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Research Paper

# Developing postharvest disinfestation treatments for legumes using radio frequency energy

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There is an urgent need to develop technically effective and environmentally sound phytosanitary and quarantine treatments for the legume industry to replace chemical fumigation. The goal of this study was to develop practical non-chemical treatments for postharvest disinfestations of legumes using radio frequency (RF) energy. A pilot-scale 27 MHz, 6 kW RF unit was used to investigate RF heating and consequent quality attributes in treated chickpea, green pea, and lentil samples. Only 5–7 min were needed to raise the central temperature of 3 kg legume samples to 60 °C using RF energy, compared to more than 275 min when using forced hot air at 60 °C. RF heating uniformity in legume samples was improved by adding forced hot air, and back and forth movements on the conveyor at 0.56 m min$^{-1}$. The final temperatures exceeded 55.8 °C in the interior of the sample container and 57.3 °C on the surface for all three legumes, resulting in low uniformity index values of 0.014–0.016 (ratio of standard deviation to the average temperature rise) for the interior temperature distributions and 0.061–0.078 for surface temperature distributions. RF treatments combined with forced hot air at 60 °C to maintain the target treatment temperature for 10 min followed by forced room air cooling through a 1 cm product layer provided good product quality. No significant differences in weight loss, moisture content, colour or germination were observed between RF treatments and unheated controls.
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## 1. Introduction

Chickpea (*Cicer arietinum*), green pea (*Pisum sativum*), and lentil (*Lens culinaris*) are three important rotational legumes in the United States, especially in the four north-western states: Idaho, Montana, North Dakota, and Washington. Infestation by insect pests can be a major problem in harvesting, processing and marketing of these legumes. Of particular economic importance are cowpea weevil (*Callosobruchus maculatus*), a serious internal pest of several legume crops, and Indianmeal moth (*Plodia interpunctella*), a common pest of many stored products (USADPLC, 2007). These pests reduce the quality of products by direct damage through feeding and by the production of webbing and faeces. Legumes infested with cowpea weevils and other internal feeders are not often easily detected by external inspection. Regulatory agencies and importers in many countries, therefore, have established phytosanitary and quarantine protocols, often including postharvest disinfestation treatments, intended to prevent the introduction of such pests. These countries may set conditions on imported product, requiring phytosanitary certification obtained through inspections at the time of

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grading to show that the shipment is apparently free of live insect infestation (USDA-FGIS, 2007).

Currently, the legume industry relies on fumigation with methyl bromide (MeBr) for postharvest insect control (Carpenter *et al.*, 2000). In 2004, India imposed a non-tariff barrier requiring all imported legumes to be fumigated with MeBr and certified free of bruchids (USADPLC, 2007). However, most phytosanitary uses of MeBr were phased out in 2005 by the U.S. Environmental Protection Agency (EPA) under the Federal Clean Air Act (Browner, 1999) and the Montreal Protocol (UNEP, 2006). In addition, MeBr fumigation is only practical at treatment temperatures $\geq 5\,^{\circ}C$, with lower treatment temperatures requiring higher doses or extended exposure times. However, processing plants and warehouses in the interior northern states of the U.S. are below $5\,^{\circ}C$ during the night for more than 6 months each year (USADPLC, 2007). Therefore, there is a need to develop a practical alternative to MeBr for control of insect pests in legumes. Any alternative must also have a minimum impact on product quality and environment.

Thermal treatment methods using hot air have been investigated extensively as MeBr alternatives for disinfesting stored commodities (Fields, 1992; Dowdy, 1999; Dosland *et al.*, 2006). The application of hot air is used to increase the temperature of the stored commodity above the thermal limits of survival of the pest. Heat disinfestation treatments are relatively easy to apply, leave no chemical residues, and may offer some fungicidal activity. Unfortunately, it is difficult to accomplish disinfestation using conventional hot air heating methods without causing deleterious effects to product quality (Armstrong, 1994). Temperature and time combinations required to kill the target insects may meet or exceed those that reduce the crop nutrients, germination or shelf life (Evans *et al.*, 1983). Another common difficulty with hot air heating methods is the slow rate of heat transfer due to a high resistance of conduction within bulk materials, resulting in hours of treatment times (Evans *et al.*, 1983). The low heating rates also may increase the thermotolerance of the targeted insects (Neven, 1998; Thomas and Shellie, 2000; Beckett and Morton, 2003) caused by the induction of heat shock proteins in insects during above normal but sub-lethal thermal conditions (Yin *et al.*, 2006). Radio frequency (RF) energy offers the possibility of rapidly increasing temperatures within bulk materials. Thus there has been an increasing interest in developing advanced thermal treatments for postharvest insect control in legumes using this method (Nelson, 1996; Tang *et al.*, 2000).

