COMPARATIVE STUDY OF

RADIO-FREQUENCY AND MICROWAVE HEATING FOR PHYTOSANITARY TREATMENT OF WOOD

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ORIGINAL

Comparative study of radio-frequency and microwave heating for phytosanitary treatment of wood

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Abstract Radio-frequency (RF) and microwave (MW) heating for phytosanitary treatment of green wood in compliance with international standards for phytosanitary measures no. 15 (ISPM-15) were evaluated and compared to assess treatment time, depth of electromagnetic wave (EMW) penetration and heating uniformity. White oak (*Quercus alba*) cants (48 cm long with cross-section dimensions ranging from 10 × 10 cm^2 to 25 × 25 cm^2) were heated in a 19 MHz RF or 2.45 GHz MW laboratory oven using an equivalent heating power (3.4 kW). In each specimen, temperature was measured at different depths (distance from the upper face). Specimens were held in the treatment chamber for 2 min after the target temperature of 60 °C was achieved through the profile of the specimen to ensure compliance with the ISPM-15 treatment schedule. Thermal image analyses of treated specimens as well as theoretical depth of penetration for dielectric energy were explored. Wood specimens were also heated using RF at high power (9–11 kW) and results were compared with RF heating at 3.4 kW. For wood with cross-section dimensions of 10 × 10 cm^2 to 15 × 15 cm^2, heating rates for RF and MW were relatively similar. However, above 15 × 15 cm^2, RF heating was more than 40 % faster with greater heating uniformity than MW. The theoretical values derived for depth of penetration and thermal image analyses indicate that RF (19 MHz) penetrates wood more uniformly and is better suited than MW (2.45 GHz) for bulk volume treatments of wood.

Abbreviations

DH	Dielectric heating
d_p	Depth of EMW Penetration
EMF	Electro-magnetic field
EMW	Electro-magnetic wave
EPRF	Equivalent power radio frequency
HPRF	High power radio-frequency
ISPM	International standards for phytosanitary measures
MW	Micro-wave
RF	Radio-frequency
t_{60}	Treatment time when all temperature probes used in a DH trial recorded minimum 60 °C
WPM	Wood packaging materials

1 Introduction

Wood packaging material (WPM), for example, pallets, crates, and dunnage, make up nearly 6 % of the total global packaging consumption and is used worldwide in the shipment of 90 % of goods (FCEC 2012; Strutt et al. 2013). Every year over 1.5 billion pallets are produced worldwide, using approximately 60 million cubic meters of wood (FCEC 2012).

WPM is frequently made of lower-grade raw wood that may not have undergone sufficient levels of processing to reduce pest risk, and is identified as a major pathway for

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the introduction and spread of quarantine pests (FAO 2011; Strutt et al. 2013). The number of wood-infesting pests that have become established beyond their native range has been increasing in recent decades with increasing global trade (Brockerhoff and Haack 2011).

In response to the phytosanitary threat from untreated WPM used in international shipping, the governing body of the International Plant Protection Convention (IPPC) approved ISPM (International Standards for Phytosanitary Measures) No. 15 in 2002, entitled "Regulation of wood packaging material in international trade." When ISPM-15 was adopted, only two phytosanitary treatments for WPM were permitted: methyl bromide fumigation and heat treatment using a conventional steam or dry kiln heat chamber. Conventional heat treatment requires heating the wood to 56 °C for at least 30 continuous minutes throughout the entire profile of the wood including its core, while fumigation with methyl bromide is performed at a prescribed concentration over time (CT) at a given temperature. Conventional heat-treatment (56 °C for 30 min) is time consuming (Henin et al. 2014), while methyl bromide is classified as an ozone depleting substance and as such is being phased out in compliance with the Montreal Protocol (UNEP 2000).

Dielectric heating (DH) was formally approved by the Commission on Phytosanitary Measures (CPM) of the IPPC in April, 2013 and is described in Annex 1 of ISPM-15 as the first accepted alternative treatment to methyl bromide and conventional heating (FAO 2013). Dielectric heating or dielectric loss heating is an electromechanical phenomenon in which heat is generated within materials due to dipolar molecular friction and forward–backward oscillation of dissociative ions when subjected to high frequency alternating fields, resulting in more rapid heating than conventional heat treatment (Jiao et al. 2015). Radio-frequency (RF) and microwave (MW) are electromagnetic waves and represent two different forms of dielectric heating. The major difference between RF and MW is the frequency range used. In RF heating, the applied electromagnetic radiation frequency is generally between 3 to 300 MHz, while in MW heating the frequency ranges from 300 to 300 GHz (Jiao et al. 2015).

