

# We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

185,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index  
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?  
Contact [book.department@intechopen.com](mailto:book.department@intechopen.com)

Numbers displayed above are based on latest data collected.  
For more information visit [www.intechopen.com](http://www.intechopen.com)



# Applications of Microwave Heating in Agricultural and Forestry Related Industries

Graham Brodie

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/45919>

## 1. Introduction

Microwave frequencies occupy portions of the electromagnetic spectrum between 300 MHz to 300 GHz. The full range of microwave frequencies is subdivided into various bands (Table 1). Because microwaves are also used in the communication, navigation and defence industries, their use in thermal heating is restricted to a small subset of the available frequency bands. In Australia, the commonly used frequencies include  $434 \pm 1$  MHz,  $922 \pm 4$  MHz,  $2450 \pm 50$  MHz and  $5800 \pm 75$  MHz [1]. These frequencies have been set aside for Industrial, Scientific and Medical (ISM) applications. All these frequencies interact to some degree with moist materials.

Band Designator	Frequency (GHz)	Wavelength in Free Space (centimetres)
L band	1 to 2	30.0 to 15.0
S band	2 to 4	15 to 7.5
C band	4 to 8	7.5 to 3.8
X band	8 to 12	3.8 to 2.5
Ku band	12 to 18	2.5 to 1.7
K band	18 to 27	1.7 to 1.1
Ka band	27 to 40	1.1 to 0.75
V band	40 to 75	0.75 to 0.40
W band	75 to 110	0.40 to 0.27

**Table 1.** Standard Radar Frequency Letter-Band Nomenclature (IEEE Standard 521-1984)

The major advantages of microwave heating are its short startup, precise control, and volumetric heating [2]. In industry, microwave heating is used for drying [2-5], oil extraction from tar sands, cross-linking of polymers, metal casting [2], medical applications [6], pest control [7], enhancing seed germination [8], and solvent free chemistry [9]. Microwave heating

has been applied to various agricultural and forestry problems and products since the 1960's [10]. Studies have been undertaken to use microwave energy: to improve crop handling, storage and preservation; to provide pest and weed control for agricultural production, for food preservation and quarantine purposes; and for preconditioning of products for better quality and more energy efficient processing. This chapter is concerned with microwave heating applications in the agricultural and forestry industries for purposes other than human food processing and consists of a review, update, and discussion of some potential applications that may be of interest to the microwave power and agricultural industries.

## 2. A brief review of microwave heating in moist materials

Most agricultural and forest products are a heterogeneous mixture of various organic molecules and water, arranged in various geometries. There are some important features of microwave heating that will determine the final temperature and moisture distribution during microwave processing.

Any realistic study of microwave heating in moist materials must account for simultaneous heat and moisture diffusion through the material. The coupling between heat and moisture is well known but not very well understood [11]. Henry [12] first proposed the theory for simultaneous diffusion of heat and moisture in a textile package. Crank [13] later presented a more thorough development of Henry's work. Since then, this theory has been rewritten and used by many authors [11, 14-17]. Microwave heating can be described by a combined heat and moisture diffusion equation that includes a volumetric heating term associated with the dissipation of microwave energy in the material [17]:

$$\nabla^2(pM_v + nT) - \frac{\partial}{\partial t} \left\{ \left[ \frac{1}{\tau_v D_a} \left( 1 + \frac{(1-a_v)\sigma\rho_s}{a_v} \right) - \frac{n\rho\sigma L}{pk} \right] pM_v + \left[ \frac{C\rho}{k} \left( 1 + \frac{\omega L}{C} \right) - \frac{p(1-a_v)\omega\rho_s}{n\tau_v D_a a_v} \right] nT \right\} + \frac{nq}{k} = 0 \quad (1)$$

This can be expressed in a simpler form if  $\Omega = pM_v + nT$ :

$$\nabla^2 \Omega - \frac{1}{\gamma} \frac{\partial \Omega}{\partial t} + \frac{nq}{k} = 0 \quad (2)$$

The constants of association,  $p$  and  $n$ , are calculated to satisfy:

$$\frac{1}{\gamma} = \left[ \frac{1}{\tau_v D_a} \left( 1 + \frac{(1-a_v)\sigma\rho_s}{a_v} \right) - \frac{n\rho\sigma L}{pk} \right] = \left[ \frac{C\rho}{k} \left( 1 + \frac{\omega L}{C} \right) - \frac{p(1-a_v)\omega\rho_s}{n\tau_v D_a a_v} \right] \quad (3)$$

Essentially, the combined heat and moisture diffusion coefficient ( $\gamma$ ) has two independent values, implying that heating and moisture movement occurs in two independent waves. The slower wave of the coupled heat and moisture system is always slower than either the isothermal diffusion constant for moisture or the constant vapour concentration diffusion

constant for heat diffusion, whichever is less, but never by more than one half [12, 13]. The faster wave is always many times faster than either of these independent diffusion constants.

Considerable evidence exists in literature for rapid heating and drying during microwave processing [5, 18]; therefore it is reasonable to assume that the faster diffusion wave dominates microwave heating in moist materials whereas the slower wave dominates conventional heating. A slow heat and moisture diffusion wave should also exist during microwave heating; however observing this slow wave during microwave heating experiments may be difficult and no evidence of its influence on microwave heating has been seen in literature so far.

The fast heat and moisture diffusion wave has a profound effect on biological materials during microwave heating. In particular, very rapid heat and moisture diffusion during microwave heating yields: faster heating compared to conventional heating; and localized steam explosions which may rupture plant and animal cells [18, 19].

Other important phenomena associated with microwave heating include: non-uniform heat and moisture distribution due to the geometry of the microwave applicator [20] and the geometry of the heated material [21]; and phenomenon such as thermal runaway which manifest itself as localised "hot spots" and very rapid rises in temperature [22]. The volumetric heating term ( $q$ ) in equation (2) is strongly influenced by the geometry of the heated material. Ayappa et al. [2] demonstrate that the equation for electromagnetic power distribution generated in a slab of thickness ( $W$ ) can be described by:

$$q = \frac{1}{2} \omega \epsilon_0 \kappa'' (\tau E)^2 \left\{ e^{-2\beta z} + \Gamma^2 e^{-2\beta(W-z)} + 2\Gamma e^{-\beta(W-2z)} \cos(\delta + 2\alpha z) \right\} \quad (4)$$

It has been shown elsewhere [21] that using this volumetric heating relationship, the solution for equation (2) is:

$$\Omega(t) = \frac{n\omega\epsilon_0\kappa''(\tau E)^2}{8k\beta^2} \left\{ e^{4\gamma\beta^2 t} - 1 \right\} \left\{ e^{-2\beta z} + \left( \frac{h}{k} + 2\beta \right) z e^{\frac{-z^2}{4\gamma t}} \right\} \left( 1 + \Gamma^2 e^{-2\beta W} \right) \quad (5)$$

From this it can be deduced that the temperature/moisture profiles in thick slabs and rectangular blocks usually result in subsurface heating where the maximum temperature is slightly below the material surface [23].

The microwave's electric field distribution in the radial dimension of a cylinder can be described by [21]:

$$E = \tau E_0 \frac{I_0(\beta r)}{I_0(\beta r_0)} \quad (6)$$

The resulting solution to equation (2) can ultimately be derived [21]:

$$\Omega(t) = \frac{n\omega\epsilon_0\kappa''\tau^2 E_0^2 (e^{4\beta^2 \gamma t} - 1)}{4k\beta^2 I_0(2\beta r_0)} \left[ \frac{4\alpha\gamma t}{[J_0(\alpha r_0)I_0(\beta r_0)]^2} e^{\frac{-r^2}{4\gamma t}} + I_0(2\beta r) + \left\{ 2\beta I_1(2\beta r_0) + \frac{h}{k} I_0(2\beta r_0) \right\} (r_0 - r) e^{\frac{-(r_0-r)^2}{4\gamma t}} \right] \quad (7)$$

The temperature/moisture profiles in small-diameter cylinders, such as a plant stem, usually exhibit pronounced core heating [23, 24]. On the other hand, temperature profiles in large cylinders exhibit subsurface heating, with the peak temperature occurring slightly below the surface [23].

