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Dielectric heating as a potential post-harvest treatment of disinfesting mangoes, Part II: Development of RF-based protocols and quality evaluation of treated fruits

M.E. Sosa-Morales[a,b,*], *G. Tiwari*[c], *S. Wang*[c], *J. Tang*[c], *H.S. Garcia*[a], *A. Lopez-Malo*[b]

[a]*Unidad de Investigación y Desarrollo de Alimentos, Instituto Tecnológico de Veracruz, M.A. de Quevedo 2779, Col. Formando Hogar, Veracruz, Ver. 91897, Mexico*

[b]*Departamento de Ingeniería Química y de Alimentos, Universidad de las Américas, Puebla, Ex-Hda. Santa Catarina Mártir, Cholula, Pue. 72820, Mexico*

[c]*Department of Biological Systems Engineering, Washington State University, 213 Smith Hall, Pullman, WA 99164-6120, USA*

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With knowledge of frequency and storage dependent dielectric properties of mangoes, we studied a possible treatment that used radio frequency (RF) heating to reduce thermal treatment times in post-harvest pest control of immature mangoes. In this study, surface heating by hot water (HW) was combined with RF core heating of fruit against Mexican fruit fly (*Anastrepha ludens*) in mangoes (*Mangifera indica cv*. Tommy Atkins). Mangoes were first heated in water at 45 °C for 50 min followed by RF heating in a 27.12 MHz, 12 kW RF system for 1 min to reach 48 °C over the whole volume of the fruit. Fruit was then held in water at 48 °C for 4, 6 or 8 min, which corresponded to one level at, one above and another below the time needed to achieve 100% killing of third-instar larvae of *Anastrepha ludens* at this temperature. The controls were treated in HW at 46.1 °C for 90 min, which is a commercial disinfestation treatment approved by the U.S. Department of Agriculture's Animal and Plant Health Inspection Service (USDA-APHIS) for mangoes before shipping to the USA. After 12 days of storage at 21 °C and 90% relative humidity, RF-treated mangoes were firmer than those treated at 46.1 °C in HW ($p < 0.05$). Thus, the RF treatment improved the texture of the fruits compared with the currently used commercial HW treatment. RF treatments that brought fruit temperature to 48 °C followed by 6 or 8 min holding at this temperature should achieve the required disinfestation of mangoes without causing quality losses.

1. Introduction

World export of mangoes between 2000 and 2003 was over 714 000 metric tons representing more than US$437 millions (Hansen and Johnson, 2007). The mango has grown in importance as an export product for Mexico, and proven a success in the US market, with Tommy Atkins as the main variety exported (SAGARPA, 2003). According to the US Department of Agriculture (USDA, 2005), mangoes from Mexico must be free of the Mexican fruit fly, *Anastrepha ludens*.

Ethylene dibromide was the first employed fumigant against quarantine pests in mangoes. It was recognized as

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[*] *Corresponding author.*
E-mail address: mariae.sosa@udlap.mx (M.E. Sosa-Morales).

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a carcinogenic agent and banned in 1984 (USDHHS, 1992). After that, methyl bromide fumigation was extensively used as a quarantine treatment (Moffit *et al.*, 1992). However, methyl bromide was identified as a high ozone depletion chemical by the Montreal Protocol (UNEP, 1995). Further restrictions on chemical fumigations under international agreements (USEPA, 2001) have generated great interest in developing alternative post-harvest treatments (Wang *et al.*, 2007a).

Alternative treatments should be technically effective, environmentally friendly, and economically feasible. Heat disinfestation treatments have been proposed as an alternative for many agricultural commodities because they are relatively easy to apply, leave no chemical residues, and may offer some fungicidal activity (Armstrong, 1994; Hansen and Johnson, 2007). Thermal treatment methods include hot water (HW) immersion, vapour heat, or hot air treatments for fruit disinfestation (Sharp *et al.*, 1991; Yokoyama *et al.*, 1991; Moffit *et al.*, 1992; Paull and Armstrong, 1994; Neven *et al.*, 1996; Lurie, 1998; Mangan *et al.*, 1998; Feng *et al.*, 2004; Armstrong and Follett, 2007). In 2002, a HW immersion quarantine treatment was approved by the USDA for mangoes (USDA-APHIS-PPQ, 2002), which consists of HW immersion of the fruit at 46.1 °C for 90 min for mangoes from Mexico before shipping to the USA. A common and major difficulty with hot air or water heating methods is the slow heating rate within fruits because of the high resistance to conductive heat transfer in fruits, resulting in long treatment times (Hansen, 1992; Wang *et al.*, 2001b), which could compromise product quality. Inappropriate temperature and time combinations selected to control the target insects may exceed those that could injure the host fruit or reduce its shelf life (Armstrong, 1994). The use of heat disinfestation treatments becomes even more problematic when the targeted insects, such as fruit fly larvae in mangoes, may stay in or migrate to the centre of host fruits. Thermal energy must then be delivered to that location. Another problem is the variation in the host fruit size. For example, the heating times required for mango fruit to reach a desired core temperature (e.g., 46 °C) may vary between 90 and 240 min depending upon the size and weight of the mangoes being treated (USDA-APHIS-PPQ, 2002).