Dielectric heating is capable of instant application and the heating efficiency of this method is much higher than conventional heat transfer methods (Jiao 2012). DH is mainly applied to dielectric materials such as wood that have poor electrical and thermal conduction properties, as evidenced by the slow heat-transfer observed with conventional heating. DH systems are reported to heat materials with an efficiency of 50–70 % in comparison to 10 % for conventional ovens (Mermelstein 1997). The treatment efficiency of DH relative to conventional heating is also reflected in the treatment schedule of Annex 1 of ISPM-15, which requires 60 °C for 1 min throughout the profile of the wood compared to 56 °C for 30 min at the core for conventional treatment (FAO 2013). In a heterogeneous material like wood, the component with the highest dielectric loss factor (water in wood and inside a pest organism) will generally absorb a greater share of the energy. As reported in Wang et al. (2003) and Wang et al. (2011) who studied pest larvae and their host-fruits, a large difference between the loss factor of insect larvae and their substrate may induce differential heating. This suggests that, in some circumstances, there may be preferential heating of the insects contained in wood using DH, depending on wood MC and the type of DH (i.e., RF or MW). However, Andreuccetti et al. (1994) showed that preferential heating of larvae in wood only occurs in the case of dry wood (i.e., with a moisture content much lower than the fiber saturation point). According to a life cycle analysis, the efficiency of DH systems may reduce energy consumption during treatment and thus reduce the potential environmental impact compared with conventional heating or methyl bromide treatment (Anil 2010). Given these advantages, DH could develop into a sustainable alternative to methyl bromide fumigation and conventional heat treatment.

There are two general methods of exposing materials to DH: batch (also referred to as bulk volume or chamber processing) and continuous (also referred to as conveyor or tunnel processing). Batch treatment equipment can be either permanent or portable, and allows a large quantity of WPM to be treated at one time. In contrast, continuous process equipment uses a conveyor system that moves the WPM through the treatment chamber at a set speed. This latter approach may be preferred for treating smaller wood components prior to pallet/crate construction or for treating fully constructed pallets or crates (FAO 2014). The main factors that affect selection of batch vs. tunnel methods are penetration depth of the applied electromagnetic waves and needs of the treatment provider, including the volume of material to be treated, and whether the facility would be used only for WPM treatment or for a variety of applications such as vacuum drying.

Overall, MW heating (2.45 GHz) is a more familiar process and may be viewed as a more efficient method for treating smaller wood components (Hassan et al. 2015). Alternately, RF heating may have a distinct advantage in treating larger bulk material. High frequencies are associated with shorter wavelength; radio-frequency waves have a longer penetration depth than do microwaves due to the lower electromagnetic frequency range (Koubaa et al. 2008; Mehdizadeh 2010). The source and system design for MW and RF heating are also different (Fig. 1). In MW heating, electromagnetic waves are transmitted by single or multiple waveguides and the electromagnetic field (EMF) enters the product from all directions depending on the specific chamber design. In the case of RF heating, the

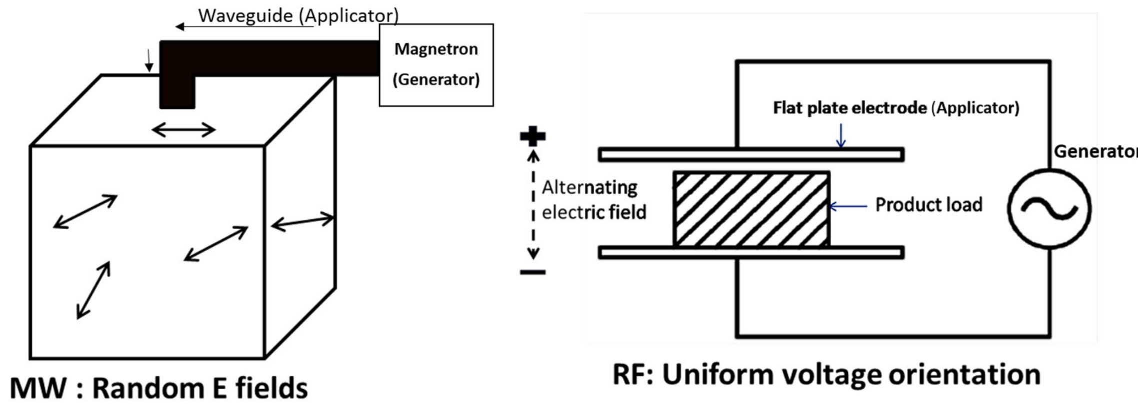

Fig. 1 Configuration and field distribution of RF and MW heating systems

electromagnetic field is commonly generated between a pair of electrode plates, which results in a singular or unidirectional EMF distribution. Furthermore, heating system efficiency is reported to be higher for RF (70 %) compared to that of MW (50 %) (Laborelec 2011; Jiao 2012). RF application systems are also generally simpler to construct than MW systems and considered more suitable for large industrial applications (Hassan et al. 2015).

Compared to MW, there are limited data available to evaluate the benefits of adopting RF for phytosanitary treatment of wood, in particular where greater penetration depth and heating uniformity are needed (Lazarescu et al. 2010; Uzunovic et al. 2012). To date, no comparative study has been published on these two forms of dielectric heating for phytosanitary treatment of wood packaging materials.

It was chosen to conduct this comparison using bulk volume or chamber processing because this method is more likely to be adopted for phytosanitary treatment when using RF technology as a pre-treatment of raw materials used for construction of WPM under ISPM-15 (Ben Wilson, PSC, Inc., personal communication). This study examined RF and MW heating of green white oak wood in compliance with ISPM-15 under bulk treatment conditions (stacks of wood/batch processing) to assess: (1) treatment time required to achieve the target temperature of 60 °C through the wood profile; (2) experimental and theoretical electromagnetic wave (EMW) penetration depths; and (3) heating uniformity through the profile of the wood specimens.