Microwave heating in spheres is similar to that in cylinders. The microwave's electric field distribution in the radial dimension of a cylinder can be described by [21]:

$$E = \tau E_o \frac{j_o(fr)}{j_o(fr_o)} \quad (8)$$

The resulting solution to equation (2) can ultimately be derived [21]:

$$\Omega(t) = \frac{n\omega\epsilon_o\kappa''\tau^2 E_o^2 (e^{4\beta^2\gamma t} - 1)}{k\beta \cdot i_o(2\beta r_o)} \left[ \frac{\alpha\gamma t}{[j_o(\alpha r_o)i_o(\beta r_o)]^2} e^{\frac{-r^2}{4\gamma t}} + \frac{i_o(2\beta r)}{4\beta} + \left\{ 2\beta \cdot i_1(2\beta r_o) + \frac{h}{k} i_o(2\beta r_o) \right\} \frac{(r_o - r)}{4\beta} e^{\frac{-(r_o - r)^2}{4\gamma t}} \right] \quad (9)$$

This analysis can be used, in conjunction with experimental data, to better understand how microwave heating affects agricultural and forestry products.

### 3. Crop drying

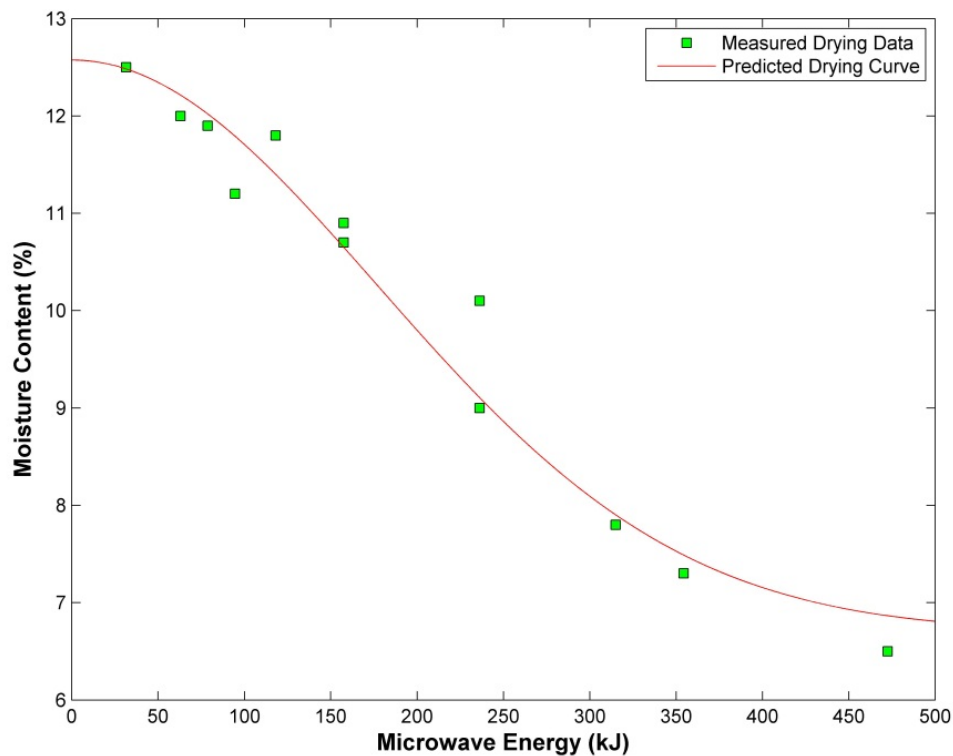
Many studies have investigated the application of microwave energy to speed up crop and wood drying [25, 26]. Higgins and Spooner [27] investigated alfalfa, which was microwave-dried for 7, 8, 9 or 10 min in a microwave oven, compared with field and convective oven-dried alfalfa. They found no differences in crude protein, *in vitro* dry matter digestibility or acid detergent lignin between the various drying methods. Microwave-dried alfalfa generally retained a higher proportion of the cell-wall constituents (neutral detergent fibre) than did field-dried alfalfa. Microwave dried Alfalfa that was treated for 7 minutes had significantly lower acid detergent fibre values than all other drying treatments.

Adu and Otten [28] studied the kinetics of microwave drying of white beans. They found that microwave drying was a falling rate process. When constant power was absorbed, seed temperature increased rapidly to a maximum value during the initial stages of drying and began to decrease gradually during the latter stages of drying. To maintain a constant drying temperature, the microwave power had to be increased progressively as the moisture content of the beans decreased due to drying.

This is linked to reductions in the dielectric properties of the beans as moisture is removed [29], which reduces the interactions between the microwave fields and the beans. The gradual decrease in seed temperature, when the drying rate decreases, is opposite to what is observed during conventional hot air drying. This may be caused by a progressively increasing heat of desorption during the drying process [30], which is a common phenomenon in hygroscopic solids. Thus, the microwave heating characteristics observed for white beans may apply to other hygroscopic solids, such as soils, wood, and fodder chaff.

Microwave drying is fast, as may be expected from the coupling of heat and moisture transport described earlier. The drying curve (Figures 1 and 3) exhibits a short relatively slow drying period, followed by a much faster almost linear relationship between applied microwave energy and moisture loss. This is followed by a more conventional falling rate drying period (Figure 1); however prolonged microwave treatment at high power leads to a phenomenon known as “thermal runaway”, which causes charring (Figure 2). Microwave treatment profoundly affects the germination performance of grains, with any reasonable application of microwave power totally inhibiting grain germination (Table 2). The microwave drying curve can be described by:

$$MC = (MC_i - MC_f) \times e^{-\left(\frac{Em}{b}\right)^2} + MC_f \quad (10)$$



**Figure 1.** Wheat grain moisture content as a function of applied microwave energy



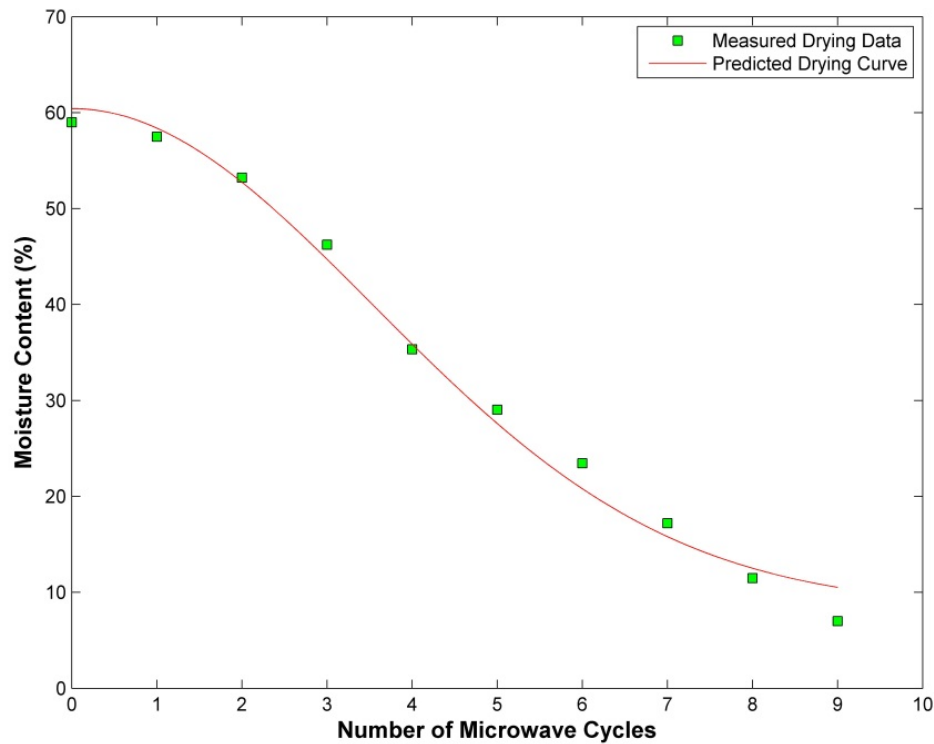


**Figure 2.** Charring of wheat during prolonged microwave treatment

Problems with thermal runaway during microwave drying can be overcome by using cyclic drying instead of continuous microwave heating [31]. In this technique, microwave energy is applied for a short time to induce rapid heating and moisture movement and then the product is allowed to equilibrate during a period with no microwave heating. This technique has been successfully applied to timber drying [31] (Figure 3). The resulting drying curve is still described by equation (10).

