreasing electrode gap, which corresponds to the increased power in the RF systems. About 4.0, 4.8, 5.6 and 7.0 min were needed to heat the 1.8 kg in-shell pistachios from 25 °C to 55 °C and the heating rates were 7.5 °C, 6.3 °C, 5.3 °C and 4.3 °C/min for electrode gaps of 10.5, 11.0, 11.5 and 12.0 cm, respectively. However, to obtain similar heating rates, the corresponding electrode gaps for shelled samples were reduced to 9.5, 10.0, 10.5 and 11.0 cm. The RF heating rate of in-shell samples was larger than that of shelled samples, which may be caused by the different bulk density, thermal and dielectric properties (Ling, Guo, Hou, Li, & Wang, 2015). Fast heating rate resulting in higher throughput, but heating uniformity could be negatively affected by rapid RF heating. To obtain relatively high throughput with acceptable heating uniformity, the electrode gaps of 11.5 and 10.5 cm were selected for in-shell and shelled pistachios to achieve the heating rates of 5.3 and 5.4 °C/min and used for further heating uniformity tests.

A comparison of the temperature–time histories of pistachio is shown in Fig. 4 for the centre of a 7 cm thick sample using only hot air heating at 55 °C and only RF heating with electrode gaps of 11.5 and 10.5 cm for in-shell and shelled pistachios. During 55 °C forced air heating, it took about 82 and 117 min for the central temperatures of in-shell and shelled samples to reach 53.2 and 52.1 °C, respectively. This could have been caused by the poor heat conduction within the bulk low-moisture pistachio samples. The reduced voids in shelled pistachios reduced air flow and increased heating time. However, with RF heating, only 5.6 and 5.5 min were required for two types of pistachios to increase from 25 to 55 °C. The significantly reduced heating time demonstrated that RF energy could provide practical and effective disinfestation treatments for pistachios.

Fig. 5 shows the temperature–time histories in the sample centre as influenced by the sample thickness and cooling methods. Based on the cooling curves, about 115 and 150 min were needed for the 7 cm deep in-shell and shelled samples to cool from 55 °C to 30 °C with natural room air, respectively. However, the cooling time decreased

Table 1
Temperature and heating uniformity index (mean ± SD over 2 replicates) of pistachios after RF treatments using different operational conditions.

Location	RF only	RF + hot air	RF + movement	RF + mixing	RF + hot air + movement + mixing
In-shell pistachio temperature (°C)					
Top layer	56.1 ± 3.7	57.6 ± 3.0	56.7 ± 3.1	56.0 ± 2.4	57.5 ± 2.2
Bottom layer	58.9 ± 3.4	59.4 ± 3.2	59.1 ± 3.0	–	–
Interior kernel	53.8 ± 3.0	54.8 ± 2.7	53.7 ± 2.8	53.9 ± 2.1	54.9 ± 1.8
In-shell pistachio heating uniformity index (λ)					
Top layer	0.112 ± 0.011	0.085 ± 0.007	0.089 ± 0.013	0.070 ± 0.009	0.059 ± 0.009
Bottom layer	0.094 ± 0.009	0.086 ± 0.011	0.080 ± 0.008	–	–
Interior kernel	0.096 ± 0.013	0.082 ± 0.003	0.089 ± 0.007	0.065 ± 0.004	0.051 ± 0.006
Shelled pistachio temperature (°C)					
Top layer	52.6 ± 3.2	53.3 ± 2.8	53.0 ± 2.8	53.2 ± 2.4	54.8 ± 2.1
Bottom layer	54.3 ± 3.1	55.0 ± 2.7	54.6 ± 2.9	–	–
Interior kernel	53.6 ± 2.8	54.6 ± 2.5	53.8 ± 2.6	54.0 ± 2.2	54.7 ± 1.9
Shelled pistachio heating uniformity index (λ)					
Top layer	0.108 ± 0.008	0.090 ± 0.011	0.090 ± 0.008	0.075 ± 0.013	0.061 ± 0.008
Bottom layer	0.097 ± 0.010	0.081 ± 0.007	0.091 ± 0.004	–	–
Interior kernel	0.089 ± 0.006	0.079 ± 0.011	0.082 ± 0.009	0.067 ± 0.005	0.055 ± 0.007

Table 2
Moisture content (MC, % w.b.) of the in-shell and shelled pistachios before and after RF treatments.

