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Review

Radio frequency heating for postharvest control of pests in agricultural products: A review

Lixia Hou[a], Judy A. Johnson[b], Shaojin Wang[a,c,*]

[a] College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling, Shaanxi 712100, China
[b] USDA, Agricultural Research Service, San Joaquin Valley Agricultural Sciences Center, 9611 S. Riverbend Avenue, Parlier, CA 93648-9757, USA
[c] Department of Biological Systems Engineering, Washington State University, 213 L.J. Smith Hall, Pullman, WA 99164-6120, USA

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ABSTRACT

Radio frequency (RF) treatment is one of the most promising physical disinfestation methods in agricultural products due to rapid heating, deep penetration depth, and leaving no chemical residues. This paper focuses on reviewing uses of RF energy for disinfestation of agricultural products. It provides a brief introduction on the basic principle of RF heating technology, analyzes the differential heating of pests in host products at RF range, and discusses the factors influencing the RF heating uniformity and the possible methods to improve heating uniformity by computer simulations. This paper presents a comprehensive review of recent progresses in developing RF treatment protocols for disinfesting fresh fruits and dry products, and recommendations for future research to effectively achieve the required RF heating uniformity and bridge the gap between laboratory research and industrial applications.

Contents

1. Introduction

One of the main issues during production, storage, and marketing of agricultural products is the damage and loss due to infestation by pests. Losses caused by pests in agricultural

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[*] Corresponding author at: College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling, Shaanxi 712100, China. Fax: +86 29 87091737.
E-mail address: shaojinwang@nwsuaf.edu.cn (S. Wang).

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products include reduced nutrition, low germination rate, and weight reduction (Yuya et al., 2009). Furthermore, the pests produce sticky substances and feces, which promote the microbial growth and reduce market price of agricultural products. It is estimated that annual losses of cereal grains due to pests is about 9% in developed countries and approximately 20% or more in developing countries (Azab et al., 2013; Huang et al., 2015b). Therefore, developing an effective and efficient disinfestation method can largely reduce pest damages to agricultural products during storage (Tang et al., 2007).

Regulatory agencies worldwide have established phytosanitary and quarantine protocols intended to prevent the movement of exotic pests through marketing channels and re-infestations during the storage. Currently, the agricultural product industry relies heavily on methyl bromide (MeBr) and phosphine fumigations for postharvest insect control (Carpenter et al., 2000). After used for commodity fumigation (Yokoyama et al., 1990), MeBr gas eventually enters the atmosphere during aeration, which results in depleting the ozone layer. Its use has been scheduled to be phased out in developed countries by 2005 and developing countries by 2015 according to the Montreal Protocol (UNEP, 1992). Phosphine fumigation is problematic because the gas corrodes copper, gold and silver, and can seriously damage electrical equipment. Fumigation with phosphine requires longer exposures than that with MeBr, making phosphine unsuitable for applications where a quick treatment is needed. Phosphine fumigation also results in increased resistance in pest populations (Fields, 1992). Regulatory actions against both MeBr and hydrogen phosphine may make these fumigants difficult to obtain or even unavailable to the industry. Therefore, thermal treatments are proposed to be non-chemical alternative to control insect pests in postharvest agricultural products (Feng et al., 2004; Tang et al., 2007).

Except for applying easily, leaving no chemical residues, and offering some fungicidal activity (Armstrong, 1994), conventional thermal disinfestation treatments often cause deleterious effects to product quality due to long heating times at the target temperature (Armstrong, 1994; Wang et al., 2001b). Recently, radio frequency (RF) energy has been widely studied to overcome the slow heating rate of the conventional heating due to its volumetric and fast heating (Tang et al., 2000). RF heating has been successfully used in many industries, such as plastic welding, curing of glue in plywood processing, textile drying, and finish drying of bakery products (Orfeuil, 1987). Many recent studies on the use of RF energy have been conducted to control insects in postharvest agricultural products (Nelson and Payne, 1982; Nelson, 1996; Tang et al., 2000; Marra et al., 2009). With long wavelengths and large penetration depths, RF treatments have also been used for disinfestations in large scale industrial applications (Wang et al., 2007a,b; Jiao et al., 2012). For successful commercial implementations, the RF treatments should provide adequate insect mortality to meet quarantine or phytosanitary requirements, cannot adversely affect product quality, and be economically feasible to use in industrial operations.

Heating non-uniformity is a major problem in RF treatments, which would result in either insect survival or product damage (Birla et al., 2004; Wang et al., 2005b, 2008). Hot air or water as surface heating, sample moving, and mixing are commonly used to improve the RF heating uniformity (Hansen et al., 2006a,b; Wang et al., 2006, 2014; Tiwari et al., 2008; Gao et al., 2010; Sisquella et al., 2013). With the computer simulation, RF heating uniformity has also been improved by placing the samples in the middle of the two plate electrodes and using a similar dielectric material around the samples (Jiao et al., 2014).

Based on the dielectric properties difference, the differential heating between the target insects and host products has been observed both theoretically and experimentally, resulting in the insects reaching a lethal temperature while the product is heated to lower temperatures that do not cause quality loss (Wang et al., 2001a, 2010; Birla et al., 2005; Tiwari et al., 2008; Gao et al., 2010; Jiao et al., 2012; Hou et al., 2014). By exploring differential heating, the time and the product temperature needed for effective RF treatments could be significantly reduced, thereby reducing adverse effects on product quality and enabling a greater throughput of product in a processing plant (Nelson, 1996; Shresth and Baik, 2013; Wang et al., 2013). This is important to systematically analyze possible selective RF heating of the insects in agricultural products.

The purposes of this review are (1) to introduce the basic principle of RF heating, (2) to analyze the differential heating in pests and host products in RF range, (3) to discuss the potential methods to improve RF heating uniformity by computer simulations, (4) to review the literature on RF treatments for control of pests in agricultural products, and (5) to propose recommendations for the future research to enhance practical applications of RF heating to postharvest control of pests in agricultural products.

2. Properties of RF heating

2.1. Principle of RF heating

RF heating is one of thermal treatments using electromagnetic energy to heat the pest to its lethal temperature with holding an adequate time. When any material with polarized molecules and charged ions is subjected to an electromagnetic field that rapidly changes direction, heating occurs as polarized molecules and charged ions interact with the alternating electromagnetic field, resulting in frictional losses as they rotate and move (Barber, 1983). The higher the frequency of the alternating field, the greater the energy imparted to the material, until the frequency is so high that rotating molecules cannot keep up with the external field due to lattice limitations (Zhao et al., 2000). In RF heating, the applied frequencies are between 10 and 300 MHz, and specifically allocated to be 13.56, 27.12, and 40.68 MHz by the US Federal Communications Commission (FCC) to avoid disturbing with the communication system.

Many factors influence the RF heating of agricultural products. However, the major factors are dielectric properties of agricultural products and distribution of electromagnetic fields, which determine the thermal energy in agricultural products converted from electromagnetic energy. RF energy generates heat volumetrically and rapidly within agricultural products by the combined effects of polarization mechanisms of dipole rotation and ionic conduction, which are discussed in the following section (Piyasena et al., 2003).

2.1.1. Dielectric properties

Most of agricultural products act as an electric capacitor to store electrical energy, and also as a resistor to transform electric energy to thermal energy, thereby heating the products. These abilities are defined by dielectric properties (ε) normally described by the following equation (Risman, 1991):

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{1}$$

where $j = \sqrt{-1}$. ε' is the relative dielectric constant, and describes the ability of a material to store energy in response to an applied electric field (for a vacuum $\varepsilon' = 1$). ε'' is known as the relative electric loss factor, and describes the ability of a material to dissipate energy in response to an applied electric field, which typically results in heat generation.

