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ELIMINATION OF *CRYPTOLESTES FERRUNGINEUS S.* IN WHEAT BY RADIO FREQUENCY DIELECTRIC HEATING AT DIFFERENT MOISTURE CONTENTS

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Abstract—Radio frequency (RF) dielectric heating was tested to control *Cryptolestes ferrungineus S.* in the bulk wheat samples (ca.152 g, dia. = 50 mm, ht. = 100 mm) at the MCs (%, w. b.) of 12, 15, and 18 using a pilot-scale RF heater (1.5 kW, 27.12 MHz) in the batch mode. When the temperature of the hottest spot (geometric center) of the sample, T_H was at 80°C, all the adult insects were found dead at the cold spots, near bottom-wall, at 50.7 to 56.0°C depending up on the wheat MCs. The temperatures of the insect-slurries higher than that of the bulk wheat by 0.8 to 15.1°C indicated the selective heating of the insects. The mortalities of adult insects were almost constant within the quarantine period, QP1 (5 wk). The elapsed time during QP1 had a significant effect only on the insects' mortalities with the wheat at 12% MC. The wheat MC had only marginal significance on the absolute mortalities of insects. The larvae were completely destroyed at temperatures between 55 and 60°C. The complete mortality of all life stages (eggs, larvae, pupae, and adults) of the insect was achieved at T_H = 80°C without any emergence of the insects during QP2 (8 wk). The RF treatment enhanced the germination of the wheat kernels at 12% MC while it was decreased by 2 to 33% depending up on the wheat MC, and the treatment temperature. Temperature had no significant effect on the falling numbers, and the yields of flour, bran, and shorts, and the peak bandwidth and the MC of the wheat, and the flour protein values. The means of the mixing-development-time deferred from the controls mostly for the wheat at 15% MC and T_H = 70°C, and 18% MC and T_H = 70 and 80°C. The mean-peakheight and the color values varied between 4 and 16%, and 3 and 6% off the controls depending up on the temperatures. The uniform temperature of 60°C should be enough

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to control all life stages of the insect completely with a little or no changes in the important product qualities and germination of the wheat at MCs safe for the storage. Future research mainly focused on better estimation of the insect-to-grain electric field intensities is essential.

1. INTRODUCTION

The radio frequency (RF) disinfestation technique to control the insects in stored products does not use any chemicals. It relies on the interactions between electromagnetic (EM) energy and the materials, and is governed by the characteristics of the EM energy, and the electrical, thermal, and the physical properties of the material. The effectiveness of this emerging technique has been tested by researchers with different microwave and RF frequencies, power levels, treatment times, commodities, insects, etc. [1–6]. Although the existing disinfestation methods (heat, cold, and mechanical pressure) are chemical-free, they are very time consuming and tedious. The common practices of using pesticides and fumigants possess a direct threat to human health and environment. The exporting countries also must comply with the importing countries maximum residue limits on chemical/pesticides. Therefore, a smart approach is to use a chemical/pesticide-free, rapid, and efficient technique. The RF dielectric heating could be a viable technique. The electrical properties of a material important to this technique, the dielectric constant (ε') and the dielectric loss factor (ε''), and the loss mechanisms that generate heat in the material during RF treatments can be found in [7]. As the temperature of a material changes, there will be a change in the ε'', and which in turn, affects how the material's temperature changes, and so on. Therefore, the RF dielectric heating is a complex phenomenon that couples both the electromagnetics, and the heat and mass transfer. In contrast to the conventional heating, the RF heating involves bulk heating, and as a big advantage, the insects could be heated as soon as the RF radiation starts. This single technique may also be equally effective for multiple insect controls.

Rusty grain beetle of size ca. $1.5 \times 0.5 \times 0.3$ mm is found worldwide. Both adults and larvae attack the kernels, and they feed on the germ and endosperm of the grain. Heavy infestation of this insect also leads to other damage by causing the grain to heat (developed from the insects' metabolism) and spoil, and by spreading fungal spores (due to the temperature differential causing convection currents leading to migration of moisture and fungal spores) in the stored grain [8]. Infestation of wheat grain by rusty grain beetle is therefore an important problem.

Nelson [9] reported a complete mortality of the adult rice weevils (*Sitophilus oryzae L.*) in stored hard red winter wheat (*Triticum aestivum L.)* at 40°C and 39 MHz. The ε'' of the insect was reported to be about five times greater than that of the wheat over the frequency range from 50 kHz to 12 GHz at 24°C. No temperature dependence of the insects' ε was reported. Guo et al. [10] reported that the ε'' of the chestnut weevil was much higher than that of the chestnut over the temperature range from 20 to 60°C, and that differential heating of the weevil might be more practical between 10 and 100 MHz based up on the ε'' of the insect-slurries. The ε'' of the insect-slurries might be quite different from that of the live insects due to the insects' cuticles, size, and shapes. For example, the ε'' at 100 MHz increased by about 30% comparing to the live ones when the measurements were done on slurry of the fifth instar whole codling moth larvae infesting apples [11]. It showed a higher RF sensitivity to the exposed ionic contents of material, and the importance of considering the whole insects for RF disinfestation. Rashkovan et al. [12] reported ε of the granary weevil and wheat at frequencies between 20 and 150 MHz at 25°C. The ε'' of the insect, in average, was 8.5 times higher than that of the wheat. The work was primarily focused on the estimation of the absolute electric field inside an isolated particle in terms of the external electric field. Temperature dependence of the ε of the insects and the wheat were not considered. Hamid et al. [13] reported a total mortality of three common types of wheat insects, *Tribolium confusum, Sitophilus granarius* and *Cryptolestes ferrungineus.* Although *Cryptolestes ferrungineus*, the insect pests investigated in this research, was considered, the applied technique used microwave frequency at 2.45 GHz, and no measurements on the ε of the test insects were conducted. Some interesting findings have been reported towards the RF and microwave treatments of fruits, and nuts [14]. Dielectric behaviour of the fruit flies, medfly (egg and larvae), melon fly, Mexican and oriental flies was investigated at frequencies between 1 MHz and 1.8 GHz, and the temperatures between 20 and 60°C. They concluded that the ionic conduction dominated the dielectric behavior in the RF range, and due to the same magnitude of the ε'' of the subtropical and tropical fruits and the insects, the differential heating of insects in these fruits is not possible when they are treated together in an RF system. Wang et al. [15] measured ε of the fifth-instar codling moth larvae, Indian-meal moth, Mexican fruit fly, and Navel orange worm along with almond and walnut for RF and MW treatments at frequencies from 27 MHz to 1.8 GHz, and at temperatures from 20 to 60°C using an open-ended coaxial probe. One interesting finding was that the