Sample type	Treatment	Whole nut	Kernel	Shell
In-shell	Control	4.85 ± 0.28a	3.47 ± 0.05a	5.79 ± 0.19a
	RF treated	4.50 ± 0.26a	3.31 ± 0.11a	5.66 ± 0.17a
Shelled	Control		3.47 ± 0.05a	–
	RF treated		3.37 ± 0.06a	–

Mean values are not significantly different ($P > 0.05$) for the same lower case letters within a column among the treatments.

dramatically when introducing forced room air and reducing sample thickness since the surface heat transfer coefficient with forced convection was higher than that in natural convection and the reduced thickness resulted in fast heat conduction. The corresponding cooling times were finally reduced to about 10 min and 20 min to cool 4 cm deep in-shell and shelled samples to 30 °C with forced air, respectively. This cooling time would be short enough in a continuous RF process for in-shell samples, but was still long for shelled samples due to reduced voids in the sample volume. This cooling time was finally reduced to only about 5 min for single layer of shelled samples with forced air, which could be applied in the nut industry after RF treatments.

3.2. Heating uniformity in RF treated pistachios

The uniformity index value allows uniformity to be objectively and quantitatively compared. Table 1 shows the temperature distribution and uniformity index of the in-shell and shelled pistachios on the surface and the interior layers after RF heating under different conditions. It should be noted that the in-shell pistachio surface (shell) temperatures were 2–4 °C higher than its kernel temperatures, which could be caused by the higher moisture content in shells (Table 2). That is, RF energy was absorbed more in materials with higher moisture content due to higher loss factor, and similar results were also observed in RF treated walnuts (Wang et al., 2007b). The highest surface temperatures observed in the bottom layer, which was located at the geometric centre of the container. Adding hot air could help to raise the sample temperatures around the container walls. Mixing was the better method to improve heating uniformity as compared to hot air and movement based on the reduced λ value. Generally, hot air, movement and mixing all improved RF heating uniformity in two types of pistachios as indicated by gradual reductions in λ values. In the industrial-scale RF treatments, mixing could be achieved by mechanical tumbling between two RF units (Wang et al., 2007a). Finally, the uniformity index of interior layer kernels was reduced to 0.051 and 0.055 for in-shell and shelled samples, respectively. This heating uniformity index values was slightly larger than those found for almonds (Gao et al., 2010), lentils (Jiao et al., 2012) and coffee beans (Pan et al., 2012), but smaller than those obtained for walnuts (Wang et al., 2007a). Therefore, the final treatment protocol was developed using the integrated RF treatments with hot air, movement and mixing.

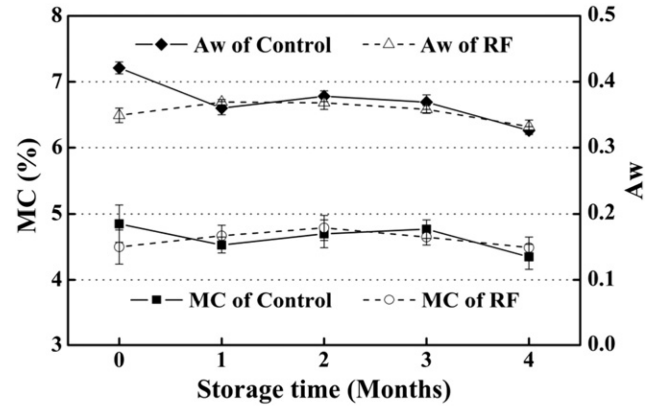

Fig. 7. Changes in moisture content (MC) and water activity (Aw) of RF treated and untreated pistachios during storage at 35 °C.

3.3. Final treatment protocol and insect mortality

Based on the above studies and thermal death kinetics of the target stored-product pest, the final treatment protocol was determined as follows. The electrode gaps of 11.5 and 10.5 cm were used for heating 1.8 and 2.0 kg with 7 cm thickness of in-shell and shelled pistachios in the RF system together with the conveyor belt movement at 8.9 and 9.1 m/h, hot air heating at 55 °C and a single mixing in the middle of the treatment time. After 5.6 and 5.5 min of heating, the RF system was turned off and the in-shell and shelled pistachios were held in hot air for 2 min, followed by forced room air (25 °C and 3.5 m/s) cooling for 4 cm depth and single-layer for in-shell and shelled samples, respectively.

Confirmation tests showed that insect mortality for the control was 0% because all 300 larvae were found alive, indicated that handling did not cause any mortality in the samples. All of RF treatments resulted in 100% mortality in the infested pistachios. The insect mortality results agreed with the thermal death time (TDT) curves of fifth-instar Indianmeal moth obtained by the heating block system (Johnson et al., 2003). The TDT curve showed that 3 min exposure to 50 °C or 1 min exposure to 52 °C should result in 100% mortality of a sample size of 600 insects (Fig. 6). In the current study, the lowest kernel temperature was higher than 52 °C after RF treatments, which was located above and to right side of TDT curve, after holding in hot air for 2 min and