Dielectric properties of agricultural products depend on the frequency of electromagnetic field, temperature, moisture content, density, and composition of agricultural products (Ryynänen,

Table 1
Dielectric properties of typical agricultural products at three temperatures and two frequencies.

Material	Moisture (% w. b.)	Temp. (°C)	Dielectric constant		Loss factor		Penetration depth (cm)		Source
			27.12 MHz	915 MHz	27.12 MHz	915 MHz	27.12 MHz	915 MHz	
Almond, *Nonpareil*	3	20	5.9	1.7	1.2	5.7	538	2	Wang et al. (2003b)
		40	5.8	3.3	0.6	6.0	708	2	
		60	6.0	3.1	0.7	6.4	618	2	
Apricots, *Prunus armeniaca*	25	20	33.9	19.7	11.8	7.1	89	3	Alfaifi et al. (2013)
		40	37.4	22.9	19.9	9.5	56	3	
		60	40.8	26.2	37.4	10.2	33	3	
'Bing' sweet cherries	88	20	91.2	73.7	293.0	16.4	8	3	Wang et al. (2003b)
		40	91.0	69.6	440.1	18.3	7	2	
		60	89.8	64.1	501.9	20.4	6	2	
Chestnut, *Castanea mollissima*	45	20	31.2	14.6	45.9	5.2	25	4	Guo et al. (2011)
		40	38.8	16.5	77.9	6.3	18	3	
		60	57.7	20.1	158.1	9.5	12	3	
Cherimoya, *Annona cherimola*	85	20	71.5	50.9	238.5	25.4	9	2	Wang et al. (2005a)
		40	68.4	48.7	339.1	26.0	7	1	
		60	70.0	56.0	480.6	31.5	6	1	
Macadamia nut, *Macadamia tetraphylla*	3	25	4.3	5.2	0.3	0.8	1121	15	Wang et al. (2012)
		40	4.3	5.1	0.4	0.9	1016	14	
		60	4.5	5.2	0.4	1.0	916	12	
Mango, *Mangifera indica*	86	20	83.1	74.0	250.1	13.8	9	3	Sosa-Morales et al. (2009a)
		40	80.5	69.5	346.4	14.9	8	3	
		60	78.9	65.0	466.0	17.5	7	2	
Navel orange, *Citrus aurantium* subsp. *bergamia*	89	25	158.2	82.4	470.1	14.8	8	3	Nelson (2003)
		65	247.6	57.2	725.5	16.3	5	2	
		95	271.5	21.5	792.4	18.5	5	1	
Nectarine, *Prunus persica* var. *nectarine*	88	20	68.9	64.0	195.8	11.6	11	4	Ling et al. (2014b)
		40	69.5	63.2	292.5	12.9	8	3	
		60	69.0	61.6	412.1	15.4	7	3	
Peach, *Prunus persica*	88	20	69.2	64.6	198.2	13.2	11	3	Ling et al. (2014b)
		40	72.9	66.1	292.4	15.3	8	3	
		60	73.1	64.4	411.4	17.7	7	2	
Persimmon, *Diospyros kaki*	75-85	20	79.8	68.4	207.5	21.1	11	2	Wang et al. (2005a)
		40	77.6	70.8	295.6	15.9	8	3	
		60	75.4	66.0	401.3	16.9	7	3	
Pistachio, *Pistacia vera L.*	15	25	11.9	7.3	6.0	1.8	104	8	Ling et al. (2014a)
		45	12.7	7.6	7.4	1.9	88	8	
		65	13.7	8.0	10.2	2.1	68	7	
Prunes, *P. domestica*	30	20	40.6	24.2	17.2	10.8	67	2	Alfaifi et al. (2013)
		40	44.4	29.1	25.4	11.8	48	2	
		60	48.9	34.2	47.8	11.3	28	3	
Plum, *Prunus domestica*	85	20	70.9	63.4	174.2	11.0	12	4	Ling et al. (2014b)
		40	66.3	57.9	228.3	10.8	10	4	
		60	62.7	52.8	285.9	11.5	8	3	
Raisins, *Vitus vinifera*	15	20	21.9	7.8	8.1	3.8	104	4	Alfaifi et al. (2013)
		40	28.0	10.9	9.8	5.2	97	3	
		60	33.8	15.2	11.4	7.2	91	3	
Red delicious apple	85	25	93.2	59.3	213.4	7.5	11	5	Nelson and Trabelsi (2008)
		45	103.7	61.8	317.8	7.2	8	6	
		65	117.5	64.6	405.1	7.7	7	5	
Soybean, 'Wayne' (*Glycine max* L.)	8	24	3.1	–	0.3	–	1035	–	Nelson and Charity (1972)
Walnut, *Juglans regia* L.	3	20	4.9	2.2	0.6	2.9	654	3	Wang et al. (2003b)
		40	5.1	3.0	0.4	2.3	995	4	
		60	5.3	3.8	0.4	1.8	1015	6	

Table 1 (*Continued*)

Material	Moisture (% w. b.)	Temp. (°C)	Dielectric constant		Loss factor		Penetration depth (cm)		Source
			27.12 MHz	915 MHz	27.12 MHz	915 MHz	27.12 MHz	915 MHz	
Red winter wheat, *Triticum aestivum* L.	11	25	4.8	3.7	4.2	1.7	99	9	Nelson and Trabelsi (2006)
		75	14.9	8.4	7.3	2.2	96	7	
		95	63.6	22.3	67.5	7.3	23	3	

1995; Piyasena et al., 2003; Nelson and Trabelsi, 2012). In general, the dielectric constant and loss factor of agricultural products increase with increasing temperature in certain frequency (Table 1), which causes those agricultural products to absorb more electromagnetic energy as their temperatures increase (Hossan and Dutta, 2012). The portion of agricultural products at higher temperature tends to absorb more energy for accelerating the temperature differences, which is called "thermal runaway" effect. On the other hand, if adequate thermal energy is converted from electromagnetic energy, the water in agricultural product is evaporated during the heating process, resulting in reduced loss factor. Less energy is absorbed in the higher temperature part than in the lower temperature one, which is termed as "temperature leveling" effect. Therefore, it is essential that the electric field in RF units should be uniform to ensure even heating. Since the temperature distribution within a material is seldom as predictable as that for a conventional process, heat distribution and penetration studies are not straightforward in a dielectric heating process.

Since dielectric properties of air are totally different from those of agricultural products, the density of pulverized or granular materials has a notable effect on the dielectric properties. Fig. 1 shows a linear relationship between bulk density and the dielectric constant or loss factor of shelled peanuts at each level of moisture contents. Dielectric properties of peanuts increase with increasing moisture content and bulk density (Guo et al., 2011; Nelson and Trabelsi, 2012).

2.1.2. Power density

The power absorbed in a unit volume of a dielectric material depends on its dielectric properties (the loss factor) and can be expressed by the Eq. (2) (Ryynänen, 1995):

$$P_V = 2\pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon'' E^2 \tag{2}$$

where P_V is the power conversion per unit volume (W/m^3), f is the frequency of electromagnetic field (Hz), ε_0 represents the dielectric constant in vacuum (8.854×10^{-12} F/m), and E is the electric intensity in agricultural products (V/m). The electric intensity in agricultural products depends on operational parameters of RF systems, the dielectric properties and geometry of agricultural products.