ε'' for the nuts, unlike other test materials, reduced as temperature increased at 27 MHz. This may help to keep the host commodity at relatively low temperature in the selective heating of the insects whose loss factor increased with increasing temperature. The slurries of the insects were used for the dielectric measurements.

In general, RF is preferred to MW in controlling insects in stored products [16, 17], and has been used at industrial scale for disinfestations of walnuts [18]. There is a need to investigate selective heating of one of the most troublesome insect pests, the *Cryptolestes ferrungineus S.*, in the stored Canadian western red spring (CWRS) wheat, cv. Lillian, at MCs safe for the storage of the wheat.

The objectives of this research are to 1) assess the temperature uniformity in the bulk samples of the wheat-insect mixture during RF heating 2) determine the immediate and the delayed mortalities of the insects at all life stages in the stored wheat, and 3) assess the physicochemical qualities and germination of the RF treated wheat.

2. MATERIALS AND METHODS

2.1. Insect Cultures and Handling

The adult rusty grain beetle (*Cryptolestes ferrungineus, S.*) collected from Agriculture and Agri-Food Canada/University of Manitoba, Canada were reared in a mixture of whole kernels of wheat (15% MC), wheat cracks, and wheat germs in a proportion of 90-5-5 (%) by weight respectively. A total of 200 insects were transferred to a 2L glass jar containing 2 kg of the rearing material. The jar was closed using a lid with a #1 filter paper at its center for the better ventilation. A total of three cultures were prepared, and placed them in a growth chamber maintained at 30°C, and 70% RH. After 10 wk, these cultures were used for the experiment as well as to prepare new cultures.

The rearing material with the insects was sieved through the Canadian standard sieve #40 onto the bottom tray, which was opened in a fume-hood to let the insects' feces and other airborne dust particles to escape out. Then the fine rearing material with the insects was transformed from the tray onto the center of a big white tray, and the insects were collected in a glass vial. The vial, a part of a vacuum aspirator, was closed with a #5 rubber stopper with two holes, one connected to vacuum source with flexible tubing, and the other to a suction pipe to suck the insects into the vial. The former was covered with a fine wire screen on the inside to keep all the insects in the vial. The insects were anesthetized with carbon dioxide gas for 30 s, and were kept in a freezer at −18°C for 2 h before use because anesthetization alone did not keep the insects inactive long enough for the permittivity, and MC measurements. The larvae were collected with a very fine bristle brush under the microscope (Wild Heerbrugg M3Z, Switzerland).

2.2. Wheat Samples

Top quality CWRS wheat, cv. Lillian at moisture content of 14.45% w. b. was procured from FlobergFarms, Shaunavon, SK, Canada, and stored in a cold room at 4°C. The wheat samples at 12% were prepared by drying a known mass of the wheat at initial MC to the pre-calculated weight in a hot-air oven (Despatch, Despatch Industries, MN, USA) set at 40°C, and those at MCs of 15, and 18% were prepared in batch by spraying 6.1 g and 36.1 g of distilled water onto 1 kg of the wheat at initial MC respectively. The samples were contained in the air-tight glass jars, and left at room temperature (24°C) for five days with periodic shaking and tumbling to achieve an equilibrium MC followed by transferring them in the cold room (4°C) until used. The samples were not stored for more than five days to prevent them from unwanted physicochemical changes. The digital scale (Symmetry, PR4200, Cole-Parmer Instrument Co., IL) with an accuracy of ±0.01 g was used for weighing.

2.3. Insect and Wheat MC Measurement

To determine the MC of the insects, aluminum moisture dishes were pre-heated in the oven for an hour at 105°C, and cooled them in a desiccator before weighing. About 1 g of the insects was placed in each of the dishes, and heated for 16 h at 105°C. The moisture dish lids were put in place before the dishes with the dried insects were taken out from the oven. The heated dishes were cooled in the desiccator before reweighing. The averages of duplicates were reported.

The MC of the wheat was determined following ASABE Standards (ASABE R2008). The procedure was similar to that adopted for the insects except the averages of triplicate each weighing about 10 g of the wheat were dried for 19 h at 130°C. In both cases, the samples were weighed with an Ohaus analytical scale with an accuracy of ±0.0001 g, and the standard hot-air oven was used for drying.