Dielectric heating can be a viable potential alternative against pests in fruits (Nelson, 1996). Microwave (MW) and radio frequency (RF) energy have been widely used in food processing because of the fast and volumetric heating (Metaxas and Clee, 1993; Jones, 1997; Tang *et al.*, 2000; USDA, 2000). MW alone or combined with other heat treatments has been studied for control of insects in cherries (Ikediala *et al.*, 1999) and mangoes (Varith *et al.*, 2007). Those studies showed some degree of fruit quality degradation due to non-uniform heating. RF heating has advantages over MW in that RF energy can penetrate deeper into fresh fruits, such as apples, oranges, cherries (Wang *et al.*, 2003) and mangoes (Sosa-Morales *et al.*, submitted for publication), thus can potentially provide more uniform heating (Birla *et al.*, 2004; Wang *et al.*, 2007a). RF heating has recently been studied as possible phytosanitary and quarantine treatments in walnuts (Wang *et al.*, 2001a; Wang *et al.*, 2002a; Wang *et al.*, 2006b; Wang *et al.*, 2007b), apples (Wang *et al.*, 2006a), oranges (Birla *et al.*, 2005), cherries (Ikediala *et al.*, 2002; Monzon *et al.*, 2006), and persimmons (Tiwari *et al.*, 2008) with certain degrees of success. Birla *et al.* (2005) developed a fruit mover for oranges to reduce uneven RF heating. The same fruit mover was further used to combine fast RF core heating with the HW surface treatment to improve heating uniformity in apples (Wang *et al.*, 2006a), oranges (Birla *et al.*, 2005) and persimmons (Tiwari *et al.*, 2008), which indeed led to acceptable fruit quality. The overall goal of this research was to study the possibility of including RF heating as a part of HW thermal treatment against Mexican fruit fly in mangoes in order to reduce treatment time and improve product quality. Based on positive results from previous research (Tiwari *et al.*, 2008) and preliminary tests, we decided to use water at a moderate temperature (45 °C) to preheat mango for a certain time followed by RF core heating in a fruit mover to bring the whole fruit to 48 °C, a lethal temperature for Mexican fruit fly even after a short time exposure.

Specific objectives of this study were to: (1) determine suitable operational parameters of the fruit mover and the preheating time at 45 °C for the required RF heating uniformity at 48 °C, (2) develop treatment protocols using water assisted RF heating to control Mexican fruit fly in mangoes, and (3) evaluate product quality of treated mangoes based on the room storage at 21 °C, 90% relative humidity (RH) for 12 days.

2. Material and methods

2.1. Fruits

Physiologically mature mangoes (*Mangifera indica* cv. ‘Tommy Atkins’) with average weight of 374.4 ± 35.8 g (length 10.8 ± 0.5 cm, width 8.5 ± 0.3 cm, and height 7.6 ± 0.3 cm) were imported from a Mexican grower (Agro Exportadora Jorge Eli, Michoacán, Mexico) and acquired through a distributor located in Spokane, WA, USA. Fruits were refrigerated and transferred to room temperature for 24 h prior to the treatments. Mangoes had initial average total soluble solids (TSS) 11.9 ± 0.3%, titratable acidity (TA) 1.1 ± 0.1% (expressed as citric acid), pH 3.5 ± 0.1, pulp colour 78.9 ± 1.8, 5.6 ± 1.3, 47.8 ± 3.6 in L^*, a^*, b^* scale, and firmness 9.3 ± 1.2 N.

2.2. Operational conditions of the fruit mover in the RF system

Prior to RF treatments, tests about movement and rotation of mangoes were conducted only in the fruit mover, which was designed and described in detail by Birla *et al.* (2004). Movement of the fruit immersed in water within the mover was obtained by using a centrifugal pump (Mod 2PC27, Dayton electrical Mfg. Co., Niles, IL). To select the optimal conditions aimed to obtain constant movement of the fruits, five, six and seven mangoes were placed in the fruit mover with low (45 l min^{-1}), medium (50 l min^{-1}) and high (55 l min^{-1}) flow rates in a circulation water pipe. The rotation speed (rpm) of mangoes in peripheral and axial directions was evaluated to select the operational conditions of the fruit mover in RF treatments.

2.3. Treatment design

Combination of HW surface heating and RF core heating has been successfully used to improve heating uniformity and reduce quality losses for oranges (Birla *et al.*, 2005), apples (Wang *et al.*, 2006a), and persimmons (Tiwari *et al.*, 2008). A similar approach was used in this study to control third-instar *A. ludens* in mangoes. Previous studies revealed a log linear relationship between the minimum thermal death time and temperature required to completely kill a population of 600 third-instar *A. ludens* (Hallman *et al.*, 2005):

$$\log t_h = 14.554 - 0.286T \qquad (1)$$

where t_h is the holding time (min) at the treatment temperature (T, °C).

Total insect mortality was dependent on the cumulative thermal exposure of the fruit during the entire treatment process. The cumulative lethal time (LT, min) of the treatment at the least heated part of the fruit (the fruit core) was estimated after the actual temperature–time history of that location was recorded in the treatment according to Tang *et al.* (2000):

$$LT = \int_0^t 10^{\left(T(t)-T_{ref}\right)/z} dt \qquad (2)$$

where $T(t)$ is the recorded core temperature as a function of time t (min), T_{ref} is a reference temperature to standardize comparison, and the z value indicates the sensitivity of insect thermal mortality to changes in temperature. The value of z for third-instar *A. ludens* was derived from the negative inverse of the slope of the thermal death time curve expressed in Eq. (1) to be 3.5 °C based on the method described by Tang *et al.* (2000). The LT value was calculated using Eq. (2) by inputting the temperature–time history $T(t)$ of the fruit core, z value of 3.5 °C for *A. ludens*, and the reference temperature, T_{ref} (*e.g.* 48 °C), and integrating it over the entire time period.

The lethal thermal time concept has been used extensively in thermal processing calculations for commercial production of canned foods and recently used in developing heat treatments for pest control in fruits (Wang *et al.*, 2002b; Hansen *et al.*, 2004). The equivalent LT obtained using Eq. (2) was used to develop an RF and HW combination treatment that would deliver the same thermal lethality to Mexican fruit fly as that of the commercial HW quarantine treatment.