Microwave Power (%)	Microwave treatment time (minutes)		
	3.5	7.0	10.5
20	88%	42%	4%
50	46%	0%	0%
70	6%	0%	0%
100	0%	0%	0%
Control	90%	88%	94%

**Table 2.** Effect of microwave drying of 700 g samples of wheat in a 750 W, 2.45 GHz, domestic oven on germination percentages of grains



**Figure 3.** Wood moisture content as a function of the number of microwave energy cycles applied

Walde, et al. [32] studied the effect of microwave drying on the grinding properties of wheat. The microwave dried samples were crisp and consumed less energy for grinding compared to the control samples. The Bond's work index for the bulk sample was  $2.26 \text{ kWh kg}^{-1}$  compared to  $2.41 \text{ kWh kg}^{-1}$  for the control samples of equal moisture content. These studies indicated that microwave drying of wheat before grinding helps reduce power consumption in wheat milling. The microwave drying did not change the total protein content, but there were some functional changes in the protein, which was evident from gluten measurements.

Studies have also been carried out on the dry milling characteristics of maize grains, which were dried previously from different initial moisture contents (MCi) in a domestic microwave oven [33]. The MCi ranged from 9.6% to 32.5% on a dry sample basis. Drying was also carried out in a convective dryer at temperatures of  $65 - 90^\circ \text{C}$ . The drying rate curve showed a typical case of moisture loss by diffusion from grains. The dried samples were ground in a hammer mill and the Bond's work index was found to decrease with increasing duration of microwave drying. There was no difference in protein and starch content between the different treatments. Viscosity measurements were made with 10% suspensions of the flour in water which were heated to  $80 - 90^\circ \text{C}$  and allowed to cooled. Viscosity decreased with increasing microwave drying of the grains. The colour analysis showed that flour of the microwave-dried samples was brighter than the control and convective dried samples. Based on these and other studies, microwave drying of agricultural and forestry commodities appear to be a viable alternative to conventional



methods, especially when rapid drying and high throughputs of moist material are desirable.

#### 4. Quarantine

Dried timber, nuts and fruits are commonly treated by chemical fumigation to control field and storage pests before being shipped to domestic and international markets. Because chemical fumigants such as methyl bromide are no longer available [34], there is a heightened interest in developing non-chemical pest control. An important key to developing successful thermal treatments is to balance the need for complete insect mortality with minimal impact on the product quality. A common difficulty in using conventional hot-air disinfestation is the slow heating rate, non-uniform temperature distribution, and possible heat damage to heat-sensitive commodities [35]. A more promising approach is to heat the commodity rapidly using radio frequency (RF) or microwave dielectric heating to control insects [35, 36].

Interest in controlling insects, using electromagnetic energy, dates back nearly 70 years. Headlee [37, 38], cites one earlier report of experiments determining lethal exposures for several insect species to 12 MHz electric fields and the body temperatures produced in honey bees due to dielectric heating. Nelson [39] has shown that microwaves can kill insects in grain; however one of the challenges for microwave insect control is to differentially heat the insects in preference to their surrounds. Nelson [39] shows that differential heating depends on microwave frequency. It appears that using a 2.45 GHz microwave system, which is the frequency used in domestic microwave ovens, heats the bulk material, which then transfers heat to the insects; however lower frequencies heat the insects without raising the temperature of the surrounding material beyond 50°C [39].

Nzokou et al [40] investigated the use of kiln and microwave heat treatments for the sanitisation of emerald ash borer (*Agrilus planipennis* Fairmaire) infested logs. Their microwave treatment method was conducted in a 2.8 GHz microwave oven (volume: 0.062 m<sup>3</sup>, power: 1250 W) manufactured by Panasonic (Panasonic Co., Secaucus, New Jersey). Due to the limited volume of the microwave oven, two runs were necessary to treat logs assigned to each microwave treatment temperature. Their results showed that a temperature of 65°C was successful at sanitising the infested logs. Microwave treatment was not as effective as kiln treatment, probably because of the uneven distribution of the microwave fields and temperature inside the treated logs. This uneven temperature distribution is partly due to the nature of microwave heating, but may also be due to their choice of microwave chamber used during their experiments.

In spite of this, with the high costs and level of energy needed to thoroughly heat logs to the desired 65 °C using conventional heating, microwave heating is still a very attractive solution for rapid heat sterilisation of infested wood materials [40]. The problem of ensuring appropriate temperature distribution inside treated materials can be easily overcome by using appropriate microwave applicators rather than a multi-mode cavity [41]. Several options are available including conveyer belt feeds through a long choke tunnel into a

purpose built applicator [41], or projecting a very intense but short duration microwave field pulse into the material, using an antenna. Plaza *et al.* [42] have developed a system which employs a circular wave-guide energized by two microwave sources oriented at 90 ° to one another. This orthogonal orientation of the microwave fields ensures that they do not interfere with each other, but provides a high power source from relatively cheap mass produced 1 kW magnetrons. Microwave magnetrons of greater power output than 1 kW are usually one or two orders of magnitude more expensive than the 1 kW versions.

It has been shown earlier that microwave heating in moist materials, such as the body of an insect, induces a very fast moving wave of heat and water vapour [17]. The intensity of this wave is directly linked to the intensity of the microwave fields [43], therefore using very intense microwave fields may rupture the internal organs of insects, due to local steam explosions.

The interaction of electromagnetic energy with matter is determined by the dielectric properties of the material. The permittivity of a material can be expressed as a complex quantity, the real part ( $\kappa'$ ) of which is associated with the capability of the material for storing energy in the electric field of the electromagnetic wave, and the imaginary part ( $\kappa''$ ) is associated with the conversion of electromagnetic energy to heat inside the material [39]. This is the phenomenon commonly referred to as dielectric heating. The dielectric properties also determine the reflectivity of a material.

The power dissipated per unit volume in a nonmagnetic, uniform material exposed to radio frequency (RF) or microwave fields can be expressed as:

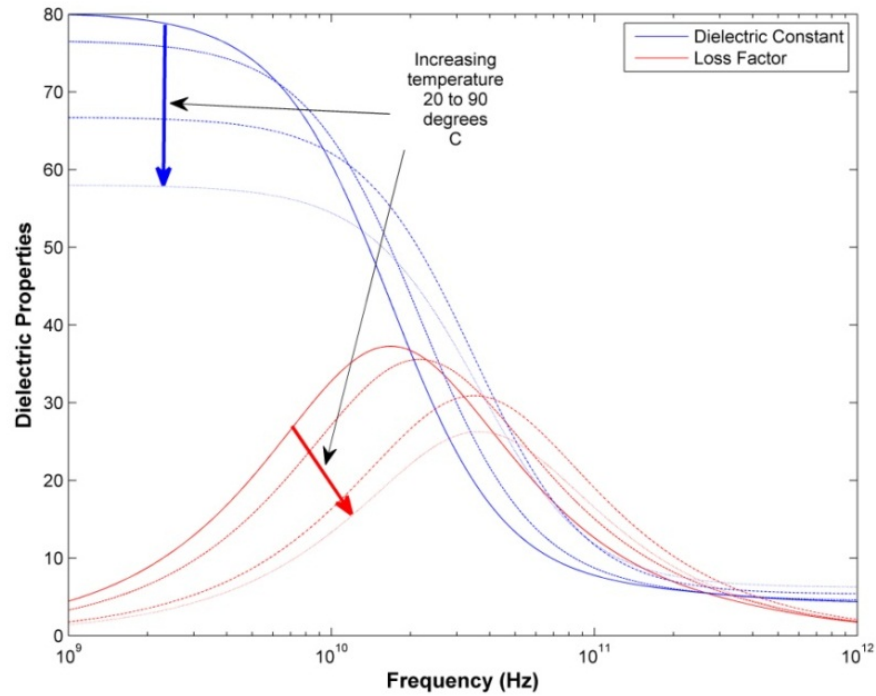
$$P = (\tau E)^2 \sigma = 55.63 \times 10^{-12} f (\tau E)^2 \kappa'' \quad (11)$$