RF energy directly interacts with commodities containing polar molecules and charged ions to generate heat volumetrically and significantly reduce treatment times as compared to conventional heating methods. Many studies have explored the possibility of using RF energy to disinfest produce of insect pests (Frings, 1952; Nelson and Payne, 1982). Hallman and Sharp (1994), and Nelson (1996) summarised research on the application of RF treatments to kill selected pests in many postharvest crops. Vadivambal *et al.* (2008) found that microwave energy at 2450 MHz with similar heating mechanism to RF treatments might also control storage insects in barley and rye but this method resulted in poor germination due to high sample temperatures. RF treatments have been developed in laboratories for control of lesser grain borers in rough rice (Lagunas-Solar *et al.*, 2007), codling moth (Wang *et al.*, 2001) and navel orangeworm in in-shell walnuts (Wang *et al.*, 2002; Mitcham *et al.*, 2004) and more recently in scaled-up operations for industrial disinfestations of in-shell walnuts with acceptable product quality (Wang *et al.*, 2007a,b). The demonstrated ability of RF heating for low-moisture products shows its potential as an environmentally friendly pest control method for legumes.

Heating uniformity in RF-treated samples is a major concern for ensuring complete control of insects and providing acceptable product quality (Wang *et al.*, 2008a). Forced hot air, product movement and product mixing were used to improve heating uniformity in RF-treated walnuts in laboratory and industrial-scale RF systems (Wang *et al.*, 2005, 2007a). Uniformity index values, defined as the ratio of standard deviation (SD) to average temperature rise during heating, have been used to evaluate RF heating uniformity (Wang *et al.*, 2005, 2008b). RF energy has large penetration depths in chickpeas (Guo *et al.*, 2008) and a low uniformity index in RF-treated lentils (Wang *et al.*, 2008b). It is, therefore, possible to obtain the desired RF heating uniformity to achieve good product quality and complete insect control, and to provide practical operational parameters for scaling up to a continuous RF process.

Understanding the thermotolerance of targeted insects is essential in developing RF treatments. Thermotolerance of insects generally decreases with an increase in temperature (Wright *et al.*, 2002; Mahroof *et al.*, 2003; Boina and Subramanyam, 2004). The mortality data for stored-product insects when exposed to moderate to high temperatures have been extensively investigated (Fields, 1992; Adler, 2002; Bruce *et al.*, 2004). Johnson *et al.* (2003, 2004) used a heating block system to simulate the heating rates ($5–10\,^{\circ}C\,min^{-1}$) obtained in RF heat treatments and reported that Indianmeal moth and red flour beetle larvae were completely killed after exposure to $52\,^{\circ}C$ for 1 and 2 min, respectively. On the other hand, lentil germination is not affected by heat treatments when the sample moisture content is less than 20% wet basis (w.b.) and treatment temperatures are less than $70\,^{\circ}C$ (Tang and Sokhansanj, 1993). Preliminary studies with cowpea weevils indicated that they may be more heat tolerant than previously tested insects because it took about 7 min at $56\,^{\circ}C$ for pupae to achieve 100% mortality. Treatment temperatures of $55–58\,^{\circ}C$ for 5–10 min should be practical for control of the targeted cowpea weevil and Indianmeal moth in legumes with RF energy without negative effects on legume germination.

The objectives of this study were to investigate heating rates and uniformity in chickpea, green pea, and lentil when subjected to forced hot air and RF energy, and to evaluate the quality of RF-treated legumes.

## 2. Materials and methods

### 2.1. *RF and hot air heating systems*

A 6 kW, 27 MHz pilot-scale RF system (COMBI 6-S, Strayfield International, Wokingham, U.K.) was used for heating chickpea, green pea, and lentil samples together with

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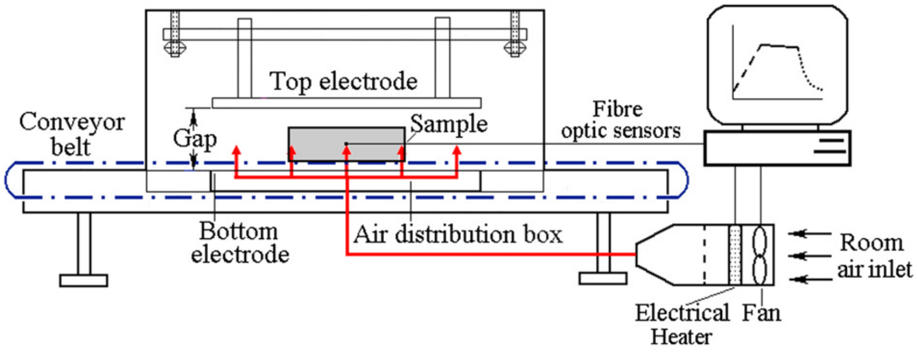


**Fig. 1 – Schematic view of the pilot-scale 6 kW, 27.12 MHz RF unit showing the two-pair plate electrodes, conveyor belt and the hot air system.**

a customized auxiliary hot air system using a 5.6 kW electrical strip heater and a blower fan (Fig. 1). The size of the parallel perforated electrode plates was 75 cm × 55 cm. A conveyor belt moved samples between electrodes during RF heating to simulate continuous processes. The gap between the two electrodes was adjusted to change RF power coupled to the samples. Samples in a plastic container (25.5 cm × 15 cm × 10 cm) (Fig. 2) were placed on the convey or belt in contact with the bottom plate electrode. The container moved back and forth on the conveyor belt at 0.56 m min$^{-1}$. The container walls were constructed from 12.7 mesh nylon screen with 0.14 cm openings (9318T27, McMaster-Carr Supply Company, Los Angeles, CA, USA) to allow hot air to pass through the samples. The hot air system provided forced hot air (air temperature of 60 °C at an air speed of 0.7 m s$^{-1}$ in the RF cavity) into the RF cavity through an air distribution box under the bottom electrode (Fig. 1).