2.4. RF Dielectric Heating System

The RF dielectric heating system with the pilot-scale RF heater of 1.5 kW (StrayfieldFastran, Berkshire, England) is shown in Figure 1. As shown in Figure 1(c), a bulk sample of the infested wheat (ca. = 152 g) was contained in a sample holder (dia. = 50 mm,

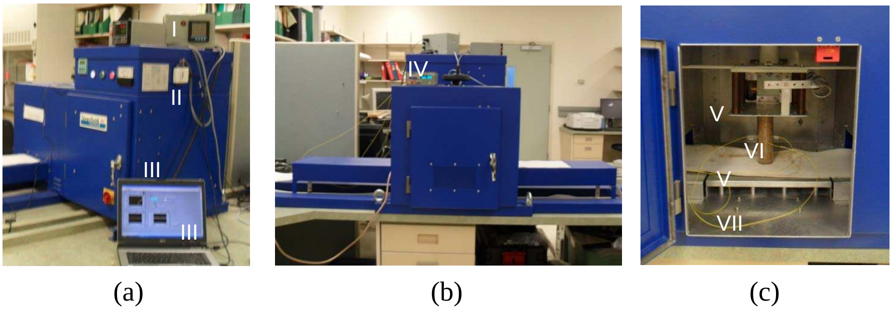

Figure 1. (a) The back, (b) front, and (c) the inside views of the RF heater; I: power meter, II: I/O device, III: data acquisition software, IV: optical thermometer device, V: electrodes, VI: wheat-insect sample, VII: fibre optic temperature sensors.

ht. = 100 mm) made of RF transparent polycarbonate. The holder was placed in-between the electrodes, the applicator housed in a metallic enclosure. The sample temperatures (T) at the specific locations were sensed using the fibre optic temperature sensors, and an optical thermometer device with an accuracy of ±0.8°C (Fiber Optic Temperature Sensor, Neoptix, Canada). The multifunction power meter (Acuvim-I Accuenergy Corp., LA) connecting the mains to the heater also transmitted the instantaneous current (A), voltage (V) and power (kW) being used by the heater to the data acquisition software through the I/O device (NI USB 6008, TX). The data acquisition program (oven.vi) developed in LabView 2010 v. 10 platform continuously acquired the T, A, V, and kW, and displayed and recorded at a predefined interval of time in the text file.

2.5. Selective Heating

A better RF selective heating yields the higher insects' mortality without heating the grain to the higher temperatures minimizing the thermal degradation of the grain qualities. For the assessment of the effectiveness of the RF selective heating the ε, the physical and the thermal properties along with the temperature dependence for the insects and the host grains are essential. The ratio of the electric field intensity within the insect to that in the host grain kernels must also be known. The measurement and the theoretical estimation for all of these quantities along with the theoretical derivations of the ratio of the power dissipation in the insects to the wheat, and the ratio of the rate of increase of the temperature of the insects' bodies to that of the wheat can be found in [7].

For an effective selecting heating of the insects, the temperature of the insects must increase rapidly to its lethal temperature comparing to the temperature of the surrounding host grain. Since it was extremely difficult to measure the internal temperatures of the live insects during the RF heating, it was estimated by measuring the temperatures of the insect-slurries in the polycarbonate cylindrical tubes (approx. dia. = 2 mm, l = 2 mm) at the desired spots within the bulk wheat samples. Although, this approach might unmask partly the effectiveness of the selective heating of the insects, the actual lethal temperature that destroyed the insects might still be higher than that of the slurries because of the insect-cuticles, which would minimize the heat losses from the intact insects' bodies to the surroundings during the RF heating.

2.6. The Bulk Sample Temperature Distribution and the Reference Temperature

As shown in Figure 2, the temperatures of the bulk wheat were measured at nine locations during the RF heating. The sensor tips were at 1 mm (W), 12.5 mm (M), and 25 mm (C) from the wall of the sample holder at the heights of 10 mm, 50 mm, and 90 mm from its base. The averages of the duplicate temperatures were reported. The

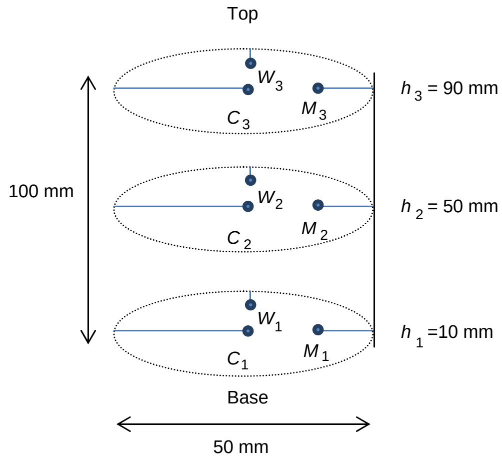

Figure 2. Locations of the fibre optic temperature sensors: 1 mm (W), 12.5 mm (M), and 25 mm (C) away from the inner wall of the sample holder at the heights of h_1 = 10 mm, h_2 = 50 mm, and h_3 = 90 mm from its base.

temperatures measured at the geometric center (mid-height-center) of the sample cylinder (C_2), T_H were used as the reference temperatures for the samples.