2 Materials and methods

2.1 Experimental material

Oak was chosen for this study because it is the most commonly used group of hardwood species by the wood pallet industry (Bush and Araman 2009) and represents a worst case scenario in terms of material density. Wood specimens were prepared from freshly processed white oak (*Quercus alba*) as axially matched sets with several discrete dimensional treatment classes for MW and RF heating trials. The experimental materials were typical of sawmill processed hardwoods sold and extensively utilized by US pallet manufacturers for construction of international/domestic shipping pallets (Brad Gething, National Wood Pallet and Container Association, Pers. Comm 2014). The full dimensions as oversized sawn log cants were rough cut as heartwood sections with standardized nominal cross-sections of 10×10, 13×13, 15×15, 20×20 and 25×25 cm^2 and subsequently processed to actual test cross-section sizes of 8.9×8.9, 11.4×11.4, 14×14, 19.1×19.1, and 24.1×24.1 cm^2, respectively. All test specimens were then cut to a 48 cm standard length with ± 0.3 cm tolerance. To minimize the potential bias due to natural variability of wood physical properties (moisture content and density) that affect dielectric heating regardless of treatment method (RF or MW), each full-length log was cut into seven equal sections. Each section was then randomly assigned to a treatment. The limitation of this approach was that only two replicates of each wood size were available per treatment.

Specimens were double wrapped in polyethylene bags and stored at −4 °C to maintain the original green condition (above the fiber saturation point, i.e., more than 30 % wood moisture content). Prior to the trials, specimens were conditioned for 72 h in an environmental chamber at 25 °C so that all specimens started at a constant ambient temperature. The chosen conditioning temperature corresponds to the complex dielectric properties used for empirical computation of depth of penetration of electro-magnetic waves (EMW) (James 1975).

Specimens were drilled at mid-length and mid-width at pre-fixed depths from the top surface for insertion of fiber optic probes to monitor the core temperature profile (Table 1; Fig. 2a). Temperatures inside the wood at varying depths were continuously monitored and recorded every 2 s using Neoptix fiber optic sensors with a multi-channel data acquisition system (Model T1S-02-W15-PR-15). These temperature sensors were factory calibrated and re-checked before experimentation using a boiling water bath and a standard laboratory thermometer. Data logging was optimized for the automated multiple channel Neoptix sensor data collection system using NeoLinktm software. The fiber optic temperature sensors do not interact with electromagnetic fields, have a short response time, and can range up to several meters in length without affecting accuracy (Guan et al. 2015).

2.2 Dielectric heating process

Wood specimens were heated in a RF oven (PSC, Inc., Model No. PP15L, 15 kW maximum operational power, 19 MHz oscillator frequency type of dielectric oven) or a MW oven (Microwave Research Applications Inc., Model BP-211, 3.4 kW maximum power, 2.45 GHz frequency with a multidirectional waveguide oven applicator design) until all the probes recorded the target temperature of 60 °C (t_{60}).

The BP-211 with waveguide is optimally designed as a research MW oven to achieve a distribution of 99 % of EMF power within the heating chamber. In contrast, RF ovens with the typical arrangement of parallel plate electrodes (paired active and ground) often generate a higher EMF intensity or uneven distribution across the electrode, which can be improved by incorporation of a secondary plate to assist with achieving a uniform field distribution (Mehdizadeh 2010). An improved electrode applicator arrangement was developed for the model PP15L RF oven based on dielectric energy with orthotropic absorption modeling and placed over the wood specimens to improve heating uniformity (Fig. 2b).

MW trials were run at full power (3.4 kW), while RF oven parameters were adjusted for each specimen tested to maintain the same or nearly equivalent operational power of 3.4 kW (Table 2). A single wood specimen of each size class was sacrificed to carefully calibrate the RF settings (plate ampere and corresponding kilo voltage, kV) to ensure the same oven capacitance level between increasingly larger specimens. This allowed for an adjustment in volumetric heat development while using the same maximum MW power.

For comparison purposes, a separate set of specimens was heated in the RF oven using the high power settings (HPRF, high power radio-frequency heating: 9.2–10.8 kW), which produced nearly three times more power than at 3.4 kW (EPRF, equivalent power radio-frequency heating: 3.3–3.4 kW). Due to the fixed power ceiling constraint of 3.4 kW, higher power trials could not be accomplished using the MW oven. There were two replicates for each specimen size and dielectric heating trial.

After all probes recorded the target temperature of 60 °C, the specimens were kept inside the oven for 2 min to ensure compliance with ISPM-15 (60 °C for 1 min). Within 2–6 min of reaching the target temperature of 60 °C, thermal images of all surfaces and cross-sections at mid-length were taken using a FLIR T-250 Thermacam. In the current experiment, "thickness" is defined as the thinnest cross-sectional dimension of specimens, whereas the distance between the top surface and a temperature recording point within an irradiated wood specimen is termed as "depth".

Specimens were weighed before and after treatment for overall moisture loss measurement due to dielectric heating. The specimens were then cross-cut near the temperature measurement points using a radial arm saw and processed for moisture content (MC) measurements as per ASTM-D4442 (2007).