### 2.2. *Comparisons of temperature profiles of legumes between hot air and RF heating*

Chickpea, green pea, and lentils were purchased from a processing plant in Kendrick, ID, USA. The average initial moisture contents were about 7% on w.b. The 100-seed weight of the tested chickpea, green pea, and lentil was 50.12 ± 0.57 g, 18.54 ± 0.35 g, and 5.08 ± 0.27 g, respectively. Ambient room temperature (23 °C) was used as the initial sample temperature for each test. Dielectric loss factor values of these three legumes at 27 MHz are similar (Guo *et al.*, 2010). Therefore,

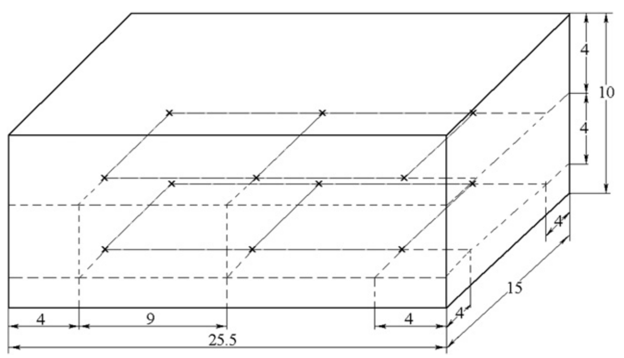


**Fig. 2 – The plastic container with 12 locations (×) for sample temperature measurements (all dimensions are in cm).**

only lentils were selected to determine the adequate electrode gap for RF heating of the samples. Lentil samples of 3 kg with 10 cm sample depth in the plastic container described above were placed on the centre of the bottom electrode and subjected to RF heating in stationary conditions with three gaps of 12.4, 13.3, and 14.2 cm. The centre temperature of the sample was measured using FISO optic sensors (UMI, FISO Technologies Inc., Saint-Foy, Quebec, Canada) during RF heating. After determining that the most appropriate gap was 13.3 cm, this gap was always used to measure the temperature–time histories of chickpea and green pea samples to a centre sample temperature of 60 °C. Centre sample temperatures for all three legumes were also measured during forced hot air heating at 60 °C. The measurement was stopped when the sample temperature change was <0.1 °C over more than 2 h.

### 2.3. *Determination of cooling method*

Rapid cooling is necessary to avoid quality degradation after RF or hot air heating. Lentil samples that had been heated to about 60 °C by hot air were used to develop appropriate cooling methods. Samples with 10, 2, and 1 cm depth held in the plastic treatment containers were subjected to ambient natural and ambient forced air cooling. The forced air cooling was obtained with a cross airflow driven by a fan and the air speed at the sample surface was measured by a rotating vane anemometer (LCA 6000, AIRFLOW Instrumentation, Buckinghamshire, UK). The measured air speeds on the sample surface were about 0.2 and 1.0 m s$^{-1}$ for the natural and forced air cooling, respectively. The temperature in the sample centre was recorded until the sample temperature dropped to 30 °C. The best cooling method was further used to determine the temperature–time histories of green pea, chickpea, and lentil samples after RF and hot air heating.

### 2.4. *Heating uniformity tests*

Heating uniformity tests were first conducted in the RF unit using seven polyurethane foam sheets. The sheets (McMaster-Carr, Los Angeles, CA) with 61.0 cm L × 40.6 cm W × 1.3 cm H were stacked on top of each other on the centre of the bottom electrode. The electrode gap was set at 12 cm for the central foam to achieve a heating rate of 5–6 °C min$^{-1}$. To examine the effect of forced hot air on RF heating uniformity,

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measurements were made with and without the forced hot air. The foam surface temperatures were measured with a digital infrared camera (Thermal CAM™ SC-3000, FLIR Systems, Inc., North Billerica, MA, USA) having an accuracy of ±2 °C. Details on measurement procedure and the precision of this camera can be found for apples, oranges, persimmons and walnuts after RF heating in Birla *et al.* (2004), Wang *et al.* (2006, 2007a), and Tiwari *et al.* (2008). Immediately upon removal from the RF system, thermal images were taken for the upper surface of each sheet, beginning with the top sheet working towards the bottom. The total measurement time for the seven sheets was about 30 s. From each of the thermal images, 45,056 individual surface temperature data points were collected from the final surface temperatures of the foam sheet and were used for statistical analyses (Wang *et al.*, 2005, 2007a). Each test was replicated twice.