2.7. Determination of Mortality

The mortality for the test insect infesting the wheat at each MC of interest was determined for the adult insects and larvae separately, and for all life stages (eggs, larvae, pupae, and adults) combined. To determine the adult insect mortalities, a total of 30 adult insects were transferred into the bulk sample of the wheat. Two minutes of time was allowed for the insects to diffuse themselves with the sample before RF irradiation of the sample. The samples were heated from 30 to 80°C in a step of 10°C because the lethal temperatures for the complete mortalities of many insects at all stages were within this temperature range [19, 20]. The absolute and relative mortalities were determined by counting the live insects immediately, (immediate mortality), and 1 day, and every week after the RF irradiation (delayed mortalities) for up to the quarantine period of 5 weeks (QP1). The relative mortalities were calculated using Abbott's formula, mortality (%) = (1-percent living in treated sample/ percent living in control) ×100 [21]. Non-uniform heating and the insect migrations to the cold spots within the bulk sample of wheat were expected during the RF heating. The later becomes more evident in the slower RF heating system. As a consequence, the cold spots would need to be heated to the insects' lethal temperature while unnecessarily heating the wheat at the hot spots to very high temperatures potentially degrading their physicochemical qualities. The averages of the triplicate mortalities were reported.

Due to the insect migration, it was learned from the experiments on the adult insects that the wheat was needed to be heated to $T_H = 80°C$ at its geometric center to achieve the temperatures, which were lower than T_H, lethal to the insects at the cold spots. Therefore, a total of 30 larvae along with a few wheat kernels was transferred into a tiny polyethylene capsule (dia. = 3 cm, ht. = 3 cm). The capsule was placed in the bulk wheat aligning its geometric center to that of the sample holder in determining the mortality of the larvae faster without overheating the sample. The temperature measured inside the capsule at the 100% immediate mortality was reported as the lethal temperature for the larvae. The sample was stored in the growth chamber for the quarantine period of QP1 to determine the absolute delayed mortalities. The averages of five repeated measurement were reported.

To determine the complete mortalities of the eggs and the pupae, a ten-week old culture with approximately 2000 adult insects (counted) and numerous eggs, larvae, and pupae (uncounted but confirmed under microscope) was divided into 10 sub-samples after thoroughly but gently mixing it. The sub-samples were subjected to the RF irradiation, and heated to the temperature that would produce 100% mortalities for the adult and the larvae followed by storing them in the growth chamber, and examining after the quarantine period of QP2 (8 wk). The quarantine period was extended from QP1 (5 wk) to QP2 (8 wk) to account for the effect of RF exposure, if any, on the development phases of various life stages of the insects towards the adult stage. The normal rearing starting with the adult insects, new adult insects emerged in QP1 (5 wk). The experiment was repeated for the wheat at entire MCs. This approach provided a better way for the assessment of the eggs and pupae mortalities because it allowed a large number of insects at various life stages to be included in the samples, saved a considerable amount of time in manually collecting the microscopic eggs, larvae, and especially the pupae, and provided with a large number of the repeated measurements for the better representation of the population giving a higher confidence in the results.

2.8. Assessment of Germination and Quality Analyses

The bulk wheat samples at 12, 15, and 18% MCs were each heated to the temperature at which the 100% mortality for all life stages of the insects was achieved. The samples were thoroughly mixed before using them for the germination and quality tests. This step was crucial for the non-uniform heating of the samples. For the germination test, a total of 30 wheat kernels were plated on a Whatman #3 filter paper moistened with 6 mL of distilled water in a 90 mm-diameter petri dish, and placed in a Ziploc® bag to keep the kernels moist, and kept in the temperature-humidity chamber at 25°C for 7 days. The averages of the triplicate were reported.

The quality tests included Hagberg falling number (FN) to determine α-amylase activity in sprout-damaged grain. The flour, bran, and shorts yields and flour protein were also included. The mixing-development-time (MDT), the time in minutes it took the dough to develop to peak consistency, which was the peak of the curve. At this point the S-S bonds in the dough mass start to breakdown and the energy required to mix it drops. As a rule the longer it takes the dough to mix to MDT the stronger the dough is but strength does not necessarily equate to the quality of the dough proteins or glutens. The maximum height of the curve expressed in percent energy was the mean-peak-height (PKH). The actual energy measured was torque with units expressed in Newton Metres (N.m). The mixograph parameter which best indicates the quality of the wheat dough or flour is PKH. Higher or larger value PKH's correlate to a higher glutenin/gliadin ratio which usually results in better (higher loaf volume) bread making potential. The peak-bandwidth (PBW) indicated the total energy in % N.m within the curve envelope or span calculated from start (0 minutes) to the end (6 minutes). PBW can also predict dough quality with higher values equating to larger bread loaf volumes. Wheat colors were measured by filling a thin-glass Petridis with 10 mm thickness of the wheat kernels, and placing it on the colorimeter (HunterLab LabScan II, Hunter Associates Inc., VA, USA) illumination window. The averages of the duplicates were reported.

The germination and the qualities were also tested on the wheat samples treated to the temperatures lower than that produced the complete mortalities. This approach allowed the assessment of the germination and the qualities of the wheat at the lower temperatures, which would be the case for the uniform RF heating systems.

2.9. Statistical Analysis

The ANOVA (Statistical Toolbox, Matlab 7, R2011a) was used to determine the statistical significances of the temperatures and the MC of the bulk wheat on the immediate and delayed mortalities, and the physicochemical qualities of the wheat at 5% confidence level ($p < 0.05$).