Eq. (2) illustrates that the power absorbed in a dielectric material is linearly proportional to the frequency, the relative dielectric loss factor and the square of the electric intensity. When the loss factor is between 2 and 100, it is effective to heat material with dielectric heating technology. Large loss factor would result in small penetration depths, which cause only skin heating. On the other hand, small loss factor means that the material, such as air and deionized water, is transparent to the electromagnetic wave (Metaxas and Meredith, 1983; Orsat et al., 2001). Thus, dielectric properties are essential parameters when assessing the feasibility of RF heating.

When the heat loss is negligible, the power dissipated over a period of time is converted into thermal energy to raise the temperature of agricultural products, and this time rate of temperature increase is given by Nelson (1996):

$$\frac{\Delta T}{\Delta t} = \frac{P_V}{C_P \cdot \rho} = \frac{55.63 \times 10^{-12} \cdot f \cdot E^2 \cdot \varepsilon''}{C_P \cdot \rho} \tag{3}$$

where ΔT is the temperature increase (°C), Δt is the heating time (s), C_P is the specific heat (J/kg/°C), and ρ is the density of agricultural products (kg/m^3). The Eq. (3) shows that the heating rate of specific agricultural products is dependent on the frequency of electromagnetic fields, electric intensity, and dielectric loss factor in addition to thermal properties.

A free-running oscillator RF system widely used in the industry is described in Fig. 2. The target material placed between top and bottom electrodes is moved on a conveyor belt to simulate continuous processes, and acts as a capacitor to store electrical energy and a resistor to transfer electric energy to thermal energy. Moving the top electrode is used to change the electrode gap, and thus regulate RF heating rate. Fig. 3 shows a typical temperature-time history at the core and surface of "Red Delicious" apples when subjected to water preheating, RF heating, holding in a hot water

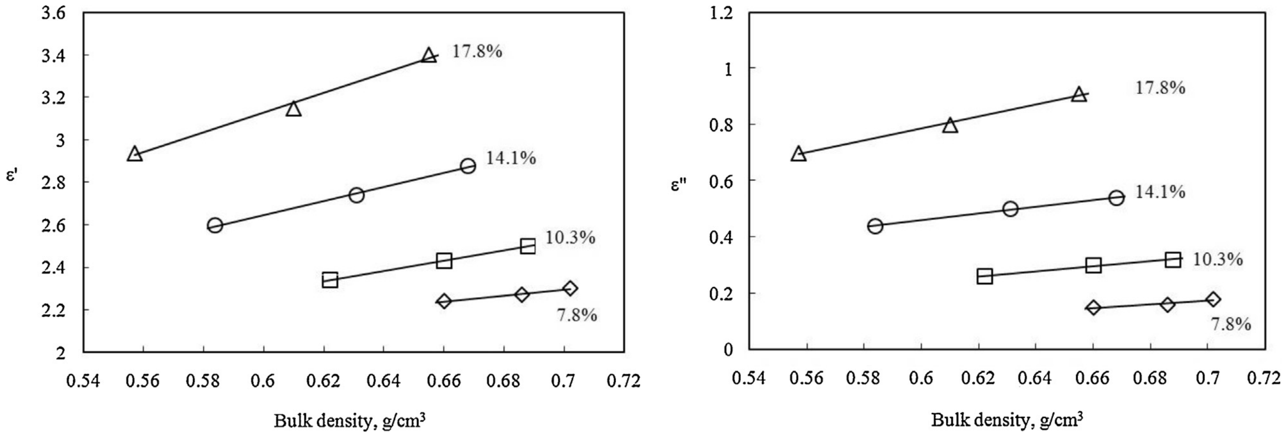

Fig. 1. Dielectric properties of shelled peanuts as a function of density at 6 GHz, 23 °C and indicated water contents (Nelson and Trabelsi, 2012).

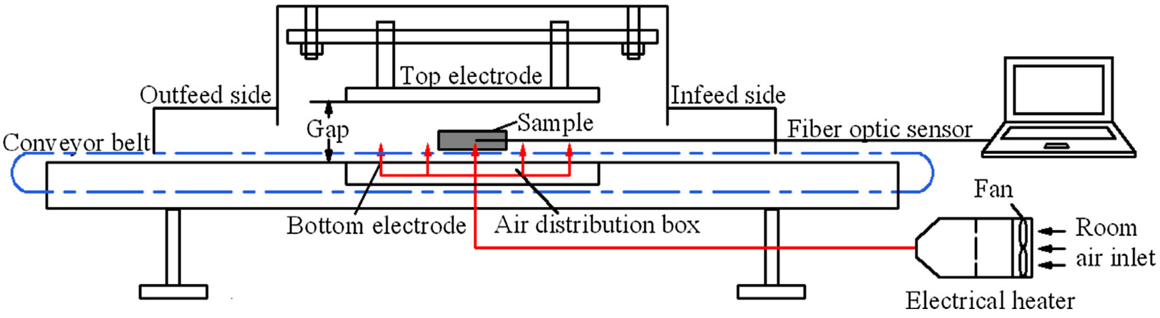

Fig. 2. Schematic view of the free-running oscillator 6 kW, 27.12 MHz RF system showing the plate electrodes, conveyor belt, the hot air system and the fiber optic sensors (Wang et al., 2010; Hou et al., 2014).

bath, and hydro-cooling. After 30 min water preheating at 45 °C, temperatures of apple core and surface reached 39 and 45 °C, respectively. The RF heating, in 45 °C tap water with 6 kW RF heating system, took only 1.25 min to bring apple core temperature of preheated apples from 39 to 48 °C. It can be concluded that the heating rate for RF heating was about 30 times greater than that heated in water bath.

2.1.3. Penetration depth

When electromagnetic waves strike an object, part of the waves is reflected, the remaining part penetrates into the material, and is gradually absorbed (Fig. 4). Theoretically, the penetration depth (d_p, m) of a material is defined as the depth below the surface of a material where the power density of a perpendicularly impinging, forward propagating electromagnetic wave has diminished by $1/e$ ($e = 1/2.7188 \approx 37\%$) from the surface value (Risman, 1991). The penetration depth is calculated as (von Hippel, 1954):

$$d_p = \frac{c}{2\sqrt{2}\pi f\left[\varepsilon'\left(\sqrt{1+(\varepsilon''/\varepsilon')^2}-1\right)\right]^{1/2}} \tag{4}$$

where c is the speed of light in free space (3×10^8 m/s).

Based on Eq. (4), the penetration depth of a material is inversely proportional to the frequency as the dielectric properties are fixed. The penetration depth of RF heating is deeper than that of microwave treatments because of its longer wavelength, which can be observed in Table 1. For agricultural products with high moisture contents, the dielectric constant and the loss factor are relatively high, resulting in small penetration depth. For dry products, the penetration depth is large, providing potential to treat large thickness of the products in RF systems.

2.2. Differential heating at RF range

Differential heating (or selective heating) is a main advantage of RF heating as compared to the conventional heating for disinfestations. In Eqs. (2) and (3), when the applied frequency and electric fields are the same both for the pests and the host products, the heat produced in the insects and the host products might be different due to different loss factor, resulting in the different final temperatures of the insects and the host products after the same period of RF heating (Huang et al., 2015a).

Fig. 5 shows the dielectric constant ε' and loss factor ε'' of hard red winter wheat and adult rice weevils for frequency range from 50 kHz to 12 GHz. The potential differential heating between pests and host wheat could exist due to a big difference of dielectric loss factor between pests and host wheat in the frequency range of 10–300 MHz. Therefore, 27.12 MHz would be the best frequency for disinfestations using RF energy.