2.3 Theoretical depth of EMW penetration

The penetration depth (d_p) of an EMW can be defined as the distance at which the intensity of an electromagnetic wave penetrating perpendicularly into a material is reduced by a factor 1/e (e, Naprian base, equal to 2.71828) of its

Table 1 Positions of inserted fiber optic probes for temperature measurements, where DSS = Distance from side surface (cm) and DTS = Distance from top surface (cm)

	10 × 10 cm^2		13 × 13 cm^2		15 × 15 cm^2		20 × 20 cm^2		25 × 25 cm^2	
	DSS	DTS	DSS	DTS	DSS	DTS	DSS	DTS	DSS	DTS
Probe 1	4.5	1.3	6	2.5	7	2.5	9.5	2.5	12	2.5
Probe 2	4.5	2.5	6	3.8	7	3.8	9.5	3.8	12	4.4
Probe 3	**4.5**	**4.4**	**6**	**5.7**	7	5.1	9.5	5.7	12	6.4
Probe 4	4.5	5.7	6	7.0	**7**	**7.0**	9.5	7.6	12	8.2
Probe 5		X		X	7	8.2	9.5	**9.5**	12	10.2
Probe 6		X		X		X		12.1	12	**12.1**
Probe 7		X		X		X		X	12	14.0

Bold values indicate Center (c) position as measured heating mid-depth of the specimens

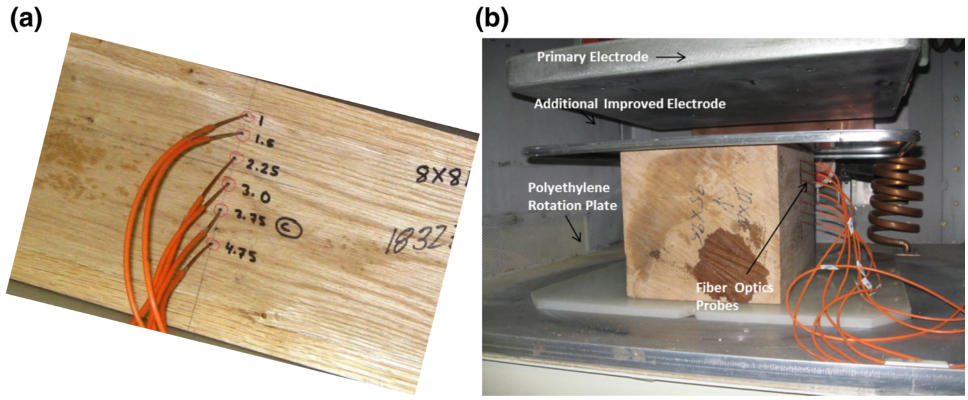

Fig. 2 **a** Positioning of fiber optic probes in 20 × 20 cm^2 specimen; **b** RF Heating trial for 25 × 25 cm^2 wood specimen

Table 2 RF oven operational parameters with computed oven power used for heating wood specimens of different dimensions

Wood nominal Cross-section (cm^2)	Thickness (cm)	Power (kW)	
		EPRF	HPRF
10 × 10	8.9	3.4	10.4
13 × 13	11.4	3.4	9.6
15 × 15	14	3.3	9.2
20 × 20	19.1	3.4	10.2
25 × 25	24.1	3.4	10.8

amplitude at the surface (Koubaa et al. 2008; Gao et al. 2012). In other words, it is the distance at which 63 % of the transmitted power has been dissipated into the material according to a heat absorption pattern that is dependent on the wave frequency.

Dielectric properties of the most interest are the dielectric constant ε′ and the dielectric loss factor ε″, which are the real and imaginary components, respectively. The loss factor or imaginary component (ε″) is the product of the loss tangent and the corresponding material dielectric constant. This inherent property strongly influences the observed energy absorption and specific attenuation and can be used to calculate the relative amount of electromagnetic energy that is converted into heat. The measurements of dielectric properties (ε′ and ε″) and the data set on the RF oven operating parameters (e.g., power density and frequency) can be used to define a theoretical penetration depth of the incident wave (Eq. 1) (Gao et al. 2012)

$$d_p = \frac{0.1592\{\lambda_\circ{}'(\varepsilon')^{0.5}\}}{\varepsilon''} \quad (1)$$

where $\lambda_\circ$ is the free space wavelength ($\lambda_\circ = c/f$, f is frequency (Hz), and c is the speed of light in free space (3×10^8 m/s).

The specific complex dielectric values for white oak used in this study exclusive to the electromagnetic frequency of the RF oven (19 MHz) and with respect to the moisture content of the heartwood material has not been published. Accordingly, computational depth of penetration as a theoretical basis of effective heat development becomes limited by the sensitivity of the predictive relationship.

2.4 Statistical analysis

To compare heating rates of MW and RF using wood of different dimensions (thicknesses), a general linear model (GLM) was run using heating method as the categorical variable, thickness of each wood specimen, and heating method*thickness interaction as fixed effects, with run time (treatment time when all temperature probes used in a DH trial recorded minimum 60 °C) as the dependent variable. The Firth adjusted maximum likelihood was used as the estimation method, followed by orthogonal contrast analysis to compare the heating rates of MW and RF. The Goodness of Fit of the linear distribution was estimated and all analyses were run using JMP Pro (v. 10.0; SAS Institute, 2012).