3. RESULTS AND DISCUSSION

3.1. Temperature Distribution within the Bulk Wheat Samples

Figure 3 shows the temperature distribution within the bulk samples of the wheat at the MCs of interest along with the RF exposure times, t (min). As the heating proceeded the temperatures of the samples decreased from the center towards the wall of the sample holder. It was attributed to the heat losses from the outer surfaces of the sample holder. The MC of the samples and the RF exposure time were inversely related at any given location and temperature, which might be due to the enhanced ionic conductivity in the wheat kernels with increasing MC resulting in the larger values of the ε'' responsible for the higher RF power dissipation in the materials. Non-uniform heating of the samples was observed. Figure 4 shows the temperature differences (ΔT) between the hot and the cold spots for the bulk wheat samples at

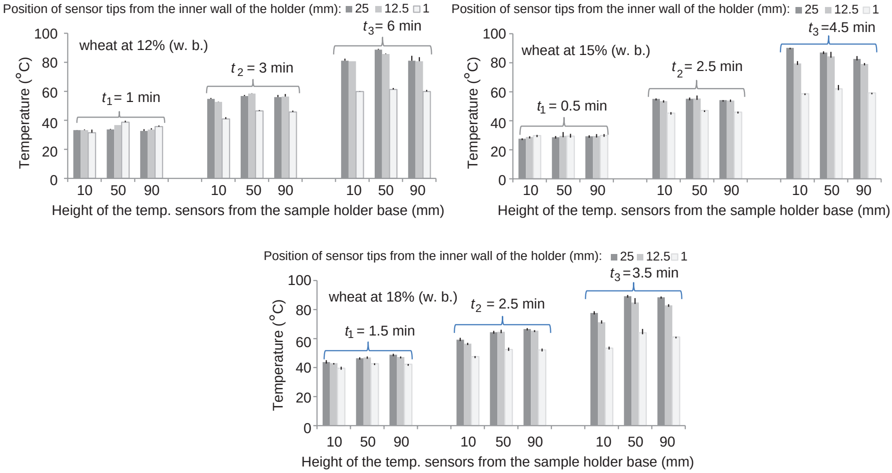

Figure 3. The temperature distribution with the standard errors (no-cap error-bars) of the bulk samples of the wheat at three MCs sensed by the optical temperature sensors placed at various locations along with the RF exposure time, t_1, t_2, and t_3 in seconds to attain the shown temperatures.

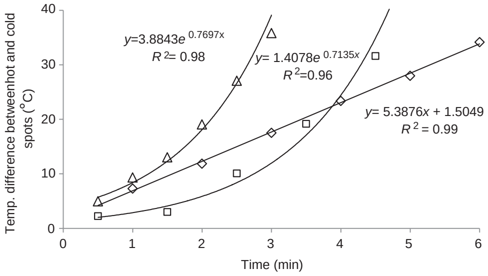

Figure 4. The temperature difference between the hottest and coldest spots in the bulk samples of the wheat at the MCs (%, w. b.) of 12 (◇), 15 (□), and 18 (Δ) as a function of the RF exposure time.

the entire MCs as a function of the RF exposure time. The ΔT for the samples at 12% MC increased linearly while it increased exponentially for the samples at the remaining MCs. The later was attributed to the stronger positive effect of the sample temperature on its ε'', which in turn, enhances the heating of the sample increasing its temperature, and so on. Most of the cold and hot spots were respectively at W_1, and at C or M for the entire sample heights. As shown in Table 1 when the bulk samples of the wheat were heated to 80°C, the differences between the temperatures at the hot and cold spots were 29.3, 26.9, and 28.9°C

Table 1. A typical temperature distribution within the bulk wheat samples −1 mm (W), 12.5 mm (M), and 25 mm (C) away from the inner wall of the sample holder at the heights of $h_1 = 10$ mm, $h_5 = 50$ mm, and $h_9 = 90$ mm from its base.

Height	RF exposure (min)	Sensor location			ΔT^a	$T^b_{\text{avg/mc}}$
		C	M	W		
$MC = 12\%$						
h_3	5.2	74.9	74.5	56.1		
h_2	5.2	80.0	79.0	57.1	29.3	68.4
h_1	5.2	74.3	69.0	50.7		
$MC = 15\%$						
h_3	4.1	76.5	74.0	56.5		
h_2	4.1	80.0	78.5	58.7	26.9	70.8
h_1	4.1	82.9	74.3	56.0		
$MC = 18\%$						
h_3	3.1	80.0	76.5	56.8		
h_2	3.1	80.0	77.6	60.1	28.9	68.8
h_1	3.1	70.9	65.9	51.1		

a: max. temperature difference within the bulk wheat sample at the specified MC.
b: average temperature of the bulk wheat sample at the specified MC.

for the wheat samples at the MCs of 12, 15, and 18% respectively. The corresponding average temperatures were 68.4, 70.8, and 68.8°C with the overall average temperature difference of 28.4°C. A temperature difference of ≈ 70°C was reported within the sample while disinfesting 50 g of barley from *Tribolium castaneum* using microwave [3].

3.2. Mortality

Figure 5 shows the absolute mortalities of the adult rusty grain beetles (MC = 49.6 ± 2.0% w. b.) infesting the wheat at 12, 15, and 18% MCs as a function of the sample temperature. A complete mortality of the insect was achieved at 80°C for the wheat at all MCs of interest. All of the insects were found dead at the vicinity of the cold spots with temperatures of 50.7, 56.0, and 51.1°C at 12, 15, and 18% wheat MCs, respectively. It suggested that there was a sufficient time for all the insects to migrate towards the cold spots as the sample was heated, and that the 100% mortality would be possible at the temperatures of the cold spots in case of uniform heating resulting in the shorter RF exposure times as well.