Current commercial HW quarantine treatment calls for heating mangoes in 46.1 °C water for 90 min (USDA-APHIS-PPQ, 2002). The temperature–time history in the centre of a 370 g mango during this treatment is shown in Fig. 1. Using Eq. (2) and the z values of 3.5 °C, the equivalent LT at the reference temperature of 48 °C for third-instar *A. ludens* in the centre of the fruit was calculated to be 6 min from the temperature–time history (Fig. 1). It has been reported by Hallman *et al.* (2005) that full exposure of third-instar *A. ludens* to 48 °C between 5.9 (calculated using 0.25th order of reaction) and 6.6 min (calculated using 0.5 order of reaction) would indeed lead to a probit 9 control (99.9968% mortality) which is a level set for quarantine requirements. In this study, we attempted to design treatments that combined water preheating with RF core heating to provide the similar thermal lethality as that of the commercial hot immersion treatment, but with reduced treatment time and, perhaps, improved product quality.

Preheating water temperature was selected to be 45 °C. This temperature was used for apples prior to RF treatment to reach 48 °C (Wang *et al.*, 2006a). Because of similar dielectric properties' values between apples and mangoes (Sosa-Morales *et al.*, in press), it was expected that the RF heating rate in mangoes could be similar to that in apples, and preheating temperature of 45 °C could also be suitable for mangoes.

For temperature–time history measurements to determine appropriate preheating time, seven mangoes were immersed in a circulating water bath (Model ZD, Grant, Cambridge, UK) at 45 °C until this temperature was reached inside the fruit,

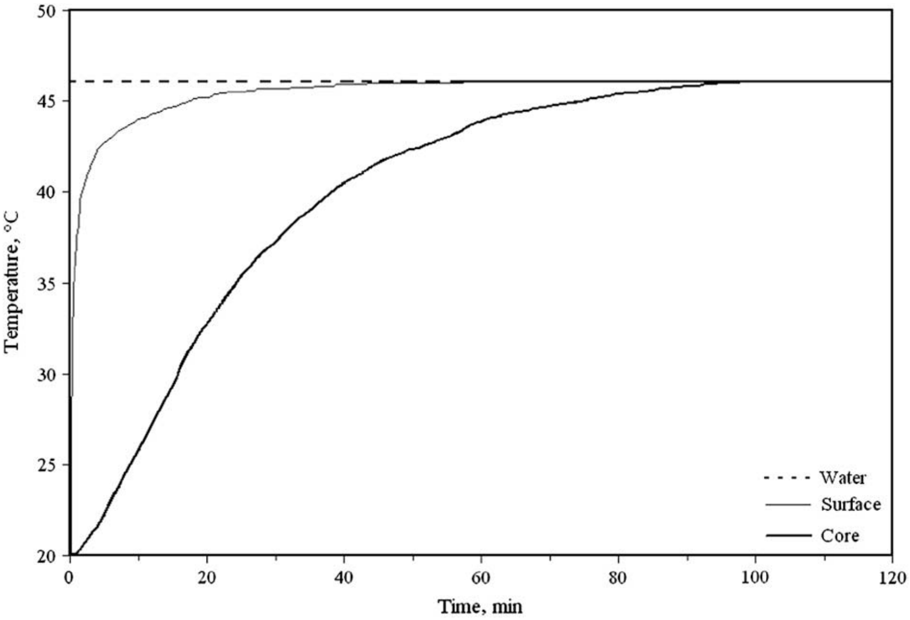


Fig. 1 – Temperature–time histories of the mango surface and core (2.72 cm depth) when subjected to water heating at 46.1 °C.

and then fruits were removed and rapidly cooled by immersion in a water bath at 4 °C. The core temperature of mangoes close to the mesocarp was measured with a calibrated Type-T thermocouple (Omega Engineering Ltd., Stamford, CT) and recorded every 5 s by a data logger (DL2e, Delta-T Devices Ltd., Cambridge, UK). Based on the temperature–time history, three possible preheating times as discussed below were evaluated for further heating uniformity tests.

For the best preheating time determination, preliminary tests were conducted with preheating times of 30, 40 and 50 min at 45 °C to compare the heating uniformity of the fruit samples after RF treatments. After preheating, mangoes were placed in a fruit mover between the two parallel electrode plates of a 27.12 MHz and 12 kW batch type RF heating system (E-200, Strayfield Int. Ltd., Wokingham, UK). The mover was filled with water at an initial temperature of 45 °C. RF heating was either conducted using an electrode gap of 320 mm and 1.8 min treatment time after preheating for 30 min resulting in an electrical current of 1.0 mA or using an electrode gap of 310 mm and 1 min treatment time after preheating of 40 or 50 min, resulting in 1.5 mA. The gap was selected from preliminary tests to control appropriate coupling of RF power into the fruit. After the circulating water temperature reached 48 °C, RF power was turned off. One randomly selected mango was taken out and quickly cut into halves to evaluate mango inner heating uniformity using infrared imaging. Because there is a hard stone in mangoes, a cut surface in dotted line was chosen for thermal imaging as it is shown in Fig. 2. One half of the mango was immediately placed into a water filled container with 95% fruit immersed in 48 °C water to reduce the heat loss from the exposed fruit surface. A thermal image of the exposed fruit was recorded by using an infrared imaging camera (ThermaCAM Researcher 2001, FLIR Systems, Portland, OR). Because of irregular shape of the mangoes, the average and standard deviation values were evaluated along the lines L1 and L2 (Fig. 2) to determine the temperature distribution after the RF treatment. The preheating time of 50 min at 45 °C water bath was selected to achieve the desired RF heating uniformity. The final treatment procedure is shown in Fig. 3. The RF-treated samples were immediately transferred to a water bath at 48 °C and were held for specified times. The fruits were then hydro-cooled in 4 °C water for 30 min. The treated mangoes were evaluated on 0, 4, 8 and 12 days during storage in a closed chamber at 21 °C and 90% RH. Each treatment was replicated three times.