3 Results and discussion

3.1 Treatment time to achieve 60 °C

The time required to reach 60 °C through the profile of wood specimens (t_{60}) for RF and MW heating increased with thickness of the specimens (Table 3; Fig. 3). Up to 14 cm thickness, the time for all probes in a given specimen to reach 60 °C (t_{60}) was similar for MW and EPRF;

Table 3 Mean t_{60} and change in moisture content after DH treatment

Nominal ned dimension (cm^2)	Heating depth (cm)	t_{60} (min)			Post-treatment MC (%)			MC (%) decrease inherent to to treatment		
		MW	EPRF	HPRF	MW	EPRF	HPRF	MW	EPRF	HPRF
10 × 10	8.9	4.2 (0.8)	4.2 (0.4)	1.2 (0.1)	64.9 (2.3)	61.3 (3.4)	63.5 (3.2)	1.6 (0.4)	0.5 (0.1)	0.8 (0.1)
13 × 13	11.4	7.0 (0.4)	9.1 (0.9)	2.5 (0.2)	65.2 (0.6)	67.3 (0.6)	65.3 (1.3)	1.3 (0.3)	0.4 (0.0)	0.5 (0.1)
15 × 15	14	10.7 (0.8)	10.4 (1.4)	4.0 (0.8)	60.7 (4.9)	59.5 (3.9)	61.3 (2.2)	1.5 (0.2)	0.8 (0.1)	0.6 (0.1)
20 × 20	19.1	34.4 (1.8)	20.6 (1.2)	5.2 (0.6)	54.4 (1.2)	63.0 (5.2)	65.5 (2.4)	6.4 (1.5)	0.4 (0.1)	0.2 (0.1)
25 × 25	24.1	53.6 (3.4)	30.7 (2.9)	8.9 (0.5)	57.5 (0.2)	62.4 (0.2)	68.5 (1.2)	[a]	[a]	[a]

Standard deviations are in parentheses. N = 2 for each treatment and specimen size

[a] Percentage could not be determined due to maximum scale reading limitation for the largest oak specimen weights

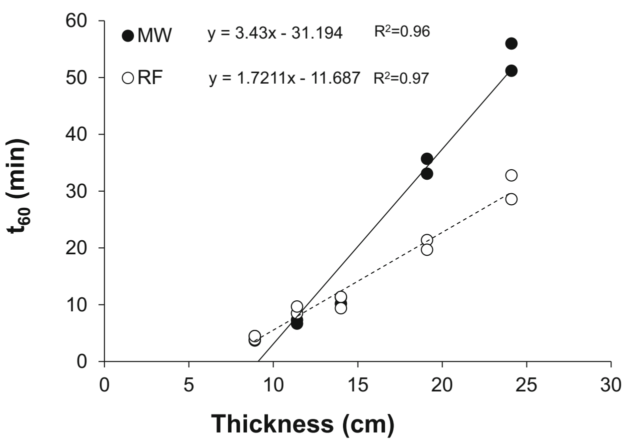

Fig. 3 Time to achieve 60 °C with DH at different thicknesses using MW or RF. *Lines* represent the linear regression fit of the data but intersection of the regression line for MW with the x-axis is not intended to imply that the data point for MW treatment of specimens 8 cm thick had a heating time of 0 min

beyond 14 cm thickness, the t_{60} was significantly less for RF, compared with MW (Table 3). A statistically significant treatment effect (MW vs. RF) was observed in the rate of temperature increase with increasing wood thickness. The GLM showed that method of treatment and thickness were highly significant for predicting run time and that the data fit a linear distribution with R^2 values >0.95 for both treatment methods (model goodness of fit: Pearson's Chi square = 176; df = 16, $P < 0.0001$; Fig. 3; Table 4). Moreover, the interaction between heating method and thickness was highly significant; run time increased faster (steeper slope) for MW with increasing thickness than for RF (Fig. 3). Thus, MW took significantly longer to reach and hold 60 °C at a given thickness compared to RF

Table 4 Computed depth of EMW penetration for white oak (*Quercus alba*) with different EMW frequencies

Frequency	Dielectric heating type	ε′	tan δ	d_p (cm)
10 MHz	RF	7.3[a]	0.21[a]	800
50 MHz	RF	6.6[a]	0.16[b]	200
2.45 GHz	MW	4.9[b]	0.2[b]	4

[a] Test material conditioned at 90 % relative humidity (~24 % wood equivalent moisture content) and 25 °C (James 1975)

[b] For 25 % moisture content at 25 °C (Olmi et al. 2000)

(Fig. 3; orthogonal contrast, Chi square = 17.5, df = 1, $P < 00001$). ISPM-15 currently states: "Where dielectric heating is used (e.g., microwave), wood packaging material composed of wood not exceeding 20 cm when measured across the smallest dimension of the piece or the stack must be heated to achieve a minimum temperature of 60 °C for 1 continuous minute throughout the entire profile of the wood (including its surface). The prescribed temperature of 60 °C must be reached within 30 min from the start of the treatment" (FAO 2013). The footnote to this section reads: "The 20 cm is based on the efficacy data currently available," and "Only microwave technology has proven to date to be capable of achieving the required temperature within the recommended time scale."

It is clear from the results (Table 3; Fig. 3) that RF heating is able to meet the current ISPM-15 requirement of achieving 60 °C throughout the wood profile in individual pieces of cants within 30 min, depending on wood size and power input. With the larger 25 × 25 cm^2 specimens, EPRF treatment time was slightly longer than 30 min (30.7 min) but much faster than for MW (53.6 min).