To optimise heating uniformity, 3 kg chickpea, green pea, and lentil samples 10 cm in depth were heated in the RF system with or without movement on the conveyor belt, with or without forced hot air, and with or without mixing. An electrode gap of 13.3 cm was used for all tests. The container movement started from the centre to the right edge of the top electrode, moved back to the left edge and then came back to the centre at 0.56 m min$^{-1}$ until the end of RF heating. A single mixing was included in the middle of the given RF treatment time. Mixing was made by bare hands in a large container (55 cm × 40 cm × 14 cm) for 20 s. After mixing, the samples were returned to the treatment container and placed back into the RF system for the remainder of the treatment time. The mixing process took less than 1 min. Before and immediately after RF treatments, the sample surface temperatures were mapped with the thermal imaging camera (Fig. 3). Each thermal image took less than 1 s. The surface temperature data in the treated area were used for statistical analyses. After that, sample temperatures at 12 positions in the container were also measured using a thin Type-T thermocouple thermometer (Model 91100-20, Cole-Parmer Instrument Company, Vernon Hill, IL, USA) having an accuracy of ±0.2 °C and 0.8 s response time. The 12 positions were equally distributed from the side walls with two points each at the right, centre, and left sides, and at two depths of 4 and 8 cm

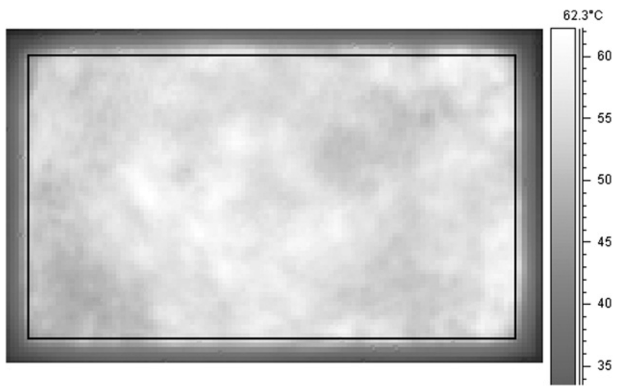


**Fig. 3 – Surface temperature (top view) distributions of lentils obtained by infrared thermal imaging within the boundary field used for statistical analyses after RF treatments (gap of 13.3 cm) without hot air heating and movement.**

from the top (Fig. 2). The average and SD values of the surface and interior sample temperatures for each replicate were used for evaluating heating uniformity. Each test was repeated twice for each legume sample.

The uniformity index, $\lambda$, is useful to evaluate heating uniformity of the treated product in a fixed configuration and a specific RF unit. It is derived experimentally from product temperature measurements during treatment, using the following equation (Wang *et al.*, 2005):

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

where $\Delta\sigma$ is the rise in SD of product temperature and $\Delta\mu$ is the rise in mean product temperature over treatment time.

### 2.5. *Treatment procedures*

RF treatment conditions can be selected at relatively low temperatures for longer holding times or higher temperatures for shorter holding times (Wang *et al.*, 2008b). Because of a need for high throughputs in industrial operations, a high-temperature and short-time treatment was selected for developing the RF processes. The targeted average temperature–time combination for complete kill of insect pests in legumes without product quality degradation was estimated to be 55 °C for 10 min, based on the thermal-death kinetics of Indianmeal moth and red flour beetle (Johnson *et al.*, 2003, 2004) and previous quality studies (Tang and Sokhansanj, 1993). Based on previously determined temperature–time histories, chickpea, green pea and lentil samples in plastic treatment containers were heated with 60 °C forced air for 312, 275, and 660 min, respectively. Similarly, based on the previously determined heating uniformity tests, the selected operational parameters for RF treatments that provided acceptable heating uniformity were conveyor belt movement of 0.56 m min$^{-1}$ and 60 °C forced air without mixing. Chickpea, green pea, and lentil samples were heated in the RF system for 5, 5, and 7 min, respectively, and held in hot air for 10 min. After treatment, samples were spread in a 1 cm thick layer on a tray and cooled by forced room air for 15, 12, and 18 min for chickpea, green pea and lentil, respectively. The untreated samples were considered as controls. Treated samples were sealed in plastic bags for quality evaluations. Each treatment was replicated thrice.

### 2.6. *Quality evaluations*

Weight loss, moisture content, colour, and germination were evaluated immediately after hot air and RF treatments. Weight loss was estimated from the sample weight difference before and after treatment. To measure moisture contents, ground seed samples (10 ~ 12 g) in triplicates for each treatment were dried in an air oven (ADP-31, Yamato Scientific America, Inc., USA) at 103 °C for 72 h (ASAE, 2008). The samples were then cooled in a closed desiccator with $CaSO_4$ at the bottom before reweighing. The moisture content was estimated from initial and final weights of the seed samples.