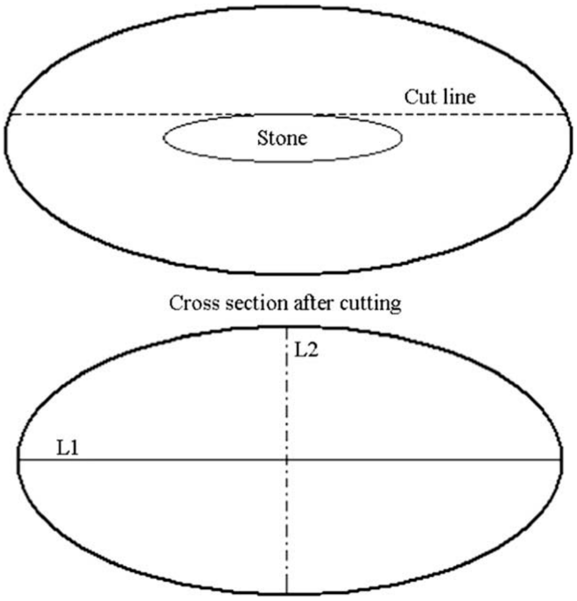


Fig. 2 – The cut surface (dotted line) along the mango stone and the lines L1 and L2 in the cross-section of the thermal image for statistical temperature analyses.

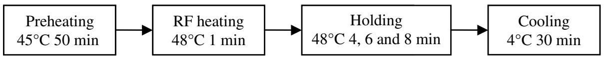


Fig. 3 – Schematic view of the proposed protocol development involving an RF treatment.

Based on isotherm thermal death kinetic studies, reported by Hallman *et al.*, (2005) 100% mortality of the third-instars *A. ludens* (Loew) should be achieved after a 6 min exposure to 48 °C. In the treatment protocol design, three holding times (4, 6 and 8 min) were selected at 48 °C, corresponding to one level at, one above and another below the required time to achieve 100% mortality (Table 1). These three RF treatments were compared with the unheated control and the commercial disinfestation treatment approved by the USDA-APHIS, United States Department of Agriculture's Animal and Plant Health Inspection Service (Table 1).

2.4. *Determination of quality parameters*

Before the experimental runs, each mango was marked with a number, and its weight was recorded. After treatments and every 4 days during the storage, three fruits of each treatment were randomly taken to determine the quality attributes as follows. Weight loss was expressed as percentage of fruit weight reduction from initial weight. TSS (%) were determined in the mango pulp by using of a hand refractometer (Model N-1α, Atago Co. Ltd., Tokyo, Japan), by measuring the °Brix of the sample. TA was determined in 10 g of pulp by titration with 0.1 N NaOH (AOAC, 1994), and expressed as percentage of citric acid. Pulp pH values were measured by direct immersion of the probe using a pH meter (AP5, Fisher Scientific, Pittsburgh, PA). Pulp colour was measured by a colorimeter (CM-2002, Minolta Corp., Ramsey, NJ) that was previously

Table 1 – Nomenclature and description of the treatments carried out in mangoes[a]

Treatment nomenclature	Treatment description
Control	No heat treatment (immersion in water at 20 °C for 90 min)
RF48 + 4	RF heating in water to 48 °C and holding for 4 min
RF48 + 6	RF heating in water to 48 °C and holding for 6 min
RF48 + 8	RF heating in water to 48 °C and holding for 8 min
HW46.1 + 90	Immersion in HW at 46.1 °C for 90 min

a Before the RF48 treatments, a preheating at 45 °C for 50 min was conducted with the mangoes. All RF and HW-treated mangoes were followed by a hydro-cooling at 4 °C for 30 min.

Table 2 – Peripheral and axial rotation velocities (rpm) of five, six, and seven mango fruits in batches at three different flow rates in the fruit mover for RF treatments

Flow rate (l min^{-1})	Five mangoes batch		Six mangoes batch		Seven mangoes batch	
	Peripheral	Axial	Peripheral	Axial	Peripheral	Axial
Low (45)	5.7 ± 0.6	1.3 ± 0.6	0	0	0	0
Medium (50)	9.7 ± 0.6	2.7 ± 0.6	8.7 ± 0.6	2.8 ± 0.3	6.0 ± 0.0	1.8 ± 0.3
High (55)	9.5 ± 0.5	1.7 ± 0.6	7.7 ± 0.6	1.3 ± 0.6	0	0

Values of 0 rpm mean that mangoes became blocked in the fruit mover.

calibrated with a reflective white tile. Colour was expressed through the L^* (darkness), a^* (green-red) and b^* (blue-yellow) parameters, and the Hue angle, h° ($\tan^{-1} b^*/a^*$), was calculated. For firmness, mango peel was cut carefully in parallel directions of the flat side of the seed in a small area. The exposed pulp was subjected to a compression test using a Texture Analyzer (TA.XT2i, Texture Technologies, Inc., Scarsdale, NY) and the Texture Expert Exceed software (2.64 Version, Stable Micro Systems). An 11 mm probe with moving speed of $1\ \text{mm s}^{-1}$ and a travel distance of 5 mm of compression was used for the test. The firmness was expressed as the maximum force in Newton (N).