Therefore in a system composed of two or more materials, there will be preferential heating in favour of the material with the least reflectivity and higher dielectric loss factor. The rate of temperature increase also depends on the density and thermal capacity of the heated material [35, 36]:

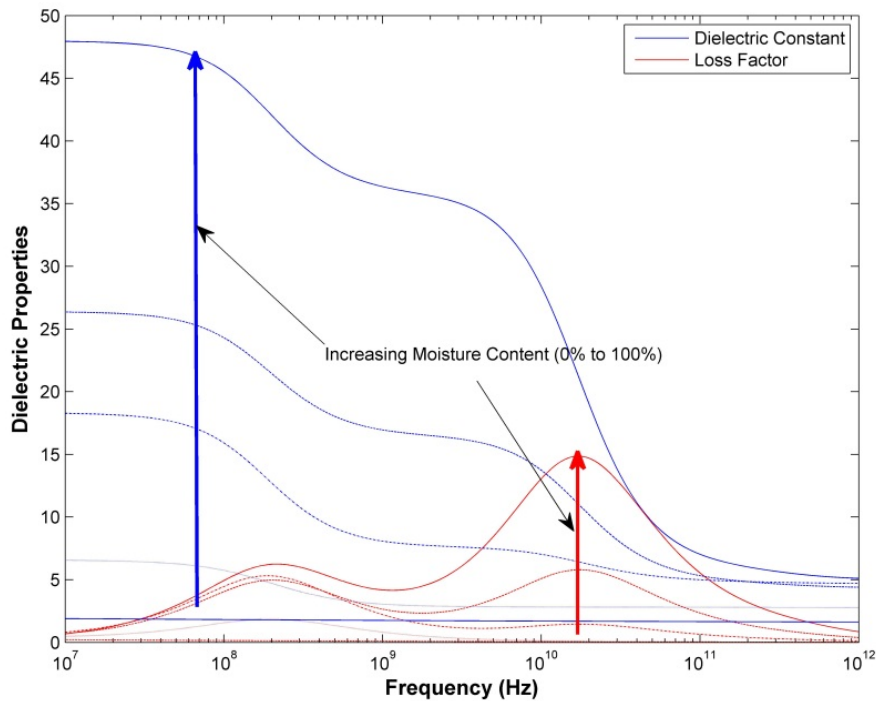
$$\frac{dT}{dt} = \frac{P}{\rho C} \quad (12)$$

Termites are a good example of insects that infest economically important products. For example, in the United States, the annual cost of treating damage caused by the Formosan termite (*Coptotermes formosanus*) exceeds \$US 1 billion [44]. The radar cross section of some insect species, including termites, has been modelled by treating them as drops of water of equivalent size and shape [45].

Liquid water exhibits dielectric relaxation at around 22 GHz [46] (Figure 4). There are higher dielectric relaxations in water at about 280 GHz [46], 4.5 THz and 15.4 THz [47]. The dielectric properties of grains, soil and wood also depend on their moisture content [48] (Figure 5).

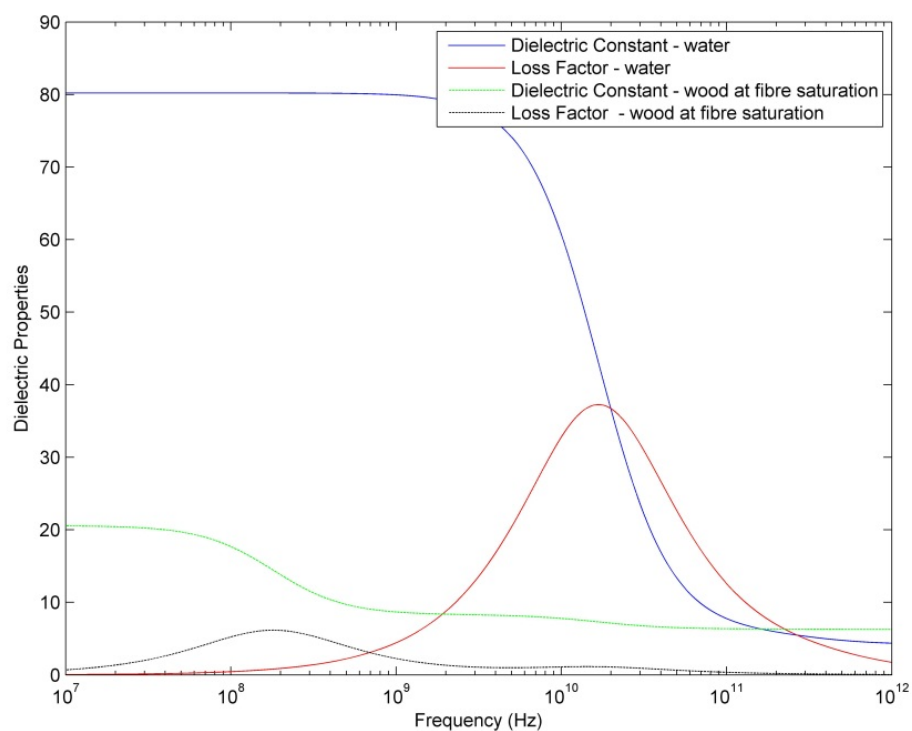


**Figure 4.** Dielectric properties of pure water as a function of frequency and temperature (calculated using equations and data from literature [46])



**Figure 5.** Dielectric properties of wood (density =  $500 \text{ kg m}^{-3}$ ) as a function of frequency and moisture content varying between 0 % and 100 % on a dry wood basis (calculated using equations and data from literature [48])

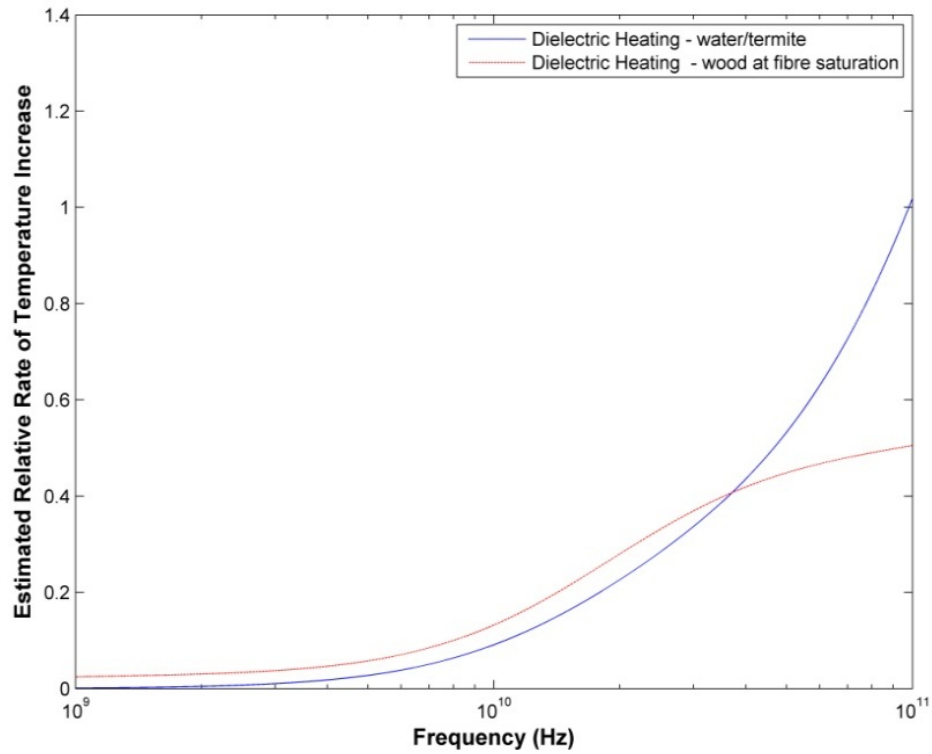
Dry wood-in-service is in hydro-thermodynamic equilibrium with its surroundings. This condition is known as the equilibrium moisture content [49]. Depending on the atmospheric conditions, equilibrium moisture content is usually about 12% moisture on a dry wood weight for weight basis. When termites invade wood, they often import moisture into the structure to maintain a suitable microclimate for their foraging activities. The maximum moisture content that wood can attain before free water begins to form is known as fibre saturation. This occurs at about 25 - 30 % moisture content [49], depending on the wood species. Fibre saturation refers to the state when all the cells are free of water and only bound water is found within the cell walls. Usually termites do not increase the moisture content beyond fibre saturation. The dielectric properties of termites (modelled as water) and wood at fibre saturation are significantly different from each other (Figure 6).