When adults of flour beetle in wheat using RF treatment at 39 MHz requires grain temperatures of 41 °C for complete mortality (Nelson and Kantack, 1966). While adults of the same species are treated in wheat at 2.45 GHz, grain temperatures above 57 °C are required for the same insect mortality (Baker et al., 1956). It seems that the energy absorption by insects is larger at 39 MHz than that obtained by wheat, resulting in the higher temperature of pests. Additionally, the temperature of insects is 14.3 ± 1.1 °C higher after 4 min of RF heating at 27 MHz than that of the walnut kernels (Fig. 6). The heating rate for the insect slurry is 1.4–1.5 times faster than for walnut kernels, confirming that the insects are indeed preferentially heated in walnuts at 27 MHz (Wang et al., 2003a).

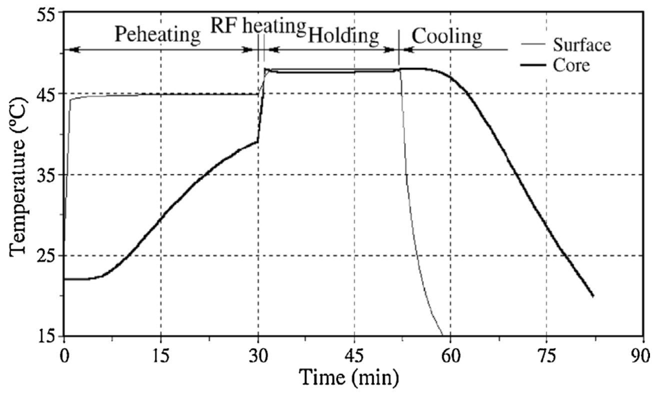

Fig. 3. Typical time-temperature history for surface and core of "Red Delicious" apples when subjected to water preheating, RF heating for 1.25 min, holding in a hot water bath for 20 min, and 30 min hydro-cooling (Wang et al., 2006).

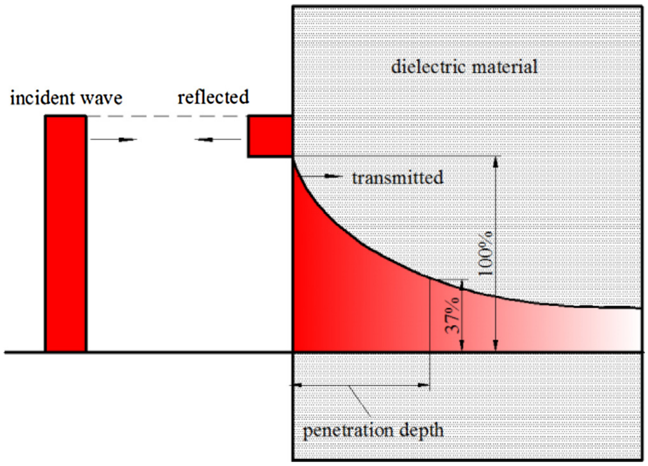

Fig. 4. Power flow when an electromagnetic wave strikes a dielectric material with high loss factor (Laborelec 2011).

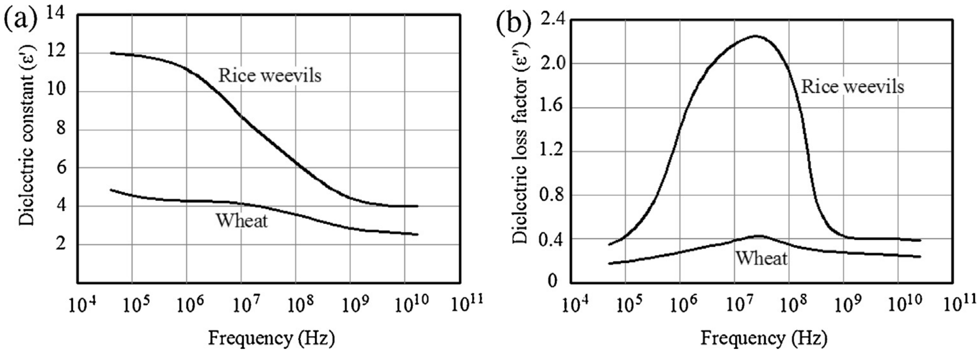

Fig. 5. Frequency dependence of (a) dielectric constant and (b) dielectric loss factor of adult rice weevils and hard red winter with 10.6% moisture content at 24 °C (Nelson and Charity, 1972).

Table 2 lists the dielectric properties of target insects in agricultural products at 27.12 and 915 MHz. The loss factor of pests is higher than that of the host agricultural products, especially the dry products (Table 1). Therefore, the RF treatments hold potential to heat the pests to lethal temperature but the agricultural products to the relatively low temperature, reducing or eliminating adverse effects of heating on agricultural product quality (Shresth and Baik, 2013; Wang et al., 2013).

2.3. Heating uniformity

Many factors are included in the design of RF heating systems, such as the voltage of the top electrode, electrode shape, and power output, shape, dielectric, thermal and dielectric properties of the samples, and position of the samples in the RF units, which may influence temperature distributions in RF treated agricultural products (Fu, 2004; Marra et al., 2009; Tiwari et al., 2011a). Heating uniformity index (λ) is commonly used for evaluating RF heating uniformity under different conditions. It is defined as the ratio of the rise in standard deviation of sample temperature to the rise in average sample temperature during treatment, and can be calculated by the following equation (Wang et al., 2008):

$$\lambda = \frac{\sqrt{\sigma^2 - \sigma_0^2}}{\mu - \mu_0} \quad (5)$$

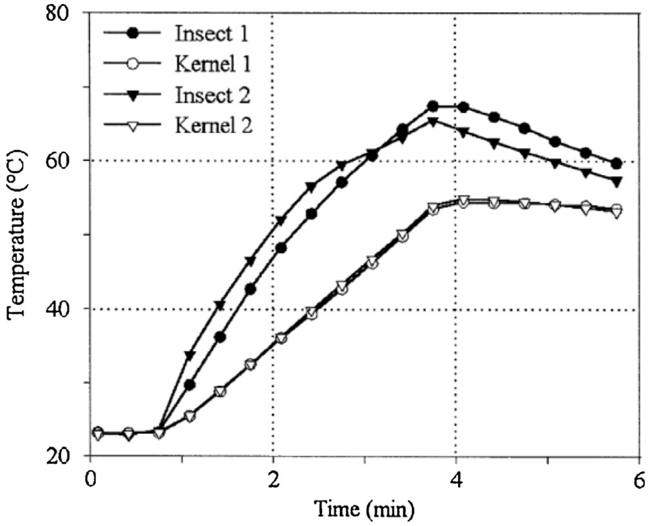

Fig. 6. Typical temperature profiles of walnut kernels and codling moth slurry when subjected to 27 MHz RF heating (Wang et al., 2003a).

where μ_0 and μ are initial and final mean temperatures (°C) of agricultural products, σ_0 and σ are initial and final standard deviations (°C) of agricultural product temperatures over treatment time, respectively. The smaller λ values result in the better heating uniformity. In an ideal condition, λ is equal to 0, which indicates the sample temperature at every point is the same over the volume.

Many studies confirm the non-uniform RF heating in various agricultural products. Fig. 7 shows the temperature profiles (top view) of treated coffee beans after 4.6 min RF heating at a fixed gap of 14 cm and an initial temperature of 24 °C. The temperatures in the corners and edges of container are higher than those in the center (Pan et al., 2012). Fig. 8 shows temperature distributions in apples after water preheating, RF heating, holding and cooling. By combining preheating in hot water (Fig. 8a) and core-focused RF heating, a fairly uniform temperature (47.3 ± 0.7 °C) is achieved in apples (Fig. 8b). Holding RF heated apples in hot water at 48 °C for 10 min further reduces the temperature gradient and improves heating uniformity (Fig. 8c). The mean temperature over the apple horizontal cross section is 47.1 ± 1.0 and 47.3 ± 0.7 °C before and after holding, respectively. Therefore, water preheating of apples is useful in reducing RF heating time and improving the RF heating uniformity in fresh fruit (Tiwari et al., 2008; Sosa-Morales et al., 2009b).