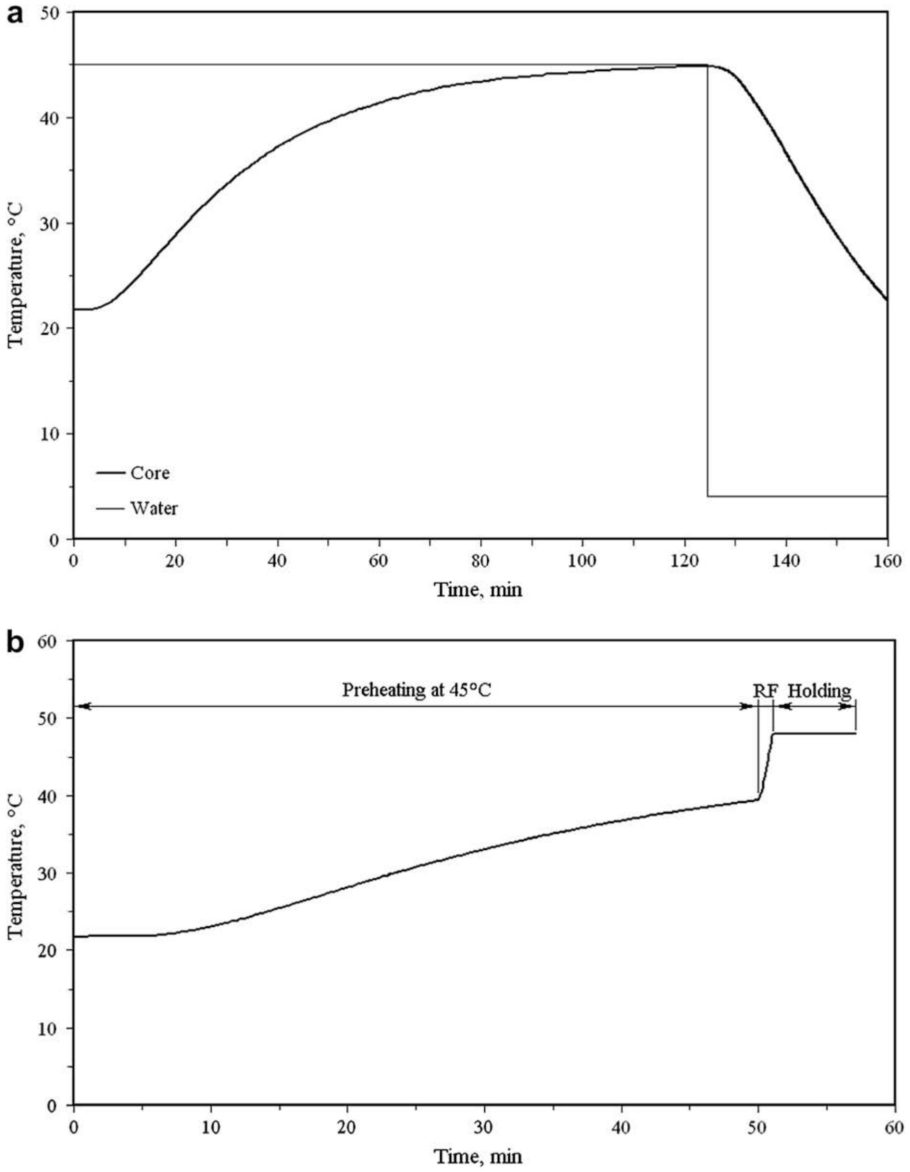


Fig. 4 – Typical temperature–time histories of the mango core (2.72 cm depth) when subjected to water preheating at 45 °C followed by hydro-cooling at 4 °C (a) and RF heating with 6 min holding (b).

2.5. *Statistical analysis*

Data were analyzed by an analysis of variance (ANOVA) and Tukey's pair-wise comparisons using the Minitab Release 14.0 software. The means were separated at the significant level of $p = 0.05$.

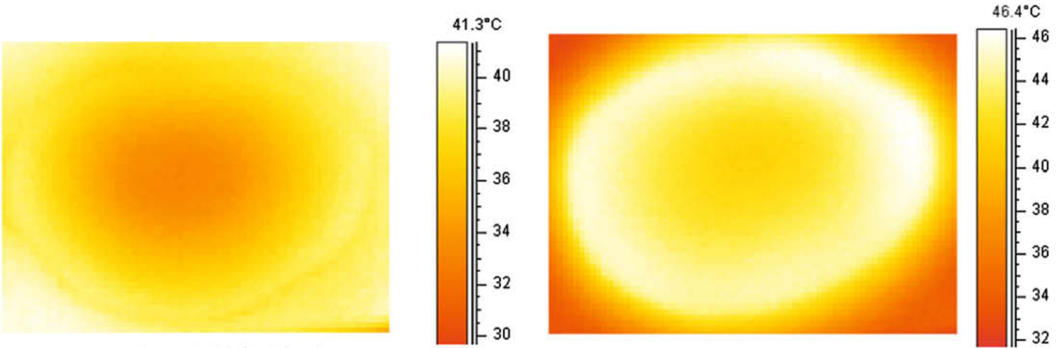
3. Results and discussion

3.1. *Operational conditions for the fruits mover*

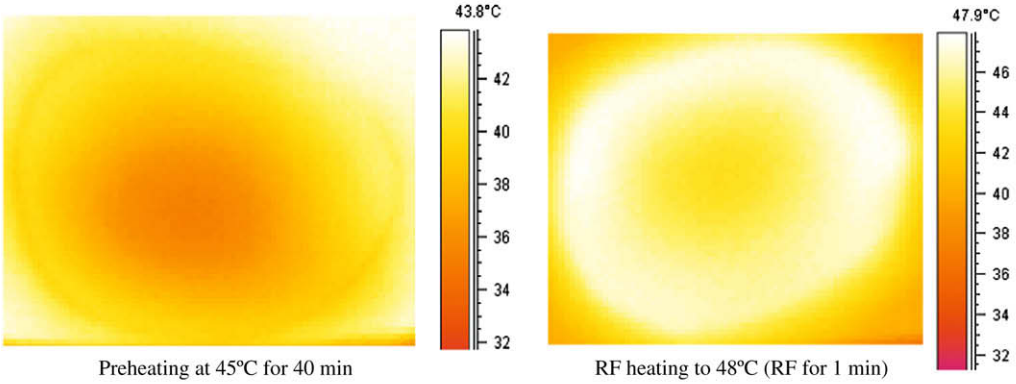
Table 2 shows the effect of batch size and water circulation rates on movement and rotation of the mangoes. For a batch six and seven mangoes using the low flow rate or seven mangoes using the high flow rate, the movement of fruits was stopped due to interlocking. According to the movement characteristics and required sample size for quality evaluation, medium flow rate with six mangoes was selected for further experiments using the fruit mover in RF systems.