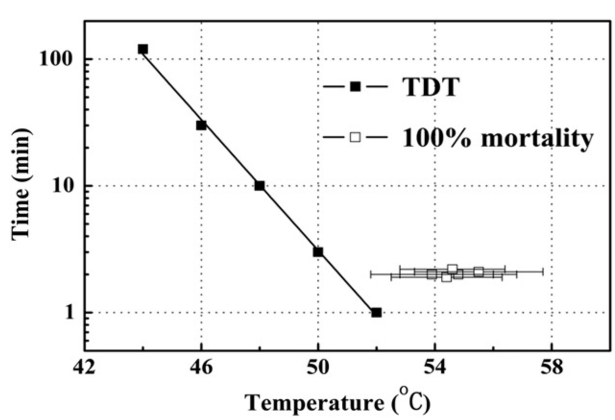

Fig. 6. Final pistachio kernel temperatures (mean ± SD) after RF treatments related to insect mortality as determined by thermal-death-time (TDT) curve for complete kill of fifth-instar Indianmeal moth larvae obtained in a heating block system (Johnson et al., 2003).

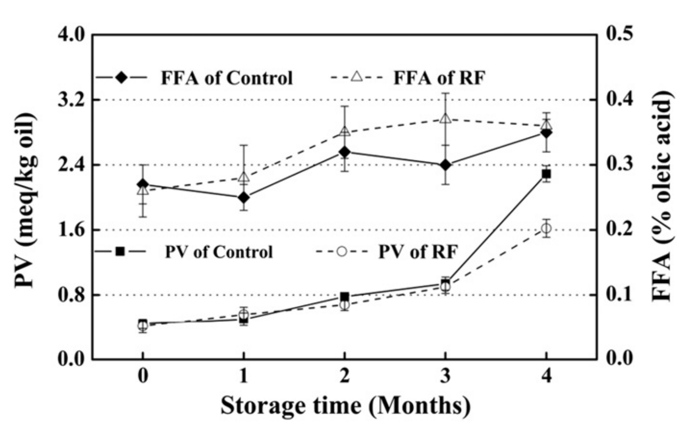

Fig. 8. Changes in peroxide value (PV) and fatty acid (FFA) value of oil extracted from RF treated and untreated pistachios during storage at 35 °C.

Table 3
Changes in the fatty acid composition of oil extracted from different treatment pistachios during storage at 35 °C.

Fatty acid (relative g/100 g)	Storage time (months)	Treatment	
		Control	RF treated
Palmitic acid (16:0)	0	10.63 ± 0.15Ab*	10.71 ± 0.21Aa
	2	11.14 ± 0.04Aa	11.09 ± 0.22Aa
	4	10.95 ± 0.07Aa	11.08 ± 0.10Aa
Palmitoleic acid (16:1)	0	1.05 ± 0.03Ab	1.09 ± 0.05Aa
	2	1.12 ± 0.02Aa	1.09 ± 0.00Aa
	4	1.04 ± 0.03Ab	1.06 ± 0.06Aa
Stearic acid (18:0)	0	1.06 ± 0.02Aa	1.07 ± 0.06Aa
	2	1.12 ± 0.02Aa	1.15 ± 0.02Aa
	4	1.10 ± 0.07Aa	1.07 ± 0.07Aa
Oleic acid (18:1)	0	55.14 ± 0.27Ab	55.10 ± 0.12Ab
	2	55.91 ± 0.05Aa	55.81 ± 0.07Aa
	4	55.79 ± 0.06Aa	55.56 ± 0.21Aa
Linoleic acid (18:2)	0	30.97 ± 0.40Aa	31.66 ± 0.51Aa
	2	30.39 ± 0.04Bb	30.51 ± 0.01Ab
	4	30.21 ± 0.14Ab	30.43 ± 0.11Ab

Mean values are not significantly different ($P > 0.05$) for the same capital letters within a row among the treatment, and for the same lower case letters within a column among the storage time.

would provide conservative and 100% mortality of Indianmeal moth for disinfestations.

3.4. Pistachio nut quality with RF treatment protocol and storage

Table 2 shows the moisture content (MC) of the in-shell and shelled pistachios before and after RF treatments. RF treatments slightly reduced average MC of whole pistachio nuts ($P > 0.05$), kernel and shell, however there was no statistically significant difference between them, indicating that the loss of saleable weight could be negligible during RF treatment for disinfestations. During the 4 months of the storage, the MC fluctuated in a narrow range both for control and RF treated pistachios. Similarly, the water activity changed mostly between 0.3–0.4 (Fig. 7). It is known that the monolayer MC of pistachios occurs at an Aw of around 0.3, which represents the range of optimal MC where dehydrated foods have the maximum shelf life (Tavakolipour, Armin, & Kalbasi-Ashtari, 2010).