**Figure 6.** Comparison of the dielectric properties of wood (density = 500 kg m<sup>-3</sup>) at fibre saturation with water

Treatment of termite infestations using microwave energy, at 2.45 GHz, has been available for some time [50, 51]. This technique does not directly heat the termites, but heats the surrounding wood to more than 55°C [52], which then causes termite mortality. Unfortunately, the combination of high reflectivity and low dielectric losses for water in the lower microwave frequency band (2.45 GHz) means that there is virtually no differential heating between the termites and wood that is at fibre saturation; however significant differential heating should occur once the frequency increases above 20 GHz (Figure 7). Research in the field of ultra-high frequencies (>20 GHz) indicates that these frequencies may selectively heat insect pests in favour of the materials they infest [52, 53]. Therefore

research into ultra-high frequency microwave based insect control should yield some valuable insights over the coming decades [52].



**Figure 7.** Relative dielectric heating and wood at fibre saturation moisture content, calculated using equation (12) and the dielectric properties of water and wood [48]

Park, *et al.*[54] studied the survival of microorganisms after heating in a conventional microwave oven. Kitchen sponges, scrubbing pads, and syringes were deliberately contaminated with wastewater and subsequently exposed to microwave radiation. The heterotrophic plate count of the wastewater was reduced by more than 99 percent within 1 to 2 minutes of microwave heating. Coliform and *E. coli* in kitchen sponges were completely inactivated after 30 seconds of microwave heating. Bacterial phage MS2 was totally inactivated within 1 to 2 minutes, but spores of *Bacillus cereus* were more resistant than the other microorganisms tested, requiring 4 minutes of irradiation for complete eradication. Similar inactivation rates were obtained in wastewater-contaminated scrubbing pads; however microorganisms attached to plastic syringes were more resistant to microwave irradiation than those associated with kitchen sponges or scrubbing pads. It took 10 minutes for total inactivation of the heterotrophic plate count and 4 minutes of treatment for total inactivation of total coliform and *E. coli*. A 4-log reduction of phage MS2 was obtained after 2 minutes of treatment with 97.4 percent reductions after 12 minutes of microwave treatment.

Devine *et al.* [55] conducted a trial in which microwave radiation, coupled with steam heat, was used to treat organic waste (1,136 kg of culled turkey carcasses), designed to simulate a



small-scale poultry mortality event. They inoculated the turkey carcasses with *Bacillus atrophaeus* spores and *Salmonella enterica* before inserting them into a purpose built portable microwave unit (Sanitec Industries), along with other organic waste. The units are designed to treat in excess of 250 kg/per hour of waste. The system has been designed so that the waste is transported through the microwave fields along a screw so that the final exposure time and temperature profile is a minimum of 30 minutes at 95 °C. The system generated a seven-log reduction in the microbial load of *Salmonella* and a five-log reduction in *Bacillus* spores. These results illustrate the potential of using microwave radiation for quarantine procedures. The following sections will illustrate more specifically how microwave energy can manage pests in agricultural and forestry systems.

## 5. Effect of microwave heating on seeds and plants

In 2006, the cost of weed management and loss of production to Australian agricultural industries was estimated to be about \$4 billion annually [56]. Depletion of the weed seed bank is critically important to overcoming infestations of various weed species [57]. Mechanical and chemical controls are the most common methods of weed management in cropping systems [58, 59]. The success of these methods usually depends on destroying the highest number of plants during their early growth stages [58] before they interfere with crop production and subsequently set further seed. These strategies must be employed continually to deplete the weed seed bank.

Interest in the effects of high frequency electromagnetic waves on biological materials dates back to the late 19<sup>th</sup> century, while interest in the effect of high frequency waves on plant material began in the 1920's [60]. In many cases, short exposure of seeds to radio frequency and microwave radiation resulted in increased germination and vigour of the emerging seedlings [61, 62]; however, long exposure usually resulted in seed death [59].

Davis *et al.* [63, 64] were among the first to study the lethal effect of microwave heating on seeds. They treated seeds, with and without any soil, in a microwave oven and showed that seed damage was mostly influenced by a combination of seed moisture content and the energy absorbed per seed. Other findings from their studies suggested that both the specific mass and specific volume of the seeds were strongly related to seed mortality [64]. This could be due to the “radar cross-section” [65] presented by seeds to propagating microwaves. Large radar cross-sections allow the seeds to intercept, and therefore absorb, more microwave energy. The geometry of many seeds can be regarded as ellipsoids or even spheres, so the microwave fields are focused into the centre of the seed (see equation 8). Therefore larger seeds focus more energy into their core, which results in higher temperatures at the centre of the seed (see equation 9), leading to higher mortality rates. Seeds whose geometry can be approximated as being cylindrical will also focus more energy into their core as their dimensions increase (see equations 6 and 7).

Barker and Craker [66] investigated the use of microwave heating in soils of varying moisture content (10-280 g water/kg of dry soil) to kill ‘Ogle’ Oats (*Avena sativa*) seeds and an undefined number of naturalised weed seeds present in their soil samples. Their results



demonstrated that a seed's susceptibility to microwave treatment is entirely temperature dependent. When the soil temperature rose to 75°C there was a sharp decline in both oat seed and naturalised weed seed germination. When the soil temperature rose above 80°C, seed germination in all species was totally inhibited.

Several patents dealing with microwave treatment of weeds and their seeds have been registered [67-69]; however none of these systems appear to have been commercially developed. This may be due to concerns about the energy requirements to manage weed seeds in the soil using microwave energy. In a theoretical argument based on the dielectric and density properties of seeds and soils, Nelson [70] demonstrated that using microwaves to selectively heat seeds in the soil "*can not be expected*". He also concluded that seed susceptibility to damage from microwave treatment is a purely thermal effect, resulting from soil heating and thermal conduction from the soil into the seeds. This has been confirmed experimentally by Brodie *et al.* [71].

Microwaves can kill a range of weed seeds in the soil [63, 64, 72], however fewer studies have considered the efficacy of using microwave energy to manage already emerged weed plants. Davis *et al.* [63] considered the effect of microwave energy on bean (*Phaseolus vulgaris*) and Honey Mesquite (*Prosopis glandulosa*) seedlings. They discovered that plant aging had little effect on the susceptibility of bean plants to microwave damage, but honey mesquite's resistance to microwave damage increased with aging. They also discovered that bean plants were more susceptible to microwave treatment than honey mesquite plants.

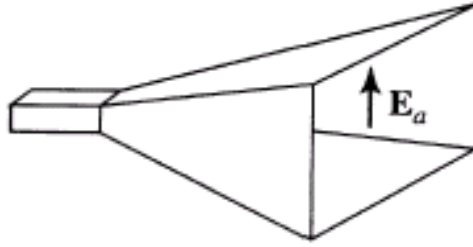
Brodie *et al.* [73] studied the effect of microwave treatment on Marshmallow (*Malva parviflora*) seedlings, using a prototype microwave system based on a modified microwave oven. The prototype system, energised from the magnetron of the microwave oven operating at 2.45 GHz, has an 86 mm by 43 mm rectangular wave-guide channelling the microwaves from the oven's magnetron to a horn antenna outside of the oven. This allowed the oven's timing circuitry to control the activity of the magnetron.