3.2. *Temperature–time history and preheating time determination*

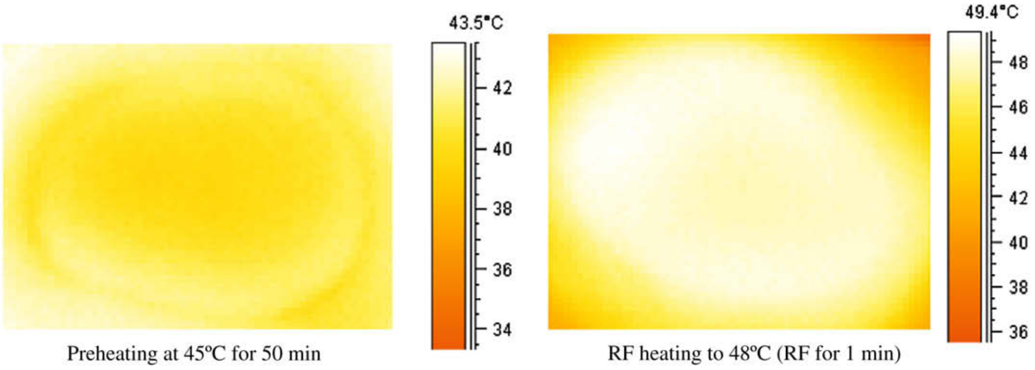
Fig. 4a shows the temperature–time history at the core of a mango during preheating and hydro-cooling. There was a 5 min thermal lag in the core temperature, mainly due to slow heat conduction. The rate of temperature change decreased sharply after heating for 60 min because of small temperature gradients between fruit surface and the core. The final core temperatures after preheating for 30, 40 and 50 min (Fig. 4a) were 33.7, 37.2 and 39.6 °C, respectively, which were in good agreement with those obtained by thermal images (Fig. 5). Based on the cooling curve, 30 min hydro-cooling reduced the fruit core temperature to 25 °C. We therefore selected 30 min cooling time to reduce the temperature effects



Preheating at 45°C for 30 min RF heating to 48°C (RF for 1.83 min)



Preheating at 45°C for 40 min RF heating to 48°C (RF for 1 min)



Preheating at 45°C for 50 min RF heating to 48°C (RF for 1 min)

Fig. 5 – Thermal images of mangoes after three preheating times and RF treatments.

Table 3 – Temperature distribution along the two lines L1 and L2 (Fig. 2) over the mango cross-section with and without RF treatments after preheating

Treatments		Temperature (°C)	
		L1	L2
Preheating at 45 °C for 30 min	No RF	35.8 ± 2.1	35.5 ± 1.8
	With RF	43.5 ± 1.5	43.2 ± 1.3
Preheating at 45 °C for 40 min	No RF	38.0 ± 1.9	37.3 ± 1.6
	With RF	45.6 ± 1.4	45.4 ± 1.1
Preheating at 45 °C for 50 min	No RF	40.2 ± 0.4	40.6 ± 0.6
	With RF	48.4 ± 0.4	48.5 ± 0.3

on product quality after the thermal treatment. Fig. 4b shows the typical temperature–time history of the mango core after subjecting to preheating at 45 °C for 50 min followed by RF heating for 1 min and holding at 48 °C water for 6 min. The equivalent LT at 48 °C was only 0.02 min and 0.17 min for the preheating and RF heating periods, respectively. The total accumulated LT of 6.19 min at 48 °C for the RF assisted heating treatments (48 °C + 6 min) could ensure the complete kill of the targeted insects judging from the LT of 6 min at 48 °C calculated for commercial HW quarantine treatments and from isotherm insect mortality data discussed earlier.

Fig. 5 shows the thermal images of mangoes after preheating at 45 °C for 30, 40 and 50 min followed by RF heating. The heating uniformity was improved by increasing preheating time and using RF core heating as indicated by temperature standard deviations along the cross-lines (Table 3). But the final average

Table 4 – Comparison of the post-harvest physical quality of control, RF and HW-treated mangoes during room storage at 21 °C and 90% RH