However, heating time for 25 × 25 cm^2 specimens was only 8.9 min with HPRF. Additional evidence that RF can meet the requirements of ISPM-15 comes from a recent study showing that RF heating kills 100 % of pinewood nematodes (*Bursaphelenchus xylophilus*) at the ISPM-15 required temperature for DH with treatment times of 1–4 min in 9 cm thick wood samples (Uzunovic et al. 2012).

As shown in Fig. 4, the 300 % increase in power input (comparing HPRF to EPRF) induced a treatment time decrease between 62 and 75 %. There was also a strong positive correlation between t_{60} and thickness. Despite the uncertain nature of the relationship between t_{60} and thickness, when the latter exceeds 25 cm, the results suggest that the treatment of a standard 4′ × 4′ commercial stack of wood (309 cm thickness) would require several hours. The finding that treatment time decreased with higher power settings has implications for phytosanitary treatment approaches using DH.

3.2 Depth of EMW penetration

Both RF and MW were able to treat specimens with thickness of 19.1 and 24.1 cm (Table 3; Fig. 3). However, with EPRF heating, t_{60} values were 40 and 43 % lower than for MW for depths of 19.1 and 24.1 cm, respectively.

Similarly, theoretically computed depths of EMW penetration, "d_p", were significantly higher for RF than that for MW heating (Table 4). With RF heating at 10 or 50 MHz, depth of penetration (d_p) was estimated as 2–8 m, while for 2.45 GHz MW this estimation was only 4 cm. Hence, multi-mode waveguides are necessary, or at least preferred, for MW treatment (waves enter the specimen from multiple directions) for effective phytosanitary treatment of larger material.

Depth of EMW penetration during DH is inversely related to the wavelength of electromagnetic waves as shown in Eq. 1 (Nelson 1967; Koubaa et al. 2008), i.e., the greater the wavelength the deeper the depth of penetration. Since RF uses much lower frequencies than MW, RF

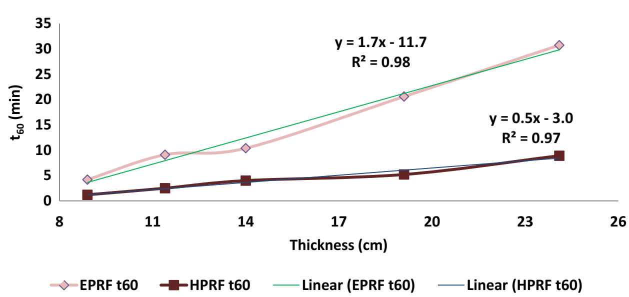

Fig. 4 Relationship between thickness and treatment time [t_{60}] for EPRF (3.3–3.4 kW) and HPRF (9.2–10.8 kW)

waves have a greater penetration depth than MW making it more suitable to rapidly treat larger materials or bulk volumes of solid WPM than can be achieved using 2.45 GHz MW heating.

3.3 Heating uniformity

Heating uniformity in green wood specimens (54–68 % moisture content) with RF and MW was assessed by comparing (1) differences between final and initial temperatures (ΔT) when all the probes reached a minimum of 60 °C at different depths (Fig. 5a–d); (2) temperature evolution at different depths of wood throughout the heating period (Fig. 6a–b); and (3) infra-red images of the front and cross-section at the mid-length of wood specimens (Fig. 7a–d).

Radio-frequency heating was more uniform than MW heating throughout the wood profile, which is evidenced by lower surface to core variation in temperature throughout the heating period (Fig. 6) as well as in ΔT at the end of treatment (Fig. 5). Also, with MW heating, the wood surface was generally much hotter than the core, especially for larger dimension specimens. For example, in 20 × 20 cm^2 specimens, ΔT for MW were 96 and 37 °C at the outer layer and core, respectively (Fig. 5c). Except for 10 × 10 cm^2, the difference between mean final and initial temperatures (ΔT) dropped within a few centimeters depth from the surface using MW (Fig. 5). This finding is in accordance with the theoretically computed penetration depth of 4 cm (1.73″) at 2.45 GHz frequency (Table 4). These results have implications for the industry if MW treatment efficiency is monitored, as suggested by Henin et al. (2008), through the measurement of wood surface temperature. Indeed, the latter only guarantee higher inside temperatures if the MW-treated wood does not exceed a few centimeters.

Similarly, temperature evolution (temperature increase with time) at different depths from the wood surface was highly variable during the heating period with MW, indicating non-uniform heating across the wood profile (Fig. 6). This heterogeneity in heating was not observed in tests with RF specimens (Fig. 6a). IR images of 20 × 20 cm^2 specimens illustrated striking temperature variations at the surface and the core of MW heated specimens (Fig. 7c, d). In contrast, thermal images of RF specimens exhibited greater uniformity in temperature across the wood profile, especially in the cross-section at the mid-length of the treated specimen (Fig. 7b).