3. Computer simulations to improve RF heating uniformity

Heating non-uniformity is one of the major obstacles for RF technology to be commercially applicable. Several interacting factors, as mentioned above, influence heating uniformity during RF heating. Experimental methods to adjust these parameters to improve the heating uniformity are time consuming, costly, and often provide limited information. In contrast, computer simulation can serve as an effective tool for rapid, cheap, and flexible analysis, and provide an optimal process to achieve the required heating uniformity without conducting the long and costly experiments (Marshall and Metaxas, 1998).

3.1. Simulation methods

Commercially available finite element based software includes COMSOL, FEMLAB, HFSS, QW3D, and TLM-FOOD HEATING (Yang et al., 2003; Chan et al., 2004; Marra et al., 2007; Dev et al., 2012). COMSOL program has been widely used to simulate the RF heating characteristics since it can solve the electromagnetic and heat transfer equations simultaneously (Jiao et al., 2014; Uyar et al., 2015). In each simulation, model geometry is first constructed according to an appointed RF heating unit and a given sample. The parameters, namely top electrode voltage, dielectric properties, thermal

Table 2
Dielectric properties of target insects at room temperature.

Insect	Moisture (% w.b.)	27.12 MHz		915 MHz		Reference
		Dielectric constant	Loss factor	Dielectric constant	Loss factor	
Codling moth, *Cydia pomonella* (L.)	74	72	238	48	12	Wang et al. (2003b)
Cowpea weevil, *Callosobruchus maculatus*	71	54	185	30	15	Jiao et al. (2011)
Chestnut weevil, *Curculio elephas*	62	54	184	35	11	Guo et al. (2011)
Indianmeal moth, *Plodia interpunctella* (Hübner)	74	81	211	40	13	Wang et al. (2003b)
Lesser grain borer, *Rhyzopertha dominica* (F.)	53	–	–	54	23	Nelson et al. (1998)
Mediterranean fruit fly (*Ceratitis capitata*) egg	–	108	235	47	16	Wang et al. (2005a)
Mediterranean fruit fly (*Ceratitis capitata*) larvae	72–78	98	342	49	19	Wang et al. (2005a)
Melon fly, *Bactrocera cucurbitae*	–	105	379	59	20	Wang et al. (2005a)
Mexican fruit fly, *Anastrephaludens* (Loew)	74	90	344	49	18	Wang et al. (2003b)
Navel orange worm, *Amyeloistransitella* (Walker)	74	80	308	45	16	Wang et al. (2003b)
Oriental fruit fly, *Bactrocera dorsalis*	–	99	399	53	19	Wang et al. (2005a)
Red flour beetle, *Tribolium castaneum* (Herbst)	48	–	–	52	20	Nelson et al. (1998)
Rice weevil, *Sitophilus oryzae* (L.)	47	–	–	46	19	Nelson and Charity (1972)
Rusty grain beetles, *C. ferrugineus*	49	10	8	–	–	Shresth and Baik (2013)
Sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.)	54	–	–	60	25	Nelson et al. (1998)

conductivity, and heat transfer coefficient of the treated materials are inputted before simulation. Once the simulation solution is obtained, average temperature and heating uniformity index of the sample are calculated at the target point, surface and volume. Then, samples are placed at predestined positions in the RF unit, and heated at simulated treatment protocols to verify the model and the simulation solution. Different criteria and indexes, such as RF power density (Neophytou and Metaxas, 1998), temperature uniformity (Tiwari et al., 2011a), the average, maximum, and minimum temperatures (Romano and Marra, 2008), have been used to study, evaluate, and compare the RF power and heating uniformity in samples. Birla et al. (2008) report that simulation and experimental results are in good agreements since root mean square of temperature difference between the experimental and simulated temperature distributions is 0.98 °C for model fruits.

3.2. Applications of computer simulation

Starting from the mid 1990s, a number of papers have simulated the RF system, discussed the factors to influence the RF heating uniformity and the methods to improve the heating uniformity. The first attempt to model RF systems was reported by Neophytou and Metaxas (1996, 1998). These efforts are made to simulate the electrical field for RF heating systems and compare solutions from both electrostatic and wave equations. A further step towards improving the understanding of RF applicators by computer simulation is discussed by Chan et al. (2004) who establish a 3-D RF model to simulate an actual RF system using HFSS software. Then they evaluated their model by comparing simulated temperature map for a 1% Carboxy–Methyl–Cellulose (CMC) solution with an actual temperature map taken with an infrared thermal camera.

The simulation results in Tiwari et al. (2011a) show that cubic shapes are more suitable for RF heating since cubes provide a more even heating. Spherical shapes are the less favored due to the lowest RF heating uniformity among considered shapes. Their results further reveal that the heating uniformity in cuboid shaped samples, first decreases and then increases with the increase in sample size. The shape of samples also influences the temperature distribution, and the higher temperature in a cuboids sample is at the edges, while an ellipsoid has higher temperatures in the center parts. Tiwari et al. (2011b) analyze temperature values of wheat flour after 3 min RF heating with a fixed electrode gap of 155 mm. Temperature values of wheat flour in cuboid box after RF heating, are higher at the mid layers followed by top and bottom layers.

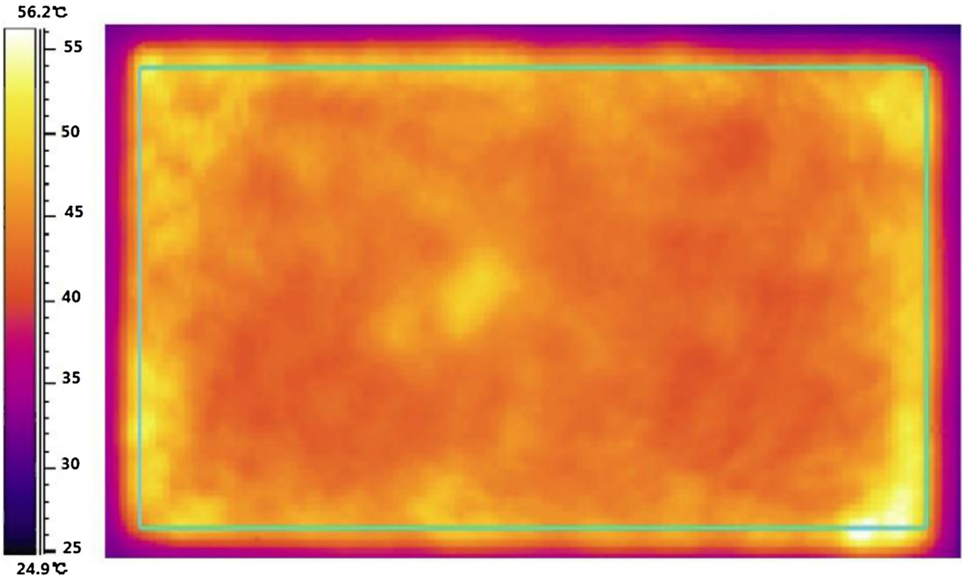

Fig. 7. Surface temperature profiles (top view) of coffee beans by infrared thermal imaging after RF heating (Pan et al., 2012).