A computer vision system (CVS) was used to measure colour values of treated seed samples. The CVS included a lighting system, a Nikon D70 Digital camera (6.1 megapixel

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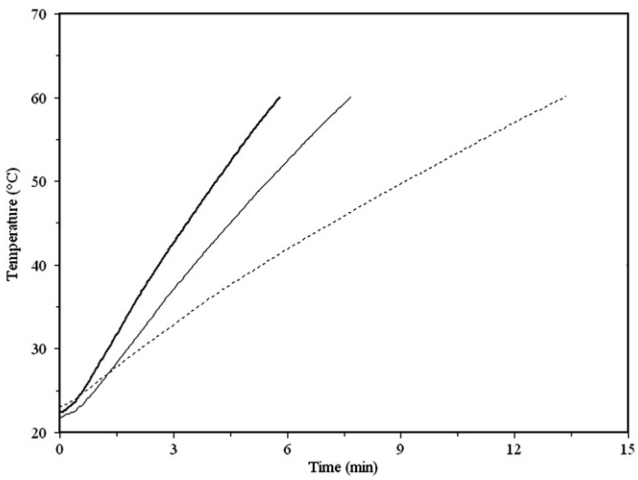


**Fig. 4 – Temperature–time histories of the RF heated lentils in the centre of the 10-cm thick container as a function of the electrode gap (— 12.4 cm, – 13.3 cm, and - - - 14.2 cm) without movement, hot air heating, and mixing.**

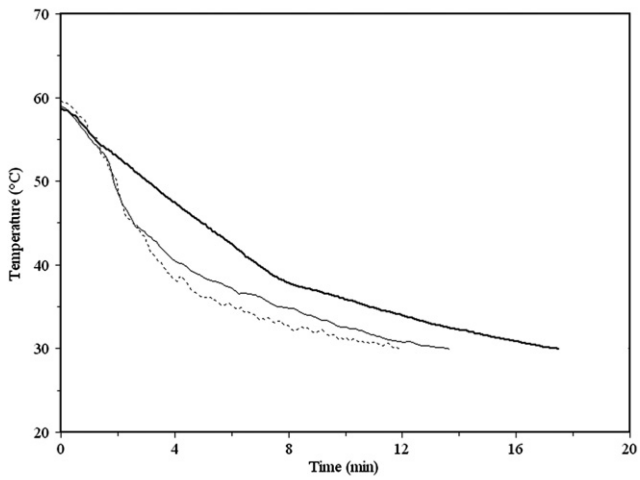


**Fig. 6 – Typical cooling curves of chickpea (–), green pea (- - -), and lentil (—) in the sample centre with 1 cm thick under forced room air cooling.**

resolution and 18–70 mm DX Zoom Nikkor Lens) and a Pentium IV desktop computer with image-processing software. A rectangular white box filled with a seed sample was placed at the bottom of a shooting tent. A detailed description of the camera installation, fluorescent light, and the measurement procedure is given by Kong *et al.* (2007). Colour images of 30 seed surfaces per treatment were captured and stored in the computer using Adobe Photoshop CS (Adobe Systems Inc., USA). These colour values were then converted to Hunter *L* (darkness), *a* (green–red), and *b* (blue–yellow) parameters. Germination rate was determined by immersing 30 legume seeds in water for 24 h at room temperature and holding them on germination paper saturated with distilled water in Petri dishes for two days in the dark under ambient conditions. Finally, geminated seeds were counted and the germination percentage was calculated.

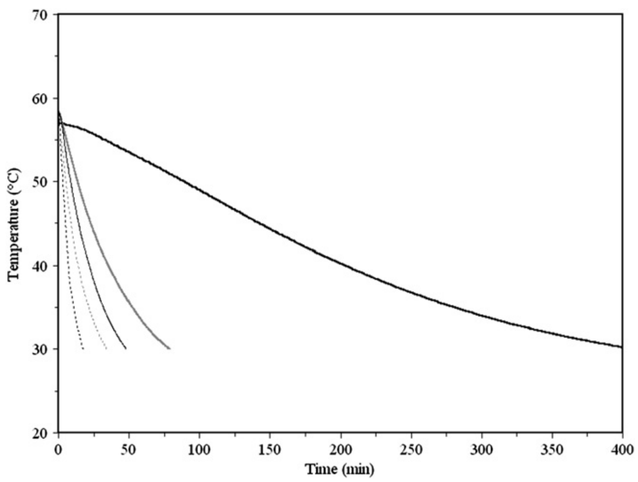


**Fig. 5 – Cooling curves of lentils in the sample centre as a function of sample thickness (— 10 cm under natural air cooling, – 2 cm, and - - - 1 cm) under natural (grey 50%) or forced (black) room air cooling.**

The average and SD values for weight loss, moisture content, colour values and germination were calculated over three replicates. The measurement of individual quality attribute was subjected to one-way analysis of variance (ANOVA) and means were separated using Tukey's method (SAS Institute, 2002, Cary, NC) at a significance level of 0.05.