Treatment [temp (°C) + time (min)]	Days after treatments			
	0	4	8	12
Weight loss (%)				
Control	$-0.70 \pm 0.30^{a,*}$	1.11 ± 0.07^{a}	2.04 ± 0.38^{a}	2.73 ± 0.39^{a}
RF48 + 4	$-0.40 \pm 0.61^{a,b}$	1.47 ± 0.65^{a}	2.16 ± 0.39^{a}	3.15 ± 0.53^{a}
RF48 + 6	-0.19 ± 0.26^{b}	1.22 ± 0.28^{a}	2.02 ± 0.04^{a}	2.98 ± 0.46^{a}
RF48 + 8	-0.12 ± 0.24^{b}	1.19 ± 0.38^{a}	2.28 ± 0.68^{a}	2.29 ± 0.20^{a}
HW46.1 + 90	-0.73 ± 0.52^{a}	1.07 ± 0.09^{a}	2.50 ± 0.89^{a}	2.74 ± 0.45^{a}
Soluble solids (°Bx)				
Control	11.90 ± 0.16^{a}	$13.36 \pm 0.26^{a,b}$	13.96 ± 0.29^{a}	14.46 ± 0.55^{a}
RF48 + 4	11.70 ± 0.48^{a}	12.63 ± 0.89^{b}	14.13 ± 0.30^{a}	14.90 ± 0.90^{a}
RF48 + 6	12.06 ± 0.20^{a}	$13.30 \pm 0.11^{a,b}$	14.13 ± 0.85^{a}	14.66 ± 0.76^{a}
RF48 + 8	11.73 ± 0.32^{a}	$13.86 \pm 0.24^{a,b}$	14.10 ± 0.24^{a}	14.43 ± 0.54^{a}
HW46.1 + 90	11.93 ± 0.20^{a}	13.26 ± 0.35^{a}	14.26 ± 0.57^{a}	14.53 ± 0.76^{a}
TA (% citric acid)				
Control	1.13 ± 0.15^{a}	0.73 ± 0.04^{a}	0.42 ± 0.11^{a}	0.13 ± 0.04^{a}
RF48 + 4	1.13 ± 0.08^{a}	0.72 ± 0.13^{a}	0.39 ± 0.12^{a}	0.12 ± 0.03^{a}
RF48 + 6	1.09 ± 0.10^{a}	0.71 ± 0.10^{a}	0.44 ± 0.13^{a}	0.14 ± 0.03^{a}
RF48 + 8	1.18 ± 0.15^{a}	0.75 ± 0.02^{a}	0.43 ± 0.10^{a}	0.12 ± 0.02^{a}
HW46.1 + 90	1.08 ± 0.12^{a}	0.63 ± 0.18^{a}	0.30 ± 0.06^{a}	0.13 ± 0.02^{a}
pH values				
Control	3.44 ± 0.13^{a}	3.89 ± 0.40^{a}	4.11 ± 0.50^{a}	4.99 ± 0.28^{a}
RF48 + 4	3.64 ± 0.18^{a}	3.88 ± 0.09^{a}	4.21 ± 0.18^{a}	5.14 ± 0.43^{a}
RF48 + 6	3.67 ± 0.05^{a}	3.88 ± 0.37^{a}	4.42 ± 0.37^{a}	4.72 ± 0.34^{a}
RF48 + 8	3.47 ± 0.14^{a}	3.81 ± 0.26^{a}	4.52 ± 0.34^{a}	4.99 ± 0.03^{a}
HW46.1 + 90	3.66 ± 0.13^{a}	3.94 ± 0.22^{a}	4.21 ± 0.19^{a}	4.96 ± 0.07^{a}
Hue angle of the pulp (h^{o})				
Control	83.61 ± 1.27^{a}	82.01 ± 1.24^{a}	81.46 ± 3.26^{a}	79.19 ± 1.25^{a}
RF48 + 4	83.10 ± 2.23^{a}	82.69 ± 1.26^{a}	80.63 ± 1.47^{a}	77.50 ± 1.48^{a}
RF48 + 6	83.45 ± 1.42^{a}	80.86 ± 1.77^{a}	79.64 ± 0.94^{a}	78.96 ± 1.83^{a}
RF48 + 8	83.62 ± 0.76^{a}	81.15 ± 1.86^{a}	79.15 ± 1.44^{a}	78.46 ± 1.38^{a}
HW46.1 + 90	82.87 ± 1.44^{a}	80.52 ± 1.97^{a}	79.99 ± 2.64^{a}	76.87 ± 1.72^{a}
Firmness (N)				
Control	9.72 ± 1.64^{a}	4.58 ± 1.00^{a}	2.72 ± 0.55^{a}	2.11 ± 0.31^{a}
RF48 + 4	9.28 ± 1.29^{a}	$3.63 \pm 0.43^{a,b}$	2.51 ± 0.45^{a}	2.08 ± 0.51^{a}
RF48 + 6	9.25 ± 1.56^{a}	$3.82 \pm 1.30^{a,b}$	2.62 ± 0.22^{a}	1.96 ± 0.28^{a}
RF48 + 8	9.21 ± 0.81^{a}	$4.02 \pm 1.08^{a,b}$	2.52 ± 0.25^{a}	$1.57 \pm 0.32^{a,b}$
HW46.1 + 90	8.98 ± 0.32^{a}	2.76 ± 0.32^{b}	2.64 ± 0.52^{a}	1.14 ± 0.10^{b}

*Means with the same letter are not significantly different ($p > 0.05$).

temperatures did not reach the targeted temperature of 48 °C after RF heating following preheating at 45 °C for only 30 and 40 min. Therefore, preheating at 45 °C for 50 min was selected for further treatment protocol development.

3.3. *Quality of treated mangoes*

Table 4 shows the results of quality analysis of mangoes after RF treatments following preheating in HW at 45 °C for 50 min. Data for control and commercial HW treatment are included for comparison. There was no change in fruit weight after RF treatments (day 0). Mangoes gained weight after control and HW treatments, probably because of long exposure to water (total of 120 min compared to 85–89 min for the RF protocols).

All mango samples lost weight during storage at 21 °C and 90% RH. The losses ranged between 2.29 and 3.15% after 12 days of storage, having the least losses in the RF48 °C + 8 min treatment (Table 4). In general, similar weight losses were observed between control and HW treatment. The weight losses for the treatments involving RF heating were dependent on holding time at 48 °C. The observed weight losses in this study were lower than those (between 7.19 and 9.98%) reported by Ortega-Zaleta and Yahia (2000) for Manila mangoes stored for 10 days at 10 °C after exposure to controlled atmospheres and high temperatures. It has been reported that weight losses are lower when RF exposures are involved as post-harvest treatment for other commodities, such as oranges with a weight loss between 0.24 and 0.39% after 10 days of storage (Birla *et al.*, 2004), and apples with 1.56% weight loss after stored for 30 days (Wang *et al.*, 2006a).