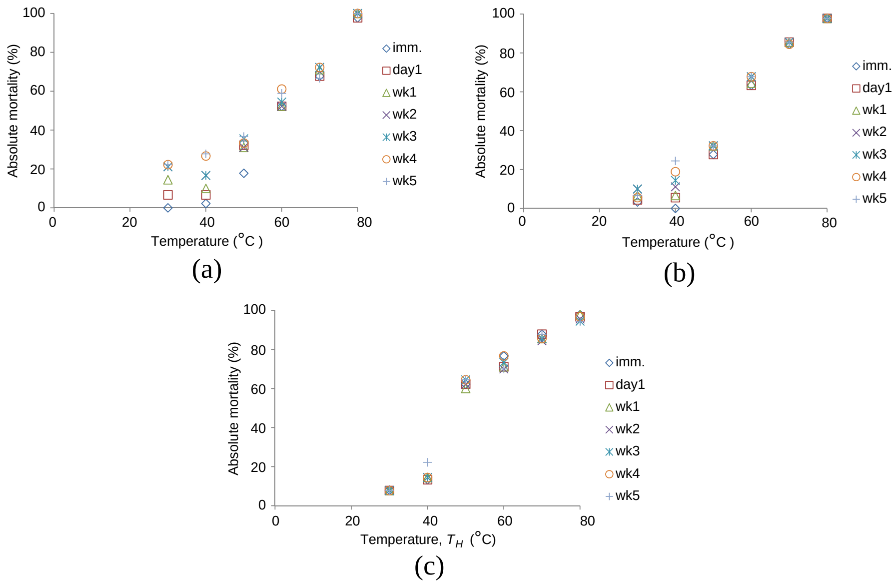

Figure 5. The absolute mortalities of the adult rusty grain beetles infesting the bulk wheat at MCs (%, w. b.) of (a) 12, (b) 15, and (c) 18 as a function of temperature, T_H, the highest local temperature of the bulk wheat-insect mixture immediately (imm.), 1 d, and up to 5 weeks after RF treatments.

When the wheat samples were at 80°C with the insect slurries at the cold spots, the temperatures of the slurries were 65.8, 61.8, and 50.3°C for the wheat samples at 12, 15, and 18% MCs respectively. Comparison of the temperatures of the bulk wheat samples at the cold spots to that of the slurries confirmed that the selective heating of the insect slurries was in effect, and the temperatures of the slurries wer higher than that of the wheat by 15.1, 5.8, and 0.8°C for the wheat samples at 12, 15, and 18% MCs respectively. The effect of the selective heating decreased with the increasing MC of the wheat, which was in agreement with the ratio of the rate of increase of the temperature of the insect to that of the wheat (or, insect-to-wheat power absorption ratio) [7]. However, the differences between the temperatures of the bulk wheat and the insect-slurries were far less than that would be predicted with the theoretical analysis. The observed lower temperatures of the insect-slurries were attributed to the assumptions made in the estimation of the electric field intensity within the wheat-insect mixture and heat conduction from tiny insects to surrounding wheat.

Figure 6 shows the relative (immediate and delayed) mortalities.

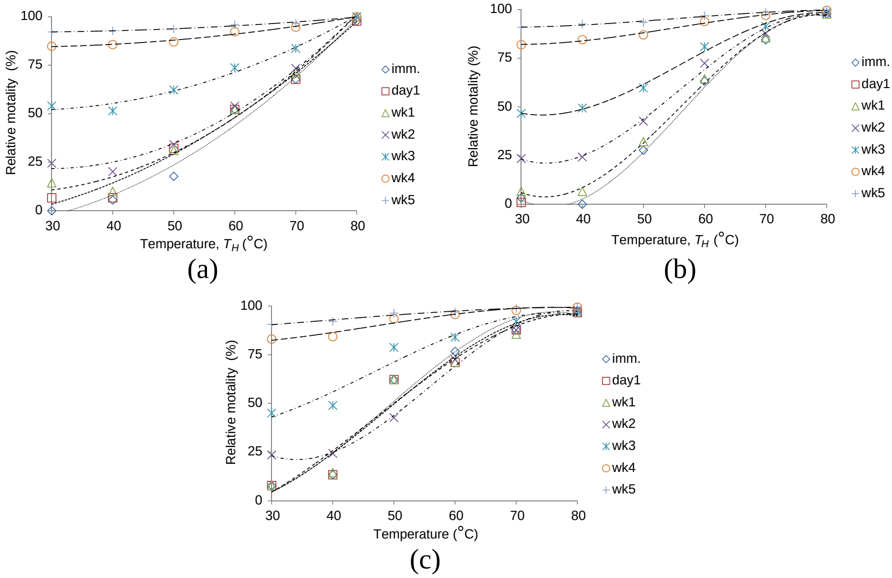

Figure 6. The relative mortalities of the adult rusty grain beetles infesting the wheat at MCs (%, w. b.) of (a) 12, (b) 15, and (c) 18 as a function of temperature, T_H, the highest local temperature of the bulk wheat-insect mixture.

All of the delayed mortalities, in general, were higher than the immediate mortalities over the entire temperature and moisture ranges. These increments were originated from the emergence of new insects in the controls as time passed by during QP1. It was not because of the decrease in the count of the live insects in the treated samples, which was almost unchanged over the entire QP1. Technically, only the denominator in the Abbott's formula increased increasing the relative mortalities.

The elapsed time during QP1 had a significant effect on the absolute delayed mortality of the insects in wheat at 12% MC ($p = 0.018$), but it had statistically insignificant effect in wheat at the MCs of 15% ($p = 0.146$) and 18% ($p = 0.462$). The MC of the wheat had a significant effect on the absolute immediate ($p \approx 0$), and the absolute delayed mortalities for 1 d ($p \approx 0.001$), and 5 wk ($p = 0.025$). The MC was statistically insignificant for the absolute delayed mortalities for 2, 3 and 4 wk ($p = 0.055$ to 0.081).