It illustrates from Fig. 8 that the mean PV and FFA values increased with storage time both for control and RF treated pistachios. However the RF treatments did not significantly affect the PV and FFA values immediately after treatment (0 d) and during 3 months of storage ($P > 0.05$). After 3 months of storage, the PV of control samples increased suddenly to 2.29 meq/kg, which was significantly different ($P < 0.05$) from that of 1.62 meq/kg for RF treated samples. This difference might be due to possible inactivation of lipoxygenase (LOX) enzymes by short RF treatments (Buranasompob et al., 2007). Five major FA determined in pistachios (Table 3) were in agreement with the FA compositions in pistachio kernels reported by Arena et al. (2007) and Givianrad, Saber-Tehrani, and Mohammadi (2013). However, no significant change ($P > 0.05$) in FA compositions was observed between control and RF treated samples during whole storage periods. The stable FA compositions under RF treatment and storage were consistent with changes of FFA values, and increased slightly to 0.26–0.37% during 4 months of storage. Similar results were also obtained by Maskan and Karataş (1998, 1999) for Gaziantep variety pistachios with storage under controlled conditions (30 °C, 27% RH).

The colour results showed that there were no significant differences ($P > 0.05$) in L^*, a^* and b^* values of inner (cotyledons) and ground kernel colour after RF treatments (Table 4). But the significant decreases and increase ($P < 0.05$) with storage time were observed for L^* values in inner kernels and a^* values both in inner and ground kernels, respectively (Table 4). Bellomo, Fallico, and Muratore (2009), in a study on pistachio kernels, observed that chlorophyll and lutein decreased with increasing storage and degradation was more rapid at higher temperatures. This would explain why pistachio kernels got darker and the decreased intensity of green colour during storage. However, there was no significant difference between controls and RF treated samples for different storage times ($P > 0.05$).

4. Conclusions

The appropriate electrode gaps of 11.5 and 10.5 cm were selected for in-shell and shelled pistachios to obtain a RF heating rate of about 5.4 °C/min. RF heating sharply reduced the heating time of pistachio samples compared to hot air heating. RF heating uniformity was improved by increasing sample surface heating through the use of 55 °C hot air, minimizing the effect of electromagnetic field variations and most importantly by position effect through sample movement and a single mixing in the middle of RF treatment time. To provide a more conservative mortality of insects and minimize the quality degradation after RF heating, the pistachio samples were held for 2 min in hot air, then followed by forced room air cooling for 4 cm depth and single-layer for in-shell and shelled samples, respectively. This treatment caused 100% mortality of fifth-instar Indianmeal moth larvae, the most heat tolerant target stored-product pest in pistachios. The effect of RF treatments on pistachio quality and storage stability was not significant, indicating that pistachios were tolerant to a short exposure at the selected treatment temperatures for thermal disinfestations. This RF technology may provide a practical, effective, and environmentally friendly method for disinfesting pistachios.

Table 4
Changes in colour value of different treatments of pistachios during storage at 35 °C.

Colour parameters		Storage time (months)			
		Treatment	0	2	4
Inner kernel colour	L^*	Control	79.18 ± 2.24Aa	78.16 ± 2.70Aa	73.85 ± 2.97Ba
		RF	78.24 ± 2.52Aa	77.45 ± 2.50Aa	74.49 ± 1.56Ba
	a^*	Control	−(6.99 ± 2.07)Aa	−(6.65 ± 2.22)Aa	−(4.88 ± 2.07)Ba
		RF	−(7.20 ± 2.06)Aa	−(6.08 ± 1.54)Aa	−(4.91 ± 1.90)Ba
	b^*	Control	45.59 ± 3.99Aa	45.34 ± 2.43Aa	44.24 ± 2.48Aa
		RF	44.95 ± 4.78Aa	44.72 ± 3.00Aa	42.68 ± 2.53Aa
Ground kernel colour	L^*	Control	70.21 ± 0.95Aa	70.11 ± 0.40Aa	69.95 ± 0.39Aa
		RF	70.97 ± 0.70Aa	70.61 ± 1.01Aa	69.59 ± 0.59Aa
	a^*	Control	−(5.81 ± 0.29)Aa	−(5.09 ± 0.29)Ba	−(4.63 ± 0.22)Ca
		RF	−(5.71 ± 0.26)Aa	−(5.33 ± 0.25)Aa	−(4.62 ± 0.44)Ca
	b^*	Control	42.96 ± 0.52Ba	41.31 ± 0.34Ab	44.16 ± 0.47Aa
		RF	41.01 ± 0.25Ba	44.29 ± 0.39Aa	43.78 ± 0.31Aa

Mean values are not significantly different ($P > 0.05$) for the same capital letters within a row among the storage time, and for the same lower case letters within a column among the treatment.

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