Horn antennas (Figure 8), like the design used in the experimental prototype are very popular for microwave communication systems [74]. The vertical plane of the horn antenna is usually referred to as the E-plane, because of the orientation of the electrical field (or E-field) in the antenna's aperture. The horizontal plane is referred to as the H-plane, because of the orientation of the magnetic field (or H-field) of the microwave energy. The H-plane electric field distribution in the aperture of a horn antenna, fed from a wave-guide propagating in the TE<sub>10</sub> mode, is approximated by:

$$E = E_o \cos\left(\frac{\pi}{a}x\right) \quad (13)$$

In the case of a cylindrical object, such as a plant stem, the microwave's electric field distribution created by a horn antenna [21] can be described by:

$$E = \tau E_o \frac{I_o(\beta r)}{I_o(\beta r_o)} \cdot \cos\left(\frac{\pi}{a}x\right) \quad (14)$$



**Figure 8.** A typical horn antenna showing the orientation of the electrical field component of the microwave energy in the antenna's aperture

The resulting temperature distribution can be described by [75] :

$$T = \frac{n\omega\epsilon_o\kappa''\tau^2E_o^2(e^{4\beta^2\gamma t} - 1)}{4k\beta^2I_o(2\beta r_o)} \left[ \frac{4\alpha\gamma t}{[J_o(\alpha r_o)I_o(\beta r_o)]^2} e^{\frac{-r^2}{4\gamma t}} + I_o(2\beta r) \right. \\ \left. + \left\{ 2\beta I_1(2\beta r_o) + \frac{h}{k}I_o(2\beta r_o) \right\} (r_o - r) e^{\frac{-(r_o-r)^2}{4\gamma t}} \right] \cdot \text{Cos}\left(\frac{\pi}{a}x\right) \quad (15)$$

Three horn applicators, with varying aperture dimension (180mm by 90 mm; 130 mm by 43 mm; and 86 mm by 20 mm), were developed and tested during various experiments [59, 73, 76, 77]. Aperture size of the horn applicator profoundly affects the treatment time needed to kill plants, with the smaller aperture needing much less time to provide a lethal dose; however the total energy density needed to kill the plants (microwave output power density multiplied by treatment time) was the same irrespective of the horn aperture size. The resulting lethal dose, which was sufficient to kill all the test species, was 350 J cm<sup>-2</sup>[75] for each plant.

Because energy rather than treatment time is the key factor in plant mortality, two options for using microwave energy to manage weeds become evident; either a prolonged exposure to very diffuse microwave fields or a strategic application of an intensely focused microwave pulse is sufficient to kill plants. Bigu-Del-Blanco, *et al.*[78] exposed 48 hour old seedlings of *Zea mays* (var. Golden Bantam) to 9 GHz radiation for 22 to 24 hours. The power density levels were between 10 and 30 mW cm<sup>-2</sup> at the point of exposure. Temperature increases of only 4 °C, when compared with control seedlings, were measured in the microwave treated specimens. The authors concluded that the long exposure to microwave radiation, even at very low power densities, was sufficient to dehydrate the seedlings and inhibit their development. On the other hand, recent studies on fleabane (*Conyza bonariensis*) and paddy melon (*Cucumis myriocarpus*)[75, 77] have revealed that a very short (less than 5 second) pulse of microwave energy, focused onto the plant stem, was sufficient to kill these plants. In both cases, rapid dehydration of the plant tissue appears to be the cause of death. This is because microwave heating results in rapid diffusion of moisture [29] through the plant stem as suggested earlier.

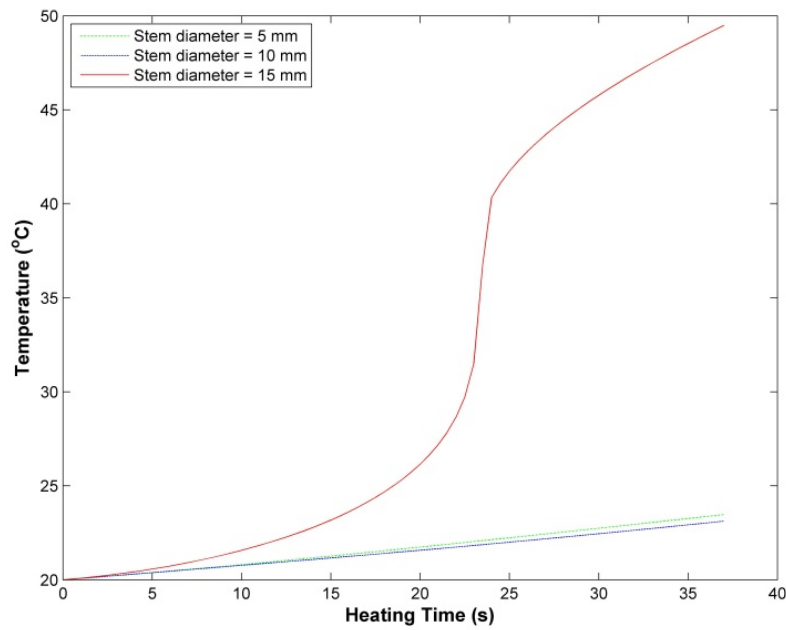
Based on energy calculations for plants and seeds on the surface of sandy soil [72, 76], the energy needed to kill dry seeds is an order of magnitude higher than the energy needed to kill already emerged plants. The microwave energy dose needed to kill a paddy melon or fleabane plant was approximately  $350 \text{ J cm}^{-2}$  (or  $35 \text{ GJ ha}^{-1}$ ) [77]. This is an order of magnitude higher than the embodied energy ( $2.2 - 3.0 \text{ GJ ha}^{-1}$ ) associated with chemical weed management [79-82]; however the real microwave energy requirements on a large scale will depend on the plant density and spatial distribution. Therefore the microwave energy requirements may be greatly reduced if appropriate techniques, such as weed seeker systems [83], are employed to only turn on the microwave unit when the system encounters a weed in the field. The growing problems of herbicide resistance [84] also warrants ongoing research and development of microwave weed control technologies. Other strategies may also reduce this energy requirement even further.

It has been well documented that the dielectric properties of most materials are temperature and moisture dependent [22, 85-88]. Ulaby and El-Rayes [89, 90] studied the dielectric properties of plant materials at microwave frequencies. Plants with high moisture content have higher dielectric constants and will therefore interact more with the microwave fields, rendering them more susceptible to microwave damage.

Equation (15) was used in an iterative calculation, where the new dielectric properties for plant based materials were recalculated after every second of microwave heating, based on the changes in temperature and moisture content of the plant during that interval of the microwave heating progresses. This results in non-linear heating responses and sudden jumps in temperature when there is no change in the applied microwave field strength (Figure 9). The sudden jump in temperature for the 15 mm diameter stem is the result of "thermal runaway". The onset of thermal runaway is also dependent on the microwave field intensity (Figure 10) and the heat transfer properties of the heated material (Figure 11). Under the influence of simultaneous heat and moisture diffusion during microwave heating, the effective thermal conductivity of a microwave heated material can be many times the normal value for the plant tissue [17] (see equation (3)).

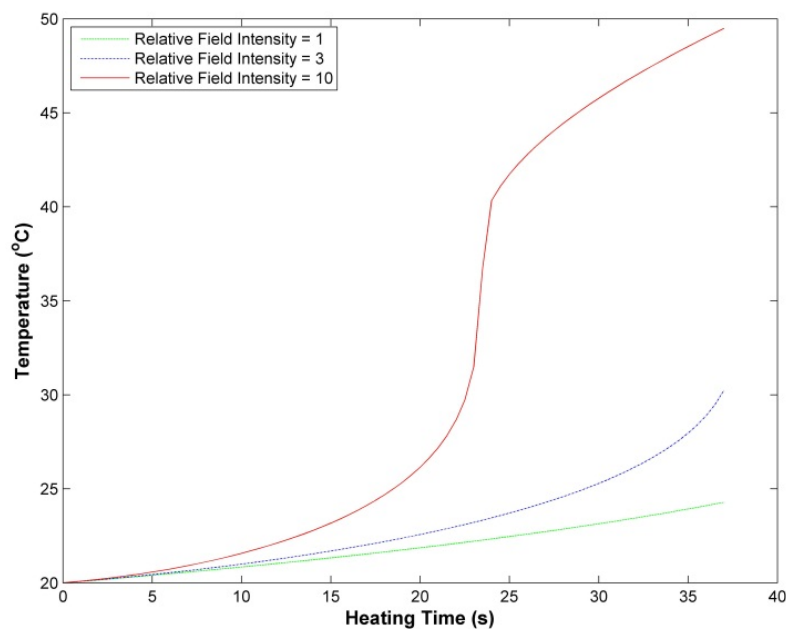
In most cases, thermal runaway is a problem during microwave heating. It usually leads to undesirable charring of the microwave heated material (see Figure 2) [91]; however it has been very effectively used in some applications such as the development of a microwave drill [92, 93] and preconditioning of wood for further preservative treatment and drying [94, 95].