It was found that 100% immediate mortality of the larvae was achieved between 55 and 60°C. The variation in the lethal temperature was attributed to the development stages of the test larvae because the lethal temperatures required for the complete mortality of insects also depend upon their development phases [22]. The test larvae were more heat resistant than their adults. However, the susceptibilities of larval and adult stages of insects vary with the species [23]. There was no emergence of new insects during QP2 confirming the 100% absolute delayed mortalities of the larvae.

When the wheat samples infested with all stages of the insects were heated to 80°C, no live insects were found during QP2 assuring the 100% absolute mortalities of the all stages of the insects. Despite the cold spots with temperatures (50.7 to 56°C) less than that required for the complete mortality (55 to 60°C), all of the larvae were still destroyed completely. The larvae might not have time enough to migrate through the wheat kernels to the cold spots before exposing themselves to the lethal temperatures during the RF heating.

The problem of the insect migration during RF heating could be minimized by using a high power RF heating system. It would also reduce the total disinfestation process time so that the heat conduction between the surrounding wheat and the tine insects would be reduced, which in turn, would also enhance the selective heating of the insects.

3.3. Germination

Figure 7 shows the effects of the RF treatment on germination of the test wheat kernels. The germination of the treated wheat kernels at 12% MC was better than the controls for entire temperatures. It was attributed to the decreasing percentage of the hard-seeds due to RF treatment. Similar to the results reported by Nelson [24] on alfalfa (lucerne) seeds the treatments were more effective at lower wheat moisture content, and the optimum germination response was observed at a certain RF treatment temperature (70°C). For the wheat kernels

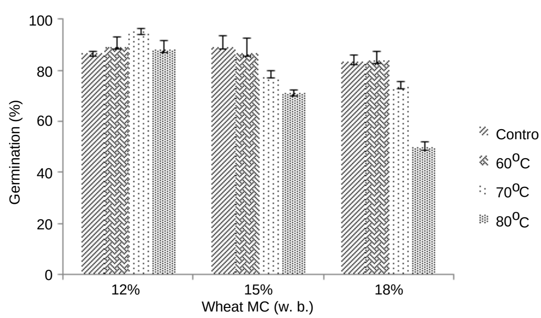

Figure 7. Comparison of the germination between the RF treated wheat kernels at the indicated temperatures and the controls (error bar = 1 Stdev).

at 18% MC the germination was slightly better when they were treated to 60°C, but was lowered for the kernels treated to 70 and 80°C by 9 and 33% respectively. At 60°C, the seed-coats of a small number of hard seeds originally presented in the sample might have been turned into water permeable seed-coats favorable for germination resulting in a slightly better germination rate. But when the temperature was continuously increased beyond this point, some physicochemical changes might have been taken place resulting in the decrease of the wheat kernels' abilities to germinate. Similar phenomenon was observed by Nelson and Walker [25]. For the wheat kernels at 15% MC, the effect was somewhat in-between those observed for the wheat kernels at 12 and 18% MCs. The germination reduced by 2, 11, and 18% comparing to the controls when the wheat kernels were treated to 60, 70 and 80°C respectively. The effect of the MC on germination was statistically insignificant for the wheat kernels treated to 60°C ($p = 0.43$, $F = 0.96$, $df = 2$), but the opposite was true for the kernels treated to 70°C ($p \approx 0$, $F = 124$, $df = 2$), and 80°C ($p \approx 0$, $F = 153$, $df = 2$).

Table 2. Comparison between the physicochemical qualities of the RF treated wheat and the controls at three levels of MCs and temperatures, and the statistical significance of the RF treatment temperature, T_H the highest local temperature of the bulk wheat-insect mixture, on the qualities of the RF treated wheat and the controls at 95% confidence level.

Temp. (°C)	Falling Number	Yield (%)			Flour protein (%)	MDT (min)	PKH (N.m)	PBW (% N. m.)	Color			MC (%,w. b.)
		Flour	Bran	Shorts					ΔE	C	H	
MC = 12.0%												
control	541.5	71.8	18.6	8.7	12.7	2.00	48.4	26.5	45.15	14.95	60.25	
60	532.5	72.1	18.7	9.2	12.5	1.85	51.1	28.8	45.04	14.86	60.13	12.5
70	522.0	71.3	18.1	9.8	12.3	1.85	53.0	30.0	45.98	15.61	61.16	11.9
80	514.5	71.5	19.0	9.6	12.4	1.65	51.3	30.6	46.42	15.83	61.72	12.0
MC = 15.0%												
control	516.0	73.9	17.0	10.1	12.5	1.90	50.1	27.9	45.40	15.18	60.51	
60	491.5	72.6	17.9	9.6	12.2	2.00	48.2	24.5	46.81	15.37	62.61	15.2
70	496.0	72.4	17.9	9.8	12.3	2.10	50.4	26.3	46.74	15.49	62.37	15.7
80	475.0	72.5	17.8	9.8	12.4	2.45	46.1	26.3	47.45	15.82	63.27	15.2
MC = 18.0%												
control	525.0	71.4	18.0	10.2	12.2	1.90	49.0	30.4	47.39	15.18	63.48	
60	397.0	72.8	17.3	9.9	12.4	2.00	49.6	29.4	47.73	15.44	63.87	16.9
70	512.5	72.7	18.2	9.2	12.2	2.55	45.1	24.4	49.11	15.92	65.70	16.5
80	476.5	73.2	18.2	8.7	12.3	4.35	41.0	23.3	48.52	16.06	64.76	16.2
p-value	0.31	0.81	0.19	0.36	0.20*E*-2	1.6*E*-3	8.1*E*-3	0.65	8.4*E*-06	2.6*E*-02	3.9*E*-04	1.3*E*-08

