TREATMENT PROTOCOL DEVELOPMENT FOR DISINFESTING LEGUMES USING RADIO FREQUENCY ENERGY

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A pilot-scale 27 MHz, 6 kW RF unit was used to investigate RF heating and consequent quality attributes in three treated legumes. Only 5-7 min was needed to raise the central temperature of 3 kg 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 samples was improved by adding forced hot air and movements on the conveyor. The final temperatures exceeded 55.8°C in the interior and 57.3°C on the surface for all three legumes, resulting in low uniformity index values of 0.014-0.016 and 0.061-0.078 for the interior and surface temperature distributions, respectively. Hot air assisted RF treatments provided good product quality.

Keywords: Heating uniformity, Legume, Protocol, RF, Quality

INTRODUCTION

Chickpea (*Ciser arietinum*), green pea (*Pisum satium)* and lentil (*Lens culinaris*) are three important rotational legumes in the United States. 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 feces. 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 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 and the Montreal Protocol. In addition, MeBr fumigation is only practical at treatment temperatures ≥5°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°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. 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 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. 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 all 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). 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. Johnson et al. (2003; 2004) used a heating block system to simulate the heating rates (5-10°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°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% w.b. and treatment temperatures are less than 70°C (Tang and Sokhansanj, 1993). Preliminary studies with cowpea weevils indicate that they may be more heat tolerant than previously tested insects because it takes about 7 min at 56°C for pupae to achieve 100% mortality. Treatment temperatures of 55-58°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 lentils when subjected to forced hot air and RF energy and to evaluate the quality of RF treated legumes.

MATERIALS AND METHODS

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 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 x 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 x 15 cm x 10 cm) were placed on the convey belt in contact with the bottom plate electrode. The container moved back and forth on the

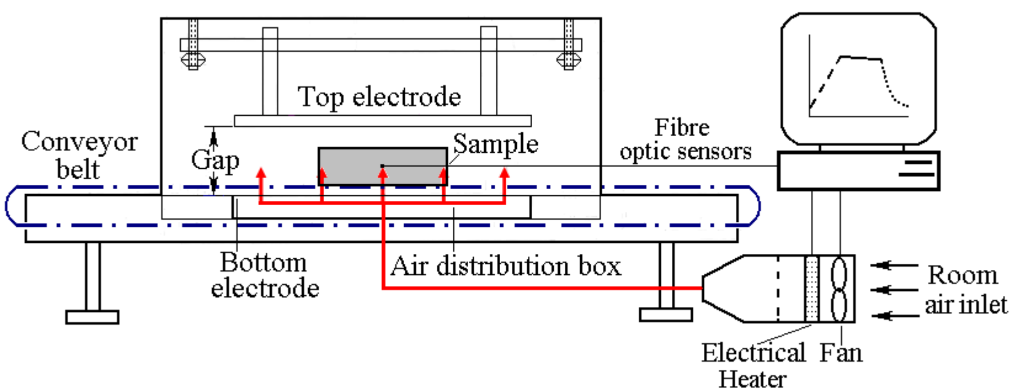

Fig. 1. Schematic view of 6 kW, 27.12 MHz radio frequency (RF) unit showing the two-pair plate electrodes, conveyor belt and the hot air system (Wang et al., 2010)

conveyor belt at 0.56 m min^{-1}. The hot air system provided forced hot air into the RF cavity through an air distribution box under the bottom electrode (Fig. 1).

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 wet basis (w.b.). 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, 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 temperature of the centre of the sample was measured using FISO optic sensors (UMI, FISO Technologies Inc., Saint-Foy, Quebec, Canada) during RF heating. After determining 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.

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 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 three samples after RF and hot air heating.

Heating uniformity tests

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. A single mixing was included in the middle of the given RF treatment time. 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. After that, sample temperatures at 12 positions in the container were also measured using a thin Type-T thermocouple thermometer. 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 from the top. The average and standard deviation 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, λ, is useful to evaluate heating uniformity, which is defined as a ratio of rise in standard deviation of product temperature to rise in mean product temperature over treatment time (Wang et al., 2005).

Treatment procedures

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 lentils, respectively. The untreated samples were considered as controls. Treated samples were sealed in plastic bags for quality evaluations. Each treatment was replicated thrice.

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 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. Colour images of 30 seed surfaces per treatment were captured and stored in the computer using Adobe Photoshop CS. 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.

The average and standard deviation 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 Turkey's method (SAS Institute, 2002, Cary, NC) at a significance level of 0.05.

RESULTS AND DISCUSSION

Heating and cooling profiles

The heating rate in RF treated lentils increased 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.

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. 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. 2 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. 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. But the heating time in lentils was sharply reduced to 7 min by RF heating. Such rapid heating rates suggests that RF energy should provide practical and efficacious disinfestation treatments for legumes, once treatment parameters are identified that will provide the required heating uniformity.

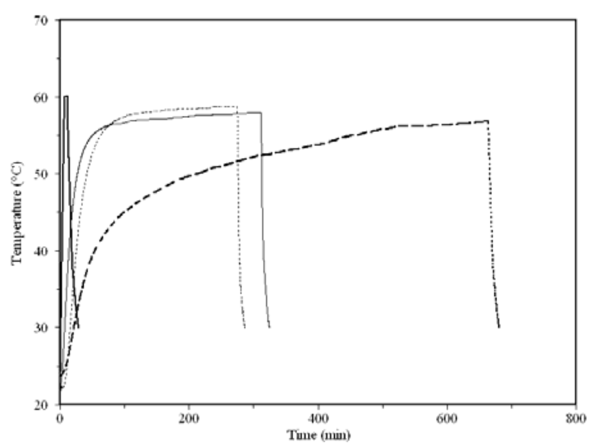

Fig. 2. Typical temperature-time histories of lentil (- - -), green pea (---) and chickpea (−) in the centre of a 10 cm thick container in hot air heating at 60°C as compared with stationary RF heating of lentils (▬) followed by forced room air cooling in 1 cm thick samples

Heating uniformity in RF treated materials

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. 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 standard deviation values (Table 1). The surface uniformity index values (λ=0.079-0.097) for legumes under stationary conditions without hot air heating in this study were comparable with that for soybeans (λ=0.080), but larger than that for lentils (λ=0.054) and smaller than that for walnuts (λ=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 1), resulting in the required temperature distribution for achieving insect control and good product quality. In the current measurement accuracy, the mixing did not significantly improve the heating uniformity of RF treated legumes (Table 1). Therefore, including hot air and movement in the design of an RF treatment protocol would be adequate to obtain the required heating uniformity.

Table 1. Comparisons of the heating uniformity index (mean ± std) 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 & 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

Quality of RF treated 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.

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.

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