Surfaces of MW specimens heated faster than their cores mainly due to limited depth of penetration of MW as discussed above. The complex MW heating pattern is the consequence of the non-uniform electromagnetic field (Mehdizadeh 1994, 2010). There is a repeated pattern of

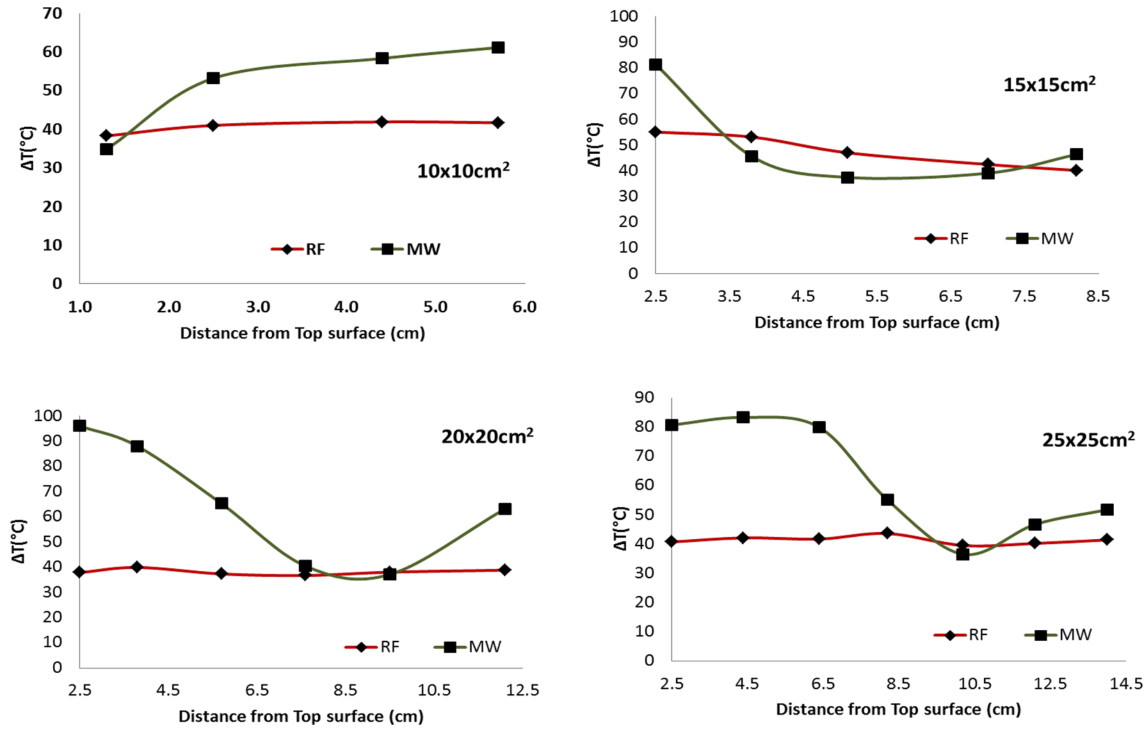

Fig. 5 Mean temperature increase (ΔT) as a function of depth as measured from the top surface of green wood specimens (60–70 % MC) of **a** 10 × 10 cm^2, **b** 15 × 15 cm^2, **c** 20 × 20 cm^2, and **d** 25 × 25 cm^2 dimensions; ΔT is the difference between final and initial temperature when all the probes reached the minimum of 60 °C

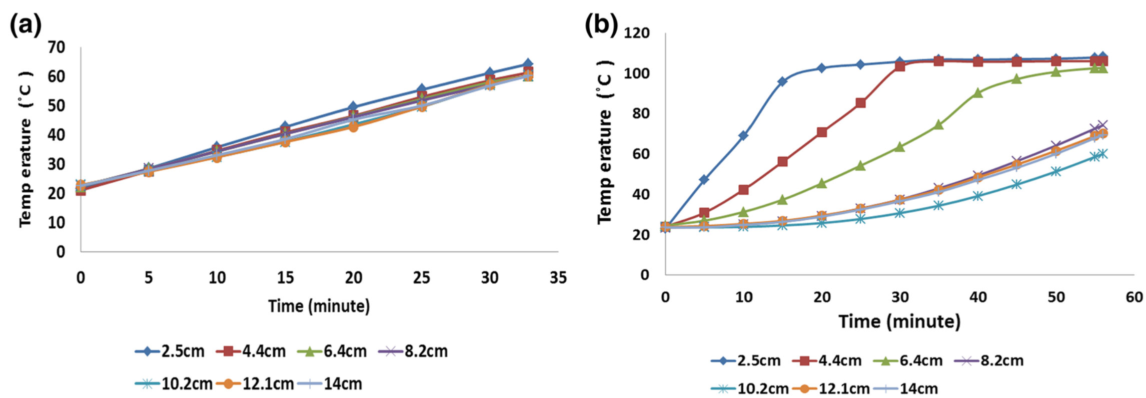

Fig. 6 Temperature evolution at different depths of 25 × 25 cm^2 wood specimens during **a** EPRF or **b** MW heating

field intensity variation within a microwave applicator, which for the most part follows a half-sine pattern. In a distance of one quarter of the operating wavelength the field intensity can change from maximum to zero and in a one-tenth of a wavelength the intensity can change by 60 %. In contrast, RF heating provides a relatively uniform field distribution with the use of a secondary electrode (Mehdizadeh 2010; Laborelec 2011; Jiao 2012).