Vriezinga has concluded that thermal runaway in moist materials, and water in general, is caused by: the specific characteristic of the dielectric properties of water, which decrease with increasing temperature [87] (Figure 4); and resonance of the electromagnetic waves within the irradiated medium due to changes in the dielectric properties of the material during heating [87, 88]. Resonance will only occur when the object's dimensions are some multiple of the wave length of the microwave fields inside the object. That is why thermal runaway only becomes evident in the 15 mm diameter stem (Figure 9), while the smaller stems are too small to allow internal field resonance. Internal steam pressure, induced by

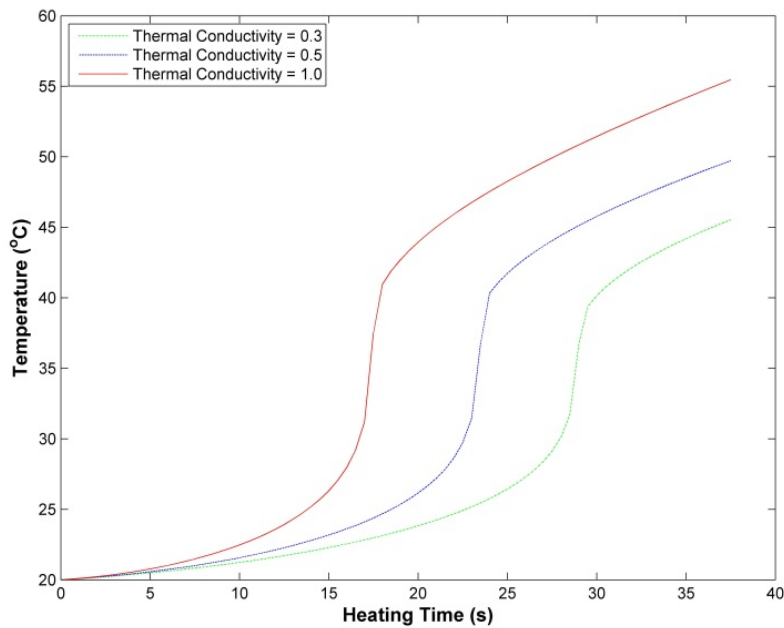


**Figure 9.** Temperature response, at constant microwave power density at a frequency of 2.45 GHz, in the centre of a plant stem as a function of plant stem diameter, calculated using equation (17) and assuming moisture content loss ( $MC = 0.87$  to  $0.10$ ) described by equation (10)

thermal runaway, may cause stem rupture, if sufficient microwave field intensity can be focused onto the plants (Figure 10).



**Figure 10.** Temperature response in the centre of a 15 mm diameter plant stem as a function of applied microwave field intensity, calculated using equation (17) and assuming moisture content loss ( $MC = 0.87$  to  $0.10$ ) described by equation (10)



**Figure 11.** Temperature response in the centre of a 15 mm diameter plant stem as a function of tissue thermal conductivity, calculated using equation (17) and assuming moisture content loss ( $MC = 0.87$  to  $0.10$ ) described by equation (10)

Moriwaki et al [96] studied the dehydrochlorination of polyvinyl chloride (PVC) by microwave irradiation using an optical fibre thermo-sensor to investigate the relationship between temperature and microwave absorption onto PVC. Their observations were that: at the beginning of microwave irradiation, the temperature rose in direct proportion to the strength of the incident microwave power and irradiation time; after exceeding a critical condition, the temperature rose quickly (thermal runaway); higher incident microwave power led to thermal runaway starting earlier in the heating process; and higher pre-heating temperatures also led to a faster onset of thermal runaway conditions. These findings are consistent with the modelling displayed in Figures 9, 10, and 11.

Total treatment time, and therefore total applied microwave energy, could be significantly reduced, if thermal runaway can be induced in weed plants during microwave treatment. For example, extrapolating the data presented in Figure 9, it takes approximately 200 to 250 seconds for the 10 mm diameter stem to reach  $40^{\circ}\text{C}$ ; however the 15 mm diameter stem reaches  $40^{\circ}\text{C}$  in 25 seconds under the same applied microwave power. Therefore the energy required to achieve this temperature rise in the 15 mm diameter stem is only 10 % of the energy needed to heat the 10 mm diameter stem.

Based on existing data, phenomena such as thermal runaway, and the nonlinear temperature/ microwave field strength relationships, it is difficult to discuss “scale up” from small laboratory studies and modelling exercises such as have been used here; however if thermal runaway can be induced in plant tissues, treatment time, and the associated treatment energy, may be drastically reduced; resulting in comparable energy needs to those

associated with conventional chemical weed control. This scenario can only be explored by further research into the microwave heating of living plants and plant based materials.

In weed control, microwave radiation is not affected by wind, which extends the application periods compared with conventional herbicide spraying. Energy can also be focused onto individual plants without affecting adjacent plants [75]. This would be very useful for in-crop or spot weed control activities. Microwave energy can also kill the roots and seeds that are buried to a depth of several centimetres in the soil [73, 97].

## 6. Microwave treatment of animal fodder

Hay is an important feed source for ruminant animals so every effort should be made to improve its feed conversion efficiency and reduce the risk of importing weed seeds as hay is transported from one location to another. Similarly, cereal grains are the base of most horse rations, because they are a valuable source of digestible energy; however their use is always associated with some risk.

The major concern when feeding cereal grains to horses is the risk of incomplete starch digestion in the small intestine, which enables significant amounts of starch to pass through to the caecum and colon. When starch is able to reach these organs it rapidly ferments producing an accumulation of acidic products, which place the horse at risk of developing serious and potentially fatal illnesses such as laminitis, colic and ulcers [98].

Dong *et al.*[99] discovered that organic matter degradability of wheat straw in the rumen of yaks was increased by around 20% after 4 min of treatment in a 750 W, 2.54 GHz, microwave oven. Sadeghi and Shawrang [100] showed that microwave treatment of canola meal increased *in vitro* dry matter disappearance, including substances that were deemed to be ruminally undegradable. Sadeghi and Shawrang [101] also showed that microwave treatment reduced the rumen degradable starch fraction of corn grain and decreased crude protein degradation of soya-bean meal [102] compared with untreated samples. No studies of microwave treatment of horse feeds could be found in the available literature.

Small scale *in vitro* pepsin-cellulase digestion experiments [103], similar to the technique developed by McLeod and Minson [104, 105], demonstrated that microwave treatment: increased dry matter percentage with increasing microwave treatment time; increased *in vitro* dry matter disappearance with increasing microwave treatment time; but had no significant effect on post-digestion crude protein content.