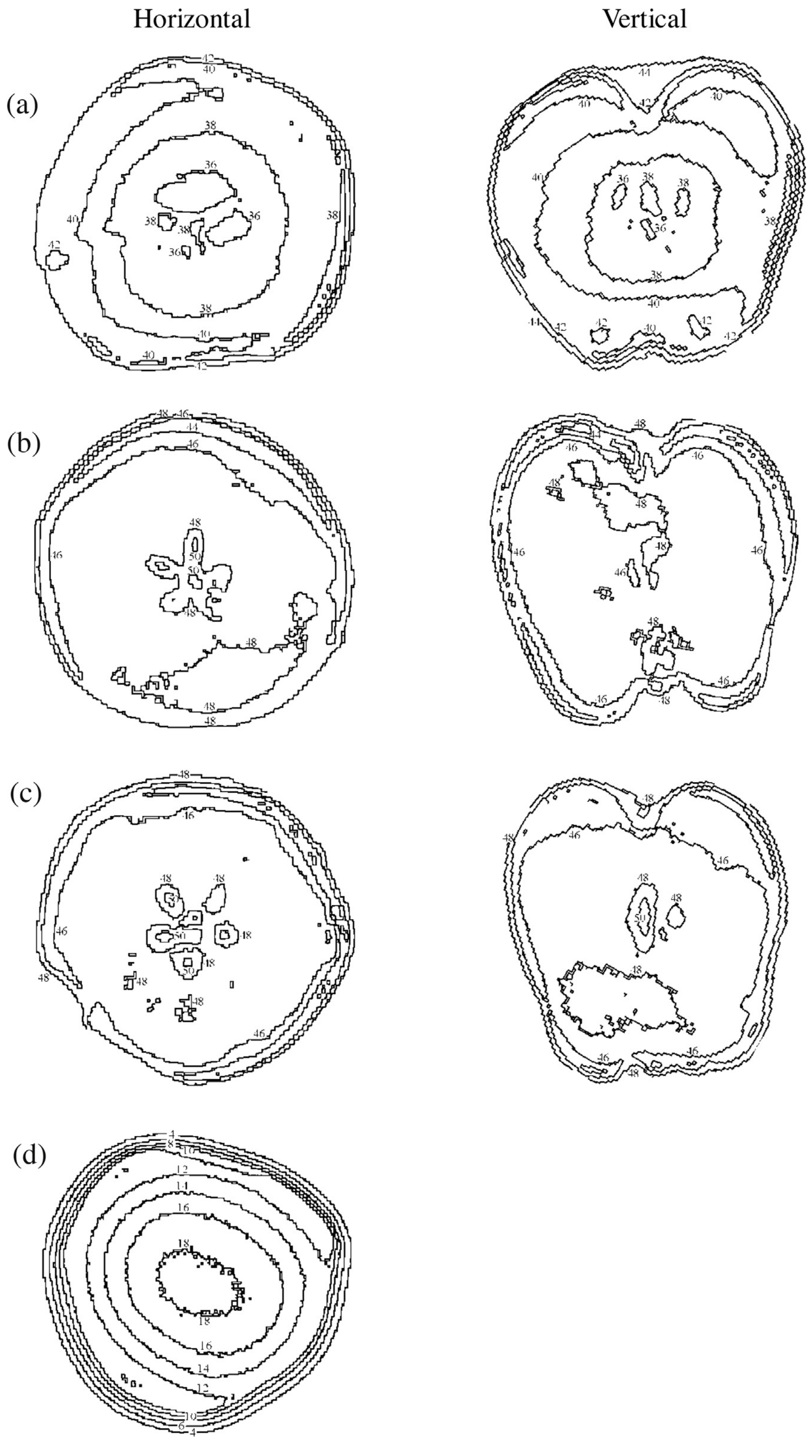

Fig. 8. Contour plot of temperature distribution obtained by thermal imaging over horizontal and vertical apple cross sections after (a) water preheating at 45 °C for 30 min, (b) RF heating from 45 to 48 °C, (c) holding 10 min at 48 °C water, and (d) hydro-cooling for 30 min (Wang et al., 2006).

Corners and edges are more heated than centers in each layer (Zhu et al., 2014; Wang et al., 2015). The similar results are found in raisins (Alfaifi et al., 2014) and soybeans (Huang et al., 2015c). Sensitivity analysis shows that the heating uniformity is most affected by the density of the samples followed by the top electrode voltage, the dielectric properties, the thermal conductivity and the heat transfer coefficient, a particular top electrode bending position and angle (Tiwari et al., 2011a,b; Alfaifi et al., 2014; Huang et al., 2015c).

After understanding the factors which influence the heating uniformity, it is necessary to find some methods to improve heating uniformity. A finite element software FEMLAB is used by

Birla et al. (2008) to develop a simulation model validated by a model fruit made from 1% gellan gel and study the effect of dielectric properties on the RF heating uniformity. They report that immersing the model fruit in water, movement, and rotation of the fruit help to improve the RF heating uniformity. Both simulation and experimental results demonstrated that using surrounding materials with similar dielectric constant could significantly improve the RF heating uniformity in target agricultural products (Birla et al., 2008; Alfaifi et al., 2014; Huang et al., 2015c).

All those studies show that in addition to the shape of sample, the heating uniformity is affected by the density, the dielectric properties, the orientation, the size of the samples, the heat transfer coefficient of surroundings, the RF output power, the thermal conductivity, the top electrode voltage, and a particular top electrode bending position and angle. The studies also show that immersing the fruit in water, movement, and rotation of the fruit help to improve the RF heating uniformity. Those simulation results could be applied to optimize the design parameters of RF systems.

4. RF treatment protocol developments

RF treatments are proposed as one of the alternative physical methods for the disinfestation of fresh fruits and dry products. When developing effective treatment protocols, it is essential to know the thermotolerant characteristics of both the target insects and products over a relatively wide range of time-temperature combinations. The positions and shapes of quality and insect thermotolerant curves are product and insect-dependent (Fig. 9). The overlap between the area below the quality curve and above the insect mortality curve identifies a range of temperatures and exposure times for complete control of the target insects without damaging the product. Developing a treatment protocol is often using small- or pilot-scale RF heating systems to determine the optimum treatment parameters. The actual development of a novel treatment protocol based on RF energy is discussed for fresh fruits and dry products in the following sections.

4.1. For fresh fruits

Early work with RF treatment for disinfestations dates back to the 1920s. However, the work was mostly stopped after 1950s, predominately for the lack of reliable methods of temperature measurement and the high operating costs of RF systems at that time. Later in 1990s, the research area of RF disinfestations was studied with attempts made to reduce the costs of RF systems and solve technical problems with advanced technologies, such as thermal imaging camera, fiber-optic temperature sensor system, dielectric properties measurement system, and computer simulation. In recent years, there has been an increased interest in RF disinfestations of agricultural products due to the fact that researchers are urgently seeking alternatives to fumigation, which has been banned due to environmental concerns.

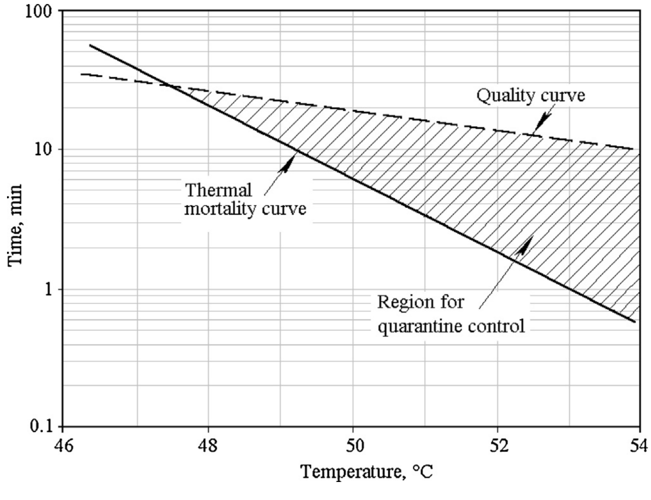

Fig. 9. Hypothetical commodity quality curve and insect mortality curve that define possible region for developing high-temperature-short-time quarantine thermal treatments (Tang et al., 2000).