## 3. Results and analyses

### 3.1. Heating and cooling profiles

Fig. 4 shows the temperature at the centre of 10 cm deep lentil samples during RF heating using three different electrode gaps. Samples were treated without movement, forced hot air, or mixing. The heating rate in RF-treated lentils increased

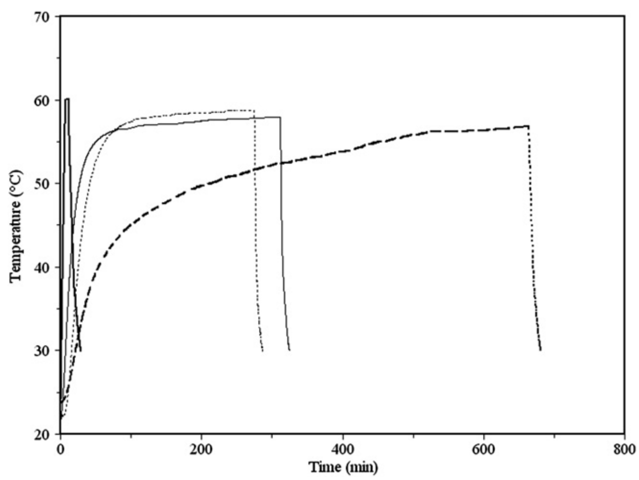


**Fig. 7 – Typical temperature–time histories of lentil (– – –), green pea (- - -), and chickpea (–) in the centre of a 10 cm thick container in hot air heating at 60 °C as compared with stationary RF heating of lentils (—) followed by forced room air cooling in 1 cm thick samples.**

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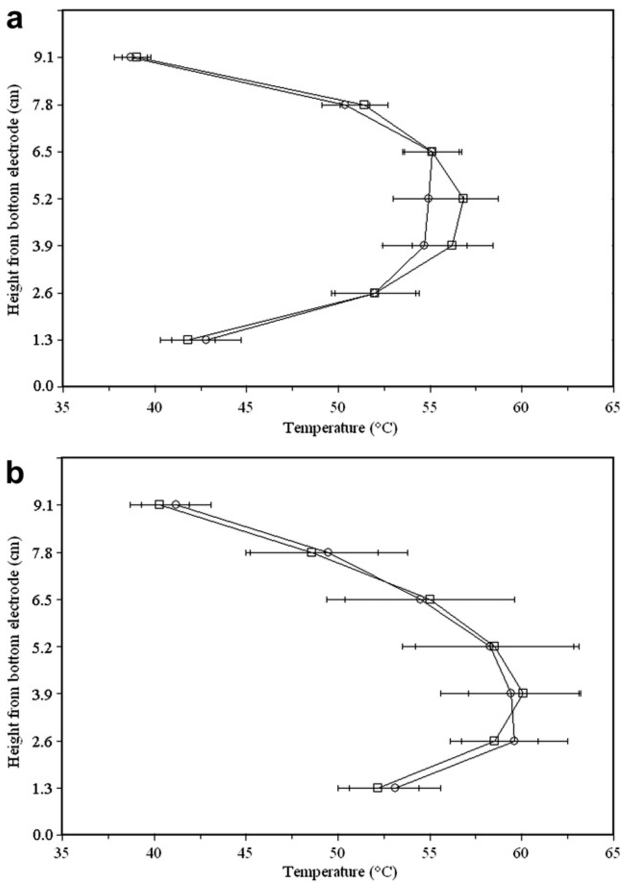


**Fig. 8 – The average and SD values of surface temperature profiles as a function of height of polyurethane foam sheets after stationary RF treatments without (a) and with (b) 60 °C hot air heating over replicates 1 (□) and 2 (○).**

with decreasing electrode gap. With an electrode gap of 13.3 cm about 7.5 min of RF heating was needed for the centre of the lentil sample to reach 60 °C so as to achieve a minimum average temperature of 55 °C for insect control but below 70 °C to avoid quality degradation. The electrode gap of 13.3 cm was selected for further tests. The heating times were about 5 min both for chickpea and green pea under the above RF heating conditions.

Temperatures at the centre of 10, 2, and 1 cm deep lentil samples during cooling in static or forced ambient air are shown in Fig. 5. About 400 min were needed to cool 10 cm deep lentil samples from 60 °C to 30 °C in static air. The cooling time decreased dramatically with reducing sample thickness and when introducing forced air. Only 1 cm deep samples in forced ambient air resulted in a cooling time short enough to achieve 30 °C in a continuous process in industry. Cooling curves for 1 cm deep samples of all three legumes in forced ambient air are shown in Fig. 6. We estimate that for final commercial treatments, 15, 12, and 18 min of forced ambient air would be needed to cool chickpea, green pea, and lentil samples, respectively.

Fig. 7 shows temperatures measured at the centre of 10 cm thick legume samples in 60 °C forced air heating compared with those in RF heating of lentils. Heating treatments were followed by forced ambient air cooling in a 1 cm deep bed. During 60 °C forced air heating, chickpea, green pea, and lentil samples took about 312, 275, and 660 min for the central temperature to reach 57.4, 58.7, and 56.5 °C, respectively. This was probably caused by the poor heat conduction within the bulk low-moisture legume samples. But the heating time in lentils was sharply reduced to 7 min by RF heating. Such rapid heating rates suggest that RF energy should provide practical and efficacious disinfestation treatments for legumes, once treatment parameters are identified that will provide the required heating uniformity.