3.4. Quality Assessment

Table 2 shows the values for the physicochemical qualities of the wheat samples at 12, 15, and 18% MCs each treated to 60, 70, and 80°C along with the controls. The RF treatment temperature had no significant effect on falling numbers, and yields of flour, bran, and shorts, and PBW of the wheat at entire MCs. The flour protein, MDT, PKH, color and MC of the wheat were affected by the RF treatment temperatures. However, comparison of the means showed that the flour protein values were still within the measurement accuracy. The means of MDT deferred from the controls mostly for the wheat at 15% MC treated to 70°C, and 18% MC treated 70 and 80°C. The mean PKH values, and the mean ΔE, C, and H values of the treated wheat samples were not more than 4, 9, and 16%, and 5.9, 4.6, and 5.7% off the controls at 60, 70 and 80°C respectively regardless of MCs. The effects of the temperature on the PKH values reduced with the MCs of the wheat. The MCs of the treated wheat samples and the controls varied from 0.15 to 2.3%.

4. CONCLUSION

Non-uniform heating of the bulk wheat (dia. 50 mm, ht. = 100 mm) was observed with the hot spot ($T_H = 80$°C) being at the geometric centre and the cold spot (52.6°C) at the bottom of the sample holder nearby the wall.

A complete mortality of the adult rusty grain beetle was achieved at $T_H = 80$°C. Therefore a complete mortality would be possible at lower uniform temperatures, and shorter RF exposure times for the rapid RF disinfestations. A high power RF heating system with a specialized applicator, in which the wheat would be "stirred" continuously as it would be transported, for example using a helix, might be a potential solution in attaining the uniform heating, and also preventing the insects migrating from the hot to the cold spots during the RF irradiation. The effect of the selective heating decreased with increasing MC of the wheat, which was in agreement with, but the magnitudes of the effect were far less than, the theoretical predictions. It demanded future research mainly focused on the accurate estimation of the insect-to-grain electric field intensities and effect of heat conduction from tiny insects to surrounding wheat. There was almost no change in the mortalities of the adult insects in the treated samples within the quarantine period (5 weeks). The MC of the wheat had only marginal significance on the absolute mortalities of the insects. The larvae were more heat resistant than the adults, and were completely destroyed at temperatures between 55 and 60°C.

For the wheat infested heavily with all of the life stages (eggs, larvae, pupae, and adults) of the insect the complete mortality was achieved at $T_H = 80°C$. This approach had some benefits such as 1) the sample preparation was extremely easy, 2) a large number of samples could be prepared for higher confidence in the results, 3) mortalities of all life stages (eggs, larvae, pupae, and adults) of the insects could be determined at once, and 4) the time saved in the sample preparation could be used in extending the quarantine period, and 5) the samples resembled the real life samples to be treated in the practical RF disinfestation systems.

At a uniform temperature of 60°C at which all life stages of the test insect could be destroyed, there would not be more than 2% decrease in germination for the stored wheat after RF disinfestation. No functional property of the wheat would be significantly affected.

In brief, a key to develop a practically viable RF disinfestation technique is to design a RF dielectric heating system that would heat bulk wheat uniformly at 60°C. At this temperature, the RF treatment would minimize the generation of hot and cold spots, thereby preventing the bad effects on the wheat at the same time maximizing the detrimental effects on insects. A potential design may consist of a high power RF heater with 50 Ω technology, and a custom built applicator. Unlike most commonly used conventional RF heaters with class C (or self-oscillator) technology, in which, the applicator can not be separated from the RF generator, the applicators in the 50 Ω technology can be built with different shapes and sizes as a separate unit to use with auger, bin-to-bin, and bin-to-chute transportation systems. At the same time, the applicator can be equipped with some accessories inside it such as RF transparent helix to move around the wheat kernels as it passes by under RF radiation.

5. NOMENCLATURE

Symbol	Description	Symbol	Description
dia.	diameter (mm)	ISM	Industrial Scientific and Medical
ht.	height (mm)		
l	length (mm)	T	temperature (°C)
MC	moisture content	A	Ampere
% w. b.	percent wet basis	V	Volt
T_H	temperature at the sample geometric center	kW	kilowatt

QP1	quarantine period of 5 wk	M_n	distance of sensor tip from sample holder wall (12.5 mm), $n = 1, 2, 3$
QP2	quarantine period of 8 wk	C_n	distance of sensor tip from sample holder wall (25 mm), $n = 1, 2, 3$
EM	electromagnetic	C_2	sample geometric center
ε'	dielectric constant	MDT	mixing-development-time (min)
ε''	dielectric loss factor	PKH	mean-peak-height (N·m)
ε	complex dielectric properties	PBW	peak-bandwidth (%, N·m)
ε_0	dielectric constant of vacuum (8.85×10^{-12} F·m^{-1})	ΔT	temperature differences between the hot and the cold spots (°C)
ε''_σ	ionic conduction loss	df	degree of freedom
ε''_d	dipole rotation loss	F	F-statistic value
f	frequency (Hz)		
RF	radio frequency	ΔE	total color difference
MW	microwave		
W_n	distance of sensor tip from sample holder wall (1 mm), $n = 1, 2, 3$	C	chroma
		H	hue

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