In the early 2000s, Ikediala et al. (2002) developed a RF treatment to control codling moth larvae, *Cydia pomonella* (Lepidoptera: Tortricidae), in sweet cherries (*Prunus avium* L.). Their results reveal that cherries treated with RF energy in air suffer thermal damage for over-heating at the points of contact with container or with other fruit. When cherries are immersed in saline water, this problem is eliminated. About 100% mortality of all insect stages tested in cherries is obtained at 50 °C after RF heating in saline water and holding 5 min. Most quality parameters (firmness, soluble solids content, titratable acidity, color, visual fruit and stem damage, pitting, bruising, and rot) are better, or comparable to MeBr fumigated fruit. The same method is used by Hansen et al. (2006a) who use RF energy to control fifth-instar codling moth in apples (*Malus sylvestris* [L.] var. *domestica* [Borkh.] Mansf.). After 2 weeks storage, "Fuji" apples tolerate heat treatment better than "Delicious" and "Gala" apples. None of the treated fruits is acceptable after storage for 60 days. Monzon et al. (2006) also apply RF energy to control fifth-instar codling moth in 'Bing' sweet cherry while quality of the RF treated cherries is only acceptable when fruit are stored to simulate air shipment. Monzon et al. (2007) develop a RF treatment to control Mexican fruit fly larvae *Anastrephaludens (Loew)* in 'Fuyu persimmon' fruit (*Diospyros kaki* L.). They evaluate the quality of persimmons after RF heating in salt solution to 48, 50, or 52 °C, holding for different times (0.5–18 min), hydrocooling, and ripening at 20 °C for 12 d. These treatments have no significantly negative effects on quality parameters of persimmons except for fruit skin color.

Hansen et al. (2005) also conduct a water-preheating and RF heating treatment to control codling moth in 'Bing' sweet cherries. Heat treatment protocols include preheating the cherries in 38 °C water bath for 6 min, followed by RF heating to achieve four treatment temperatures (50, 51.6, 53.3, and 54.4 °C), holding for different time, and then cooling at 0 °C for 8 min. No larvae survive after 24 h of treatment but cherry quality is unacceptable. Moreover, a similar RF treatment is conducted to control insects in persimmons (Tiwari et al., 2008), and mangoes (Sosa-Morales et al., 2009b) with good product quality.

Except for immersing fruit in water, Hansen et al. (2006b) try to improve heating uniformity by a pulse mode during RF treatment to control fifth-instars of codling moth in apples. Apples are immersed in water baths to 27.12 MHz RF energy at 12 kW with a pulse mode of 30s-on/30s-off for 29 min and 50 min holding in hot water, which cause 100% mortality of the larvae. All RF treated apples are also damaged by evaluating fruit quality after held at 25 °C for 1 week. That is, the thermal requirements to control codling moth larvae may exceed the injury threshold of the apples.

On the basis of immersing the fruit in water, Birla et al. (2004) design an interesting fruit-mover, which is capable of continuously rotating a fresh fruit with the purpose of improving RF heating uniformity. Further researches verify that rotation and movement of fruit improve the RF heating uniformity of oranges and fresh apples (Birla et al., 2005; Wang et al., 2006). Birla et al. (2005) develop a treatment that raised oranges temperature from 19 to 48 °C by RF heating in saline water to control Mediterranean fruit fly in oranges using the fruit mover and holding for 15 min in 48 °C hot water. The results indicate that the treatment could meet the quarantine security but a significant change in volatile flavor profiles is observed even there is no significant difference in the other quality parameters after 10 d of 4 °C storage. Wang et al. (2006) explore the application of RF treatments to control fifth-instar codling moth in fresh apples in hot water at 45 °C for 30 min, followed by RF heating to 48 °C in the fruit mover, and hot water bath holding at 48 °C for 15 min. The treatment is the most practical and effective method both for insect control and apple quality. These results suggest that water assisted RF heat treatments may provide the potential for disinfestations of fresh fruits with acceptable product quality.

4.2. For dry products

Although dry products are quite different from the fresh fruits, it is also important to improve the heating uniformity of agricultural products before developing an effective RF treatment. Heating uniformity index of almonds, beans, and walnuts is greatly reduced by using forced hot air, movement, and mixing of the samples during RF heating (Wang et al., 2007a, 2010; Gao et al., 2010; Jiao et al., 2012). The same methods are used to improve heating uniformity of chestnuts during RF heating (Hou et al., 2014, 2015). After achieving satisfactory heating uniformity, the protocol usually consists of RF heating to a target temperature, holding for pre-determined time with hot air, and cooling by forced room air in a single layer. Samples quality is not affected by the RF treatments because quality parameters of treated dry samples are not significantly different from those of controls (Gao et al., 2010; Pan et al., 2012; Hou et al., 2014). Lagunas-Solar et al. (2007) evaluate the efficacy of RF treatments by laboratory infested dried storage rough rice containing all life cycles of lesser grain borers and grain moths. Low-thermal load RF energy at 385 kHz processing at 55–60 °C bulk rice temperatures for short times (5 min) results in >99% control of all biological stages of grain moths. When higher thermal load RF energy at 20.3 MHz is applied using 50 °C for grain moths with a 2-h holding or 60 °C for grain borers with 1-h holding, the treatments provide 100% control of target insects. Under these processing conditions, no moisture losses or changes in milling quality are observed. Furthermore, Mirhoseini et al. (2009) investigate the possible pest control using RF energy and find that the required holding time for achieving 100% mortality of flour beetle in flour and rice weevil in rice are 45, 35, and 15 s at 13.56, 27.12, and 40.68 MHz, respectively. Rice weevil mortality after a 105 s exposure to 57 °C is 100% and no significant difference of samples quality is observed. Table 3 summarizes the related studies on postharvest control of pests using RF energy.

Generally, most of these RF treatment protocols include preheating in hot water for fresh fruits and using forced hot air, movement, and mixing for dry products to improve the heating uniformity. Due to narrow margin between insect control and quality requirements, the RF treatment protocols have not been scaled up for fresh fruits up to now. But due to significantly improved heating uniformity and insensitive to quality changes for dry products, the RF treatment protocols have been applied in industrial scales and hold potential for commercial applications.

4.3. Validations and scale-up applications

RF heating has been successfully applied for drying, baking and thawing of frozen meat (Piyasena et al., 2003) and in meat processing (Marra et al., 2009). However, its commercial use in disinfestations for postharvest agricultural products is rather limited.

Researchers from Washington State University, Pullman, WA, USA together with colleagues in USDA-ARS have performed the extensive investigations on validations and scale-up applications for disinfesting walnuts. First, they determine the thermal death kinetic models of codling moth, navel orangeworm, *Amyelois transitella* (Walker), and Indianmeal moth, *Plodia interpunctella* (Hübner), which are commonly found in harvested walnuts (Wang et al., 2002a; Johnson et al., 2003, 2004). The minimum temperature–time combinations that result in 100% mortality for insects show that the fifth-instar navel orangeworm is the most thermotolerant insect in walnuts and used as target insect for RF treatment validation studies. Then, the infested walnuts are heated to 55 °C by a 27.12 MHz pilot scale RF system and holding in hot air at least 5 min, resulting in 100% mortality of the fifth-instar navel orange worm. Furthermore, the rancidity, sensory qualities and

Table 3
Published Radio Frequency treatment protocols for control various insects in agricultural products.