### 3.2. *Heating uniformity in RF-treated materials*

Figs. 8a and b show the average and SD values for surface temperatures of polyurethane foam sheets as a function of sheet height after 6 min RF treatments with a gap of 12 cm without and with 60 °C forced air. The surface temperature of the foam sheets was repeatable when the electrode gap and forced hot air were maintained the same. Without forced hot air, the highest surface temperatures were observed in the three middle layers, which was close to the geometric centre of the stack. Surface temperatures at the top and bottom layers were lower than those of the middle layers probably because both top and bottom layers were exposed to ambient air (Fig. 8a). Variability in horizontal surface temperatures was low for each layer (SD 0.8–2.2 °C). Forced hot air affected the surface temperatures of the two bottom layers more than

**Table 1 – Comparisons of the temperature (mean ± SD) distribution of the three legumes after RF heating with different conditions (data were from two replicates)**

| Legumes | No hot air heating | With hot air heating | With movement | With hot air + movement | With hot air + movement + mixing |
|---|---|---|---|---|---|
| *Surface temperature (°C)* | | | | | |
| Chickpea | 64.5 ± 4.2 | 66.5 ± 4.9 | 64.9 ± 3.6 | 63.3 ± 3.2 | 69.4 ± 5.4 |
| Green pea | 61.3 ± 3.6 | 62.6 ± 3.3 | 62.7 ± 3.4 | 62.5 ± 3.0 | 64.1 ± 3.5 |
| Lentil | 56.8 ± 2.8 | 58.5 ± 2.5 | 57.5 ± 2.7 | 57.3 ± 2.2 | 63.8 ± 3.5 |
| *Middle and bottom layer temperature (°C)* | | | | | |
| Chickpea | 65.7 ± 1.3 | 64.5 ± 1.1 | 65.6 ± 1.7 | 62.0 ± 0.7 | 66.8 ± 1.0 |
| Green pea | 64.2 ± 1.6 | 63.0 ± 0.9 | 65.1 ± 1.3 | 61.5 ± 0.7 | 63.1 ± 0.6 |
| Lentil | 64.2 ± 2.6 | 58.6 ± 0.9 | 64.8 ± 1.7 | 55.8 ± 0.8 | 63.9 ± 1.0 |

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**Table 2 – Comparisons of the heating uniformity index (mean ± SD) of the three legumes after RF heating with different conditions (data were from two replicates)**

| Legumes | No hot air heating | With hot air heating | With movement | With hot air + movement | With hot air + movement + mixing |
|---|---|---|---|---|---|
| *Surface uniformity index* | | | | | |
| Chickpea | 0.097 ± 0.007 | 0.110 ± 0.018 | 0.084 ± 0.003 | 0.078 ± 0.008 | 0.114 ± 0.009 |
| Green pea | 0.089 ± 0.010 | 0.082 ± 0.029 | 0.086 ± 0.009 | 0.073 ± 0.011 | 0.085 ± 0.002 |
| Lentil | 0.079 ± 0.005 | 0.068 ± 0.004 | 0.077 ± 0.015 | 0.061 ± 0.003 | 0.086 ± 0.012 |
| *Middle and bottom layer uniformity index* | | | | | |
| Chickpea | 0.024 ± 0.005 | 0.022 ± 0.013 | 0.034 ± 0.020 | 0.014 ± 0.008 | 0.017 ± 0.003 |
| Green pea | 0.030 ± 0.006 | 0.017 ± 0.007 | 0.027 ± 0.014 | 0.014 ± 0.006 | 0.013 ± 0.007 |
| Lentil | 0.063 ± 0.016 | 0.019 ± 0.007 | 0.033 ± 0.011 | 0.016 ± 0.004 | 0.020 ± 0.006 |

those of the top two layers because hot air was blown from the air distribution box directly onto the bottom layer (Fig. 8b). Without movement through the treatment chamber, variability in horizontal surface temperatures increased (1.6–5.1 °C) in forced hot air due to the creation of hot spots close to air outlets in the distribution box. These results suggested that adding hot air could increase the top and bottom layer temperatures of legumes in the container.

Comparisons of the temperature distribution and uniformity index values of the three legumes on the surface and inside the container after RF heating under different conditions are summarised in Tables 1 and 2. In all cases, the mean temperatures after RF treatment were >55 °C, which may meet the requirements for insect control provided a sufficient holding time is used (Table 1). The surface temperatures taken by the thermal imaging camera were comparable to the interior temperatures obtained by thermocouples, although variability of surface temperatures was larger than that of interior temperatures. Hot air and movement reduced temperature variations in RF-treated legume samples based on reduced SD values. Similar results were also found in the uniformity index values (Table 2). The heating uniformity index values are keys to developing successful postharvest quarantine treatments using RF energy. The surface uniformity index values ($\lambda = 0.079$–$0.097$) for legumes under stationary conditions without hot air heating in this study were comparable with that for soybeans ($\lambda = 0.080$), but larger than that for lentils ($\lambda = 0.054$) and smaller than that for walnuts ($\lambda = 0.165$) obtained in a 12 kW RF unit (Wang *et al.*, 2008b). By increasing sample surface heating through the use of hot air and minimizing the effect of electromagnetic field variations through movement on the conveyor belt, the uniformity index was reduced to 0.061–0.078 for legumes (Table 2), resulting in the required temperature distribution for achieving insect control and good product quality. This was also in good agreement with the reduced uniformity index ($\lambda = 0.062$) for walnuts when subjected to a continuous process with hot air heating in a 25 kW industrial-scale RF system (Wang *et al.*, 2007a). In the current measurement accuracy, the mixing did not significantly improve the heating uniformity of RF-treated legumes (Table 2). In this study, the optimal RF heating uniformity was observed for RF treatments with hot air heating and movement, resulting in the smallest uniformity index values. Excluding mixing should also help increase the throughput in industrial applications. Therefore, including hot air and movement in the design of an RF