Soluble solids and pH increased, while TA, firmness and h^o in pulp decreased with the increasing storage time ($p < 0.05$) (Table 4). Values of TSS, pH, TA and h^o in mango pulp in treated samples were not statistically different from the control and the commercial HW method ($p > 0.05$). But mango firmness was affected by some treatments. After 4 days of storage, the measured firmness in RF-treated mangoes was similar to that in the control fruits, while a lower value was observed for the HW-treated mangoes. After 12-day storage, mangoes in controls, RF48 °C + 4 min, and RF48 °C + 6 min treatments had higher firmness values than those in the HW treatment ($p < 0.05$). This result suggested that the shorter treatment time and the more uniform heating were achieved by the proposed RF treatments than the currently approved commercial HW treatment. The changing trends with the storage time are typical of the ripening process in fruits (FAO, 2003) and in agreement with those reported for 'Manila' (Ortega-Zaleta and Yahia, 2000), 'Ataulfo' (Montalvo *et al.*, 2007) and 'Namdokmai' (Varith *et al.*, 2007) mango varieties. TA and firmness values of mangoes in this study were lower than those described by the above reports, which was probably caused by the different mango varieties, applied treatments, and storage conditions.

Colour parameters of pulps for the treated mangoes are shown in Fig. 6. During 12-day storage, L^* (lightness index) decreased, while a^* (greenish-redness variation) and b^* (blue-yellow index) increased with the storage time. These changes indicate that flesh in mangoes became darker, less green and more yellow. But there were no significant differences ($p > 0.05$) among colour parameters of control mangoes and the different tested treatments.

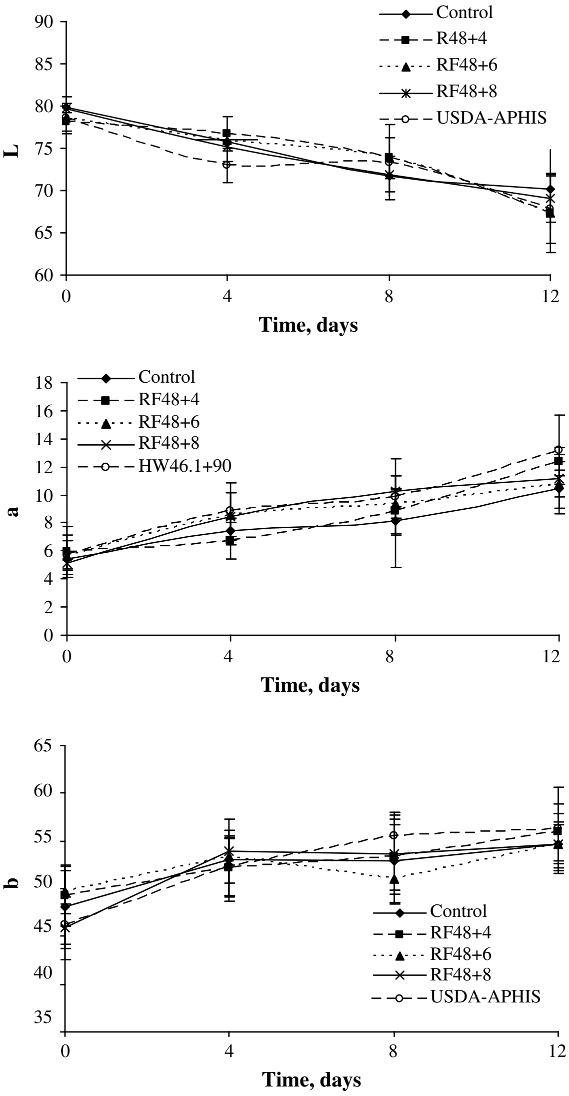


Fig. 6 – Colour of mango pulps treated with RF heating based protocols and the approved water immersion method through storage at 21 °C and 90% RH during 12 days.

3.4. *Comments for further treatments*

The RF treatments can be scaled up to treat large volumes of mangoes. A 25 kW 27 MHz RF tube system (Magnatube, Proctor Strayfield, Workingham, UK) may be used for scaling-up studies to evaluate the heating uniformity and determine engineering parameters for continuous processes. This RF system consists of an RF generator, two paired electrodes attached on the tube surface, a tube (10.2 cm in diameter and 150 cm long) and two extended plastic tubes for incoming and outgoing fruits and a pump for water circulation. The tube will be inclined 12° from horizontal to facilitate movement and rotation of fruits from one end to other (Birla *et al.*, 2007). The changed electromagnetic field direction using electrodes will improve the heating uniformity of fruits passed through the tube length. This equipment would allow us to treat large volumes of fruits continuously.

4. Conclusions

An RF HW thermal treatment was designed to improve heating uniformity in mango aiming to control Mexican fruit fly. Preheating for 50 min in water at 45 °C followed by RF heating to 48 °C and holding at this temperature for 6 min was calculated to be equivalent to commercial HW heating at 46.1 °C for 90 min in terms of thermal lethal effect for Mexican fruit fly (*A. ludens*). Tommy Atkins mangoes were able to tolerate combined water and RF thermal treatment. SST, TA, pH, and pulp colour were not affected by the treatments, resulting in similar ripening changes as observed in non-treated fruits. When RF48 °C + 4 min and RF48 °C + 6 min were applied, higher firmness values were measured. These treatments improved the mango texture and maintained the other quality variables of ripened fruits at 4 and 12 days of storage, showing an advantage over the approved water immersion protocol. For further studies, it is recommended to use the RF48 + 6 protocol, because it is sufficient to ensure the 100% mortality of the third-instar larvae of *A. ludens*.

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