Freq. (MHz)	Insects	Commodities	Lethal temperature + exposure time	Reference
12	Honey bee	No	51.4 °C + 2 min	Headlee and Burdette (1929)
6.25	Beetle (eggs and adults)	Soil, plants	50 °C	Headlee and Jobbins (1936)
11	Insects (larvae, pupae, and adults)	Flour	50 °C + 4 min or 60 °C + 30 s	Webber et al. (1946)
39	Stored insects	Store grains	41 °C + a few seconds	Nelson and Kantack (1966)
39	Yellow mealworm (eggs)	No	Exposure time (64 s) at 4 KV	Rai et al. (1972)
40	Pecan weevil	Pecan	80 °C (6.1% MC) and 53 °C (2.6% MC)	Nelson and Payne (1982)
27	Codling moth (*Cydia pomonella* (L.))	Walnuts (*Juglans regia* L.)	53 °C + 3 min	Wang et al. (2001a)
27	Navel orangeworm (*Amyelois transitella*)	Walnuts (*Juglans regia* L.)	55 °C + 5 min	Wang et al. (2002b)
27	Navel orangeworm (*Amyelois transitella*)	Walnuts (*Juglans regia* L.)	60 °C + 5 min	Wang et al. (2007b)
27	Lesser grain borers (*Rhyzopertha dominica*)	Rough rice	60 °C + 30 min	Lagunas-Solar et al. (2007)
27	Mexican fruit fly (*Anastrepha ludens*)	Mangoes (*Mangifera indica cv.* Tommy Atkins)	48 °C + 6 min	Sosa-Morales et al. (2009b)
27	Cowpea weevil (*Callosobruchus maculatus* F.)	Legumes	60 °C + 5 min	Wang et al. (2010)
27	Cowpea weevil (*Callosobruchus maculatus* F.)	Dried legumes	60 °C + 10 min	Johnson et al. (2010)
27	Cowpea weevil (*Callosobruchus maculatus* F.)	Lentils (*Lens culinaris*)	60 °C + 10 min	Jiao et al. (2012)
27	Coffee berry borer (*Hypothenemus hampei*)	Kona coffee bean (*Coffea arabica*)	48 °C + 10 min	Pan et al. (2012)
27	Rusty grain beetle (*Cryptolestes ferrungineus* S.)	Wheat	80 °C	Shresth and Baik (2013)
27	Chestnut weevil (*Curculio elephas*)	Chestnuts (*Castanea mollissima*)	55 °C + 5 min	Hou et al. (2014)

shell characteristics of treated walnuts are not affected by the RF treatment. Finally, Wang et al. (2007a,b) use two 27 MHz, 25 kW industrial RF systems to simulate the industrial processing and evaluate the energy efficiency and cost of RF treatment. An electrode gap (28.0 cm) is chosen based on the electric current and heating time, conveyor speed is set to 57 m/h, and one mixing of walnuts between continuous RF treatments. After RF treatments, average and minimum walnut temperatures are 60 °C and 52 °C, respectively. Then the walnuts are held for 5 min by hot air at 60 °C, resulting in complete control of target insects without negative effects on walnut quality after stored 20 days at 35 °C for simulating 2-year storage under commercial conditions at 4 °C. The average heating efficiency is estimated to be 79.5% when treating walnuts at 1561.7 kg/h. The overall unit electrical consumption for the processed treatments is US$ 0.0027/kg, which is comparable to this unit fumigation cost (US$ 0.0020–0.0027/kg) for commercial in-shell walnut treatments (Wang et al., 2007a,b).

Recently, Jiao et al. (2012) use a 27.12 MHz, 6 kW RF unit with a forced hot air system to conduct industrial scale-up studies on disinfesting lentils. Based on the electric current and heating time, an electrode gap is set at 14.0 cm with a conveyor speed of 7.5 m/h. To accomplish 100% cowpea weevil mortality, a RF treatment protocol is developed with forced hot air to heat lentils to 60 °C for 10 min, followed by forced ambient air cooling for 20 min. Their results show that the quality (moisture content, color, and germination) of lentils are acceptable, the average heating efficiency of the RF system is 76.5% with a throughput of 208.7 kg/h. These scale-up applications indicate that an industrial-scale RF process provides a promising physical treatment as an alternative to chemical fumigation.

5. Conclusions and suggestions for future research

A lot of literature is available on RF heating applications for postharvest insect control in agricultural products. More successful RF treatments are developed in dry products than fresh fruits, since quality of fresh fruits is sensitive to temperature variations, resulting in very limited operational region for RF treatments. Most of those studies on dry products are conducted on laboratory scale RF systems. With applications of the computer simulation and developments of fundamental data on dielectric properties, and thermotolerant characteristics of both insects and products, the RF treatment protocols have only been scaled up for industrial applications of disinfesting walnuts and lentils. There is still a need for further studies to bridge the gap between laboratory research and commercial applications. Industrial implementations of RF heating technologies depend on initial investments, maintenance costs, processing electricity consumptions, and economic incomes from the value-added products. At present, the feasible applications of novel RF heating methods are mainly limited to textile and bakery products drying. Future research on RF heating technology for disinfesting agricultural products should focus on the following areas:

1) Sensitivity analyses in the computer simulation of RF heating show that the voltage of the top electrode is an important factor to influence the electromagnetic field intensity and final temperature distributions in samples. The local voltages away from the feed strip are higher than those near the feed strip. The non-uniform voltage distribution should be taken into account for computer simulation to improve the model prediction precision. Further studies could be conducted to improve the RF heating uniformity by appropriately locating the feed strip and inductance positions on the top electrode.
2) Not all agricultural products, especially heat-sensitive fresh produce, can tolerate the thermal conditions required to control insect pests. Systematic studies on thermotolerance of both target pests and products are required to determine the commercial viability of candidate treatments. Pretreatments can be used before or during the RF processing to expand the practical operation region. For example, controlled atmosphere could be used before RF treatments to reduce the thermotolerance of insects, moistening the product surface to reduce the thermotolerance of pathogens, and mild heat treatments at low temperatures as pretreatment to increase the food adaptation to heat. Future extensive research would be required for exploring different pretreatment steps to improve the effectiveness of the RF treatments.
3) Most agricultural products are not only infested by pests but also contaminated by pathogens or moulds after harvesting. The RF treatment protocols developed for disinfesting agricultural products could be expanded to pasteurization processes based on systematic studies on relative thermotolerance of insects, pathogens, moulds and host products. It is important to integrate these disinfestation, pasteurization and drying purposes together so as to develop a feasible and effective postharvest RF technology.
4) Validated computer simulation models could be further applied to improve the RF heating uniformity by using hot air surface heating, sample movement, mixing, placing the product in the middle of the electrodes, and using surrounding materials with similar dielectric constant to that of the product.
5) Energy efficiency and cost requirements are two important factors in developing a practical and effective RF process for controlling insects in agricultural products. If this technology can be economically integrated into the current processing system, it may have a great potential as a phytosanitary treatment for the agricultural processing industry. It is desirable to compare the unit energy requirements and other associated handling costs in addition to the capital, labor and depreciation costs between the RF process and other currently used treatment methods, such as chemical fumigation and the steam heating to achieve the same level of insect control.

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