**Table 3 – Quality (mean ± SD over three replicates) comparison of three legumes between hot air and the hot air and movement assisted RF treatments**

| Treatment | Wt. loss | Moisture | Germination | Colour values | | |
|---|---|---|---|---|---|---|
| | (%) | (% w.b.) | (%) | *L* | *a* | *b* |
| *Chickpea* | | | | | | |
| Control | | 6.19 ± 0.02a | 86.66 ± 11.54a | 75.35 ± 2.03a | 4.10 ± 0.78a | 27.95 ± 0.99a |
| Hot air | 2.10 ± 0.34a[a] | 4.65 ± 0.12b | 70.00 ± 20.00a | 73.67 ± 2.72b | 4.56 ± 1.12a | 28.62 ± 1.50a |
| RF | 0.17 ± 0.13b | 6.08 ± 0.08a | 83.33 ± 11.54a | 74.71 ± 2.24a,b | 4.46 ± 0.77a | 28.20 ± 1.20a |
| *Green pea* | | | | | | |
| Control | | 6.48 ± 0.07a | 100.00 ± 0.07a | 66.51 ± 3.48a | −5.88 ± 1.65a | 25.70 ± 1.52a |
| Hot air | 0.90 ± 0.12a | 6.19 ± 0.26a | 93.33 ± 0.07a | 68.59 ± 3.44a | −4.88 ± 1.86a | 24.97 ± 1.66a |
| RF | 0.13 ± 0.07b | 5.90 ± 0.07a | 96.67 ± 0.07a | 67.84 ± 3.35a | −5.38 ± 1.34a | 24.70 ± 1.64a |
| *Lentil* | | | | | | |
| Control | | 6.54 ± 0.17a | 96.66 ± 5.77a | 58.84 ± 1.76a | 7.38 ± 1.37a | 28.39 ± 0.94a |
| Hot air | 14.68 ± 0.47a | 3.45 ± 0.13b | 96.66 ± 5.77a | 58.62 ± 2.23a | 6.54 ± 2.01a | 28.55 ± 0.88a |
| RF | 0.10 ± 0.03b | 6.49 ± 0.26a | 100.00 ± 0.00a | 58.68 ± 2.60a | 7.33 ± 2.20a | 28.86 ± 1.07a |

a Different letters with a column indicate that means are significantly different (Tukey's mean separation, $P < 0.05$).

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treatment protocol would be adequate to obtain the required heating uniformity.

### 3.3. Quality of RF-treated legumes

Table 3 compares quality values of the three legumes treated with hot air and RF energy. Initial moisture contents (6.19–6.54% w.b.) were similar for the three legumes. RF treatments did not significantly affect the moisture content of the three legumes ($P > 0.05$), but hot air treatments significantly reduced the moisture content of chickpea and lentil ($P < 0.05$). The hot air treatments resulted in significant weight loss ($P < 0.05$) in the three legumes as compared to the RF treatments, especially in lentils. For all three legumes the effects of hot air and RF treatments on colour and germination were negligible, which are in good agreement with the germination in lentils (Tang and Sokhansanj, 1993). It seems that the effects of treatment temperatures on germination of chickpea and green pea were similar to those of lentils. These effects were not significantly different from values in untreated controls ($P > 0.05$) in all cases except for $L$ values in hot air treated chickpeas. Based on these results, RF treatments should effectively disinfest postharvest legumes while maintaining good product quality.

## 4. Conclusions

RF heat treatments sharply reduced the heating time and increased the heating rate in chickpea, green pea, and lentil samples as compared to hot air heating. RF heating uniformity was greatly improved by 60 °C forced air and movement of the container between the electrodes. Mixing of legume samples between RF treatments did not further improve uniformity, and could be excluded from the protocol, consequently increasing throughput. After achieving the required heating uniformity, an RF treatment protocol was developed as a disinfestation treatment for legumes with RF heating to 60 °C held for 10 min in hot air followed by forced room air cooling in a 1-cm layer. RF treatments had little effect on any of the measured quality parameters. But hot air treatments, on the other hand, reduced sample weight and moisture contents significantly for chickpeas and lentils. RF treatments, therefore, should provide a practical, effective and environmentally friendly method for disinfestation of postharvest legumes while maintaining product quality. Future research is needed, including large scale tests, with infested product to confirm the treatment efficacy and product quality after extended storage.

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