The increase in temperature at the surfaces during MW heating may increase dielectric loss, which in turn could result in absorption of more MW energy (Wang et al. 2003; Mehdizadeh 2010). The disparity in MW surface absorption with temperature elevation can cause thermal instability, which is commonly known as “thermal run-away” (Hassan et al. 2015). An increase in the surface temperature is accompanied by greater dielectric energy absorption, resulting in local acceleration of heating and further rise of temperature causing hot spots and non-uniform heating. This additional heat build-up at the surface of MW specimens could explain the higher moisture loss (up to 6.4 %) following treatment of these specimens compared to less than 1 % loss for RF specimens (Table 3).

The electric field in RF heating is normally generated in a directional manner between a pair of electrode plates

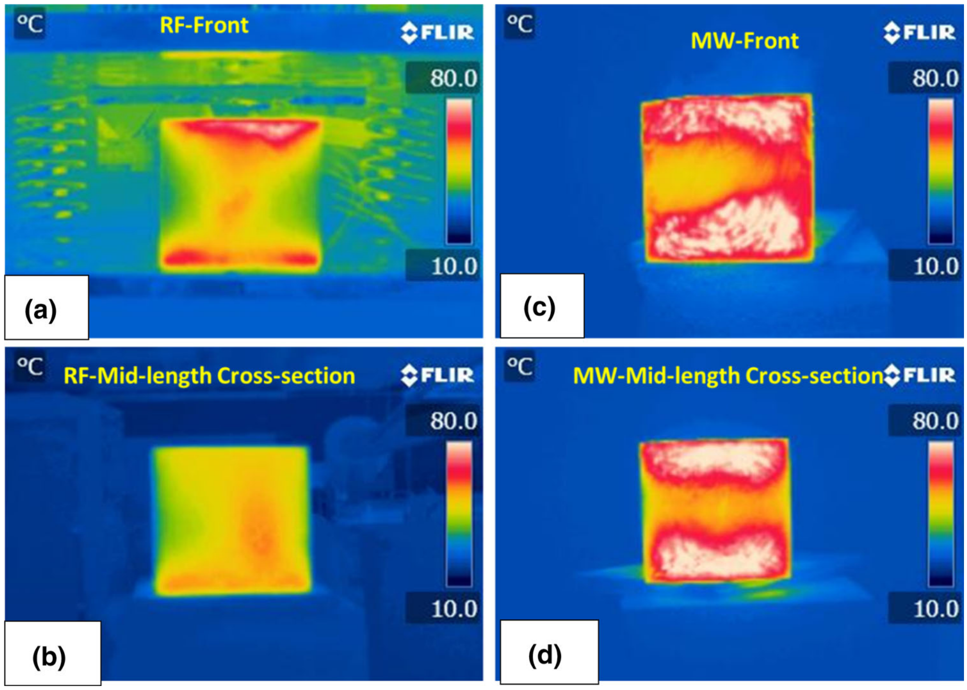

Fig. 7 Thermal images of 20×20 cm^2 specimen after EPRF (**a**, **b**) or MW heating (**c**, **d**)

(Fig. 1). In order to obtain homogeneous heating with RF radiation, the electrode geometry must fully conform to the geometry of the product to be heated (Mehdizadeh 1994). For RF heating, the product load needs to be of a regular and simple shape, while for MW treatment there is no limitation on shape of the product that can be treated. Thus, MW treatment is more suitable for heating irregular shaped materials, with such examples as walnut, salmon-fillet, macaroni, mashed potato, cakes, and many agricultural and food products successfully processed using either batch or continuous processing methods (Wang et al. 2011; Jiao et al. 2015). RF is a better choice for bulk or batch treatment of simple and regular shaped wood materials such as wood cants, pallets, and crates due to advantages in wave penetration and heating uniformity.

4 Conclusion

This study examined phytosanitary treatment of freshly sawn (MC > FSP) white oak wood of varying cross-section dimensions (10×10 m^2 to 25×25 cm^2) in compliance with ISPM-15 using a 19 MHz RF oven and 2.45 GHz MW oven. Treatment time, depth of EMW penetration and heating uniformity were compared and the major findings of the study can be summarized as follows:

- RF heating was more uniform and faster than 2.45 GHz MW heating, specifically when wood cross-section exceeded 15×15 cm^2.
- Increasing RF power by three fold significantly reduced treatment time (t_{60}) by up to 75 %. Thus, it took considerably more power to reduce treatment time (t_{60}) for larger loads, indicating power needed to meet ISPM-15 requirements (reaching 60 °C within 30 min) could be prohibitive for bulk treatment.
- RF heating effectively occurs beyond the 20 cm limit stipulated in the recently approved Annex 1 of ISPM-15. MW could not effectively heat up to the 20 cm depth limit and required more time than RF to heat larger material at the frequencies tested. Due to its low penetration depth, MW may be better adapted to the continuous treatment of thin wood layers not exceeding a few centimeters.
- RF heating meets the ISPM-15 requirement of achieving 60 °C for 1 min. This temperature threshold can be reached within 30 min in individual wood specimens, but the currently mandated 30 min time limit lacks a scientific basis and is not economically suitable for batch processing of larger material or bulk volumes.

Under the conditions of this study it was demonstrated that RF provided better heating uniformity and was less sensitive to volume effects when heating green wood to reach a critical lethal temperature compared to 2.45 GHz MW. This could be important when scaling up to treat larger volumes of wood and may be in some conditions (e.g., bulk treatment) the preferred alternative to methyl bromide (or conventional heating).

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