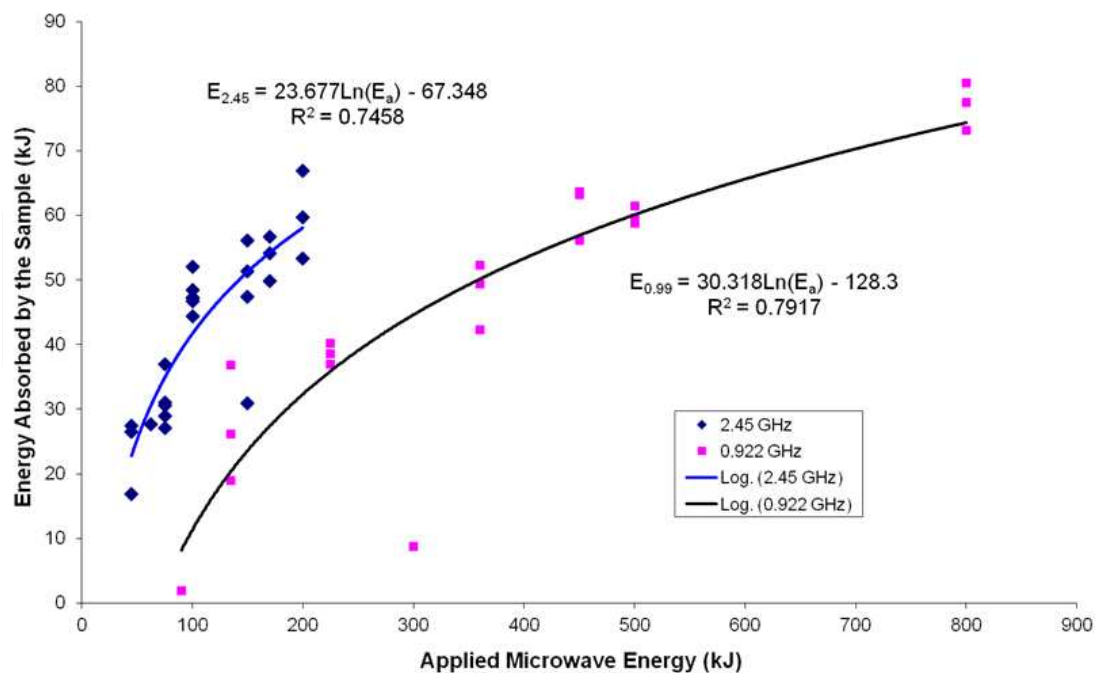
When 25 kg bags of lucerne fodder, treated in an experimental 6 kW, 2.45 GHz, microwave heating chamber [31] were subjected to a similar *in vitro* pepsin-cellulase digestion study, dry matter disappearance significantly increased compared to the untreated samples; however there was no significant difference attributable to the duration of microwave treatment. Feeding 12-14 month old Merino sheep on a "maintenance ration" of microwave treated Lucerne resulted in a significant increase in body weight instead of the relatively constant body weight that would be expected from a maintenance ration. By the end of the 5 week feeding trial the control group was only 0.4 % heavier than when they started, which



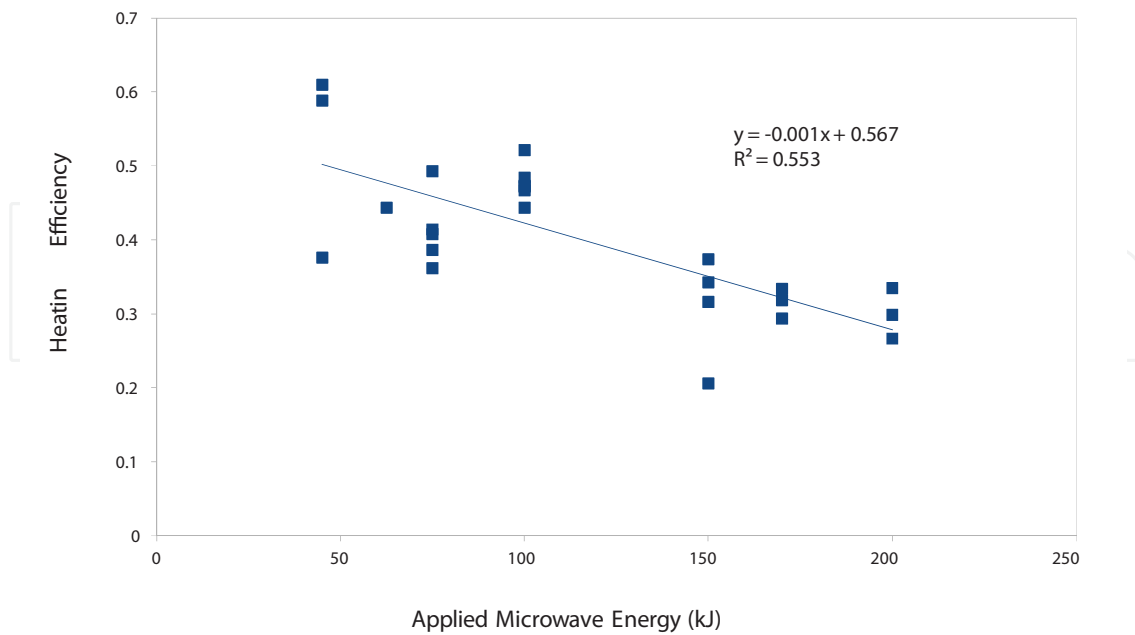
would be expected from a maintenance ration. However the group being fed the microwave treated lucerne gained 7 % of their initial body weight in the second week of the trial and maintained this body weight until the end of the trial. Their finishing weight after 5 weeks was 8.1 % higher than their starting weight [103].

*In vitro* assessment of microwave treated oats, using the Megazyme Total Starch Assay Procedure [106], which simulates the initial digestive processes in the stomach and small intestines of a horse, demonstrated significantly increased starch digestion. This implies that less undigested starch should proceed through the intestinal tract where it could cause significant health risks to the animal.

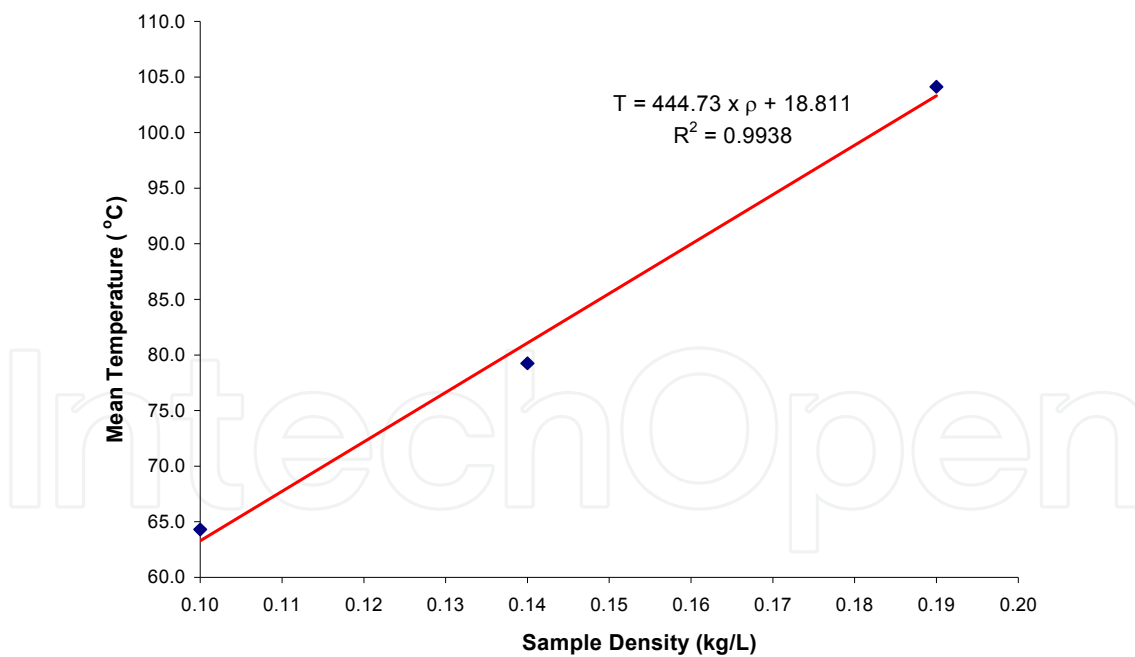
The efficiency of chaff and fodder treatment using microwave energy depends on the applied microwave energy and the frequency at which the microwave system operates. Absorbed energy, calculated by measuring the combination of sensible (temperature rise) and latent heat (moisture loss) in treated samples, is much higher at 2.45 GHz than at 922 MHz (Figure 12). It is also evident that efficiency (i.e. the ratio of absorbed energy to applied microwave energy) decreases as the applied microwave energy increases (Figure 13). This is attributable to the increasing transparency of the fodder material to microwave energy as it dries during microwave treatment. The dielectric properties, and therefore the microwave heating effect, reduce as the moisture content of plant materials decrease (Figure 5). Some of these problems of material transparency during microwave treatment can be overcome by compressing the fodder, which increases its ability to absorb microwave energy (Figure 14).



**Figure 12.** Absorbed energy in crop chaff (fodder) as a function of applied microwave energy for 922 MHz and 2.45 GHz



**Figure 13.** Microwave heating efficiency in crop chaff (fodder) as a function of applied microwave energy at 2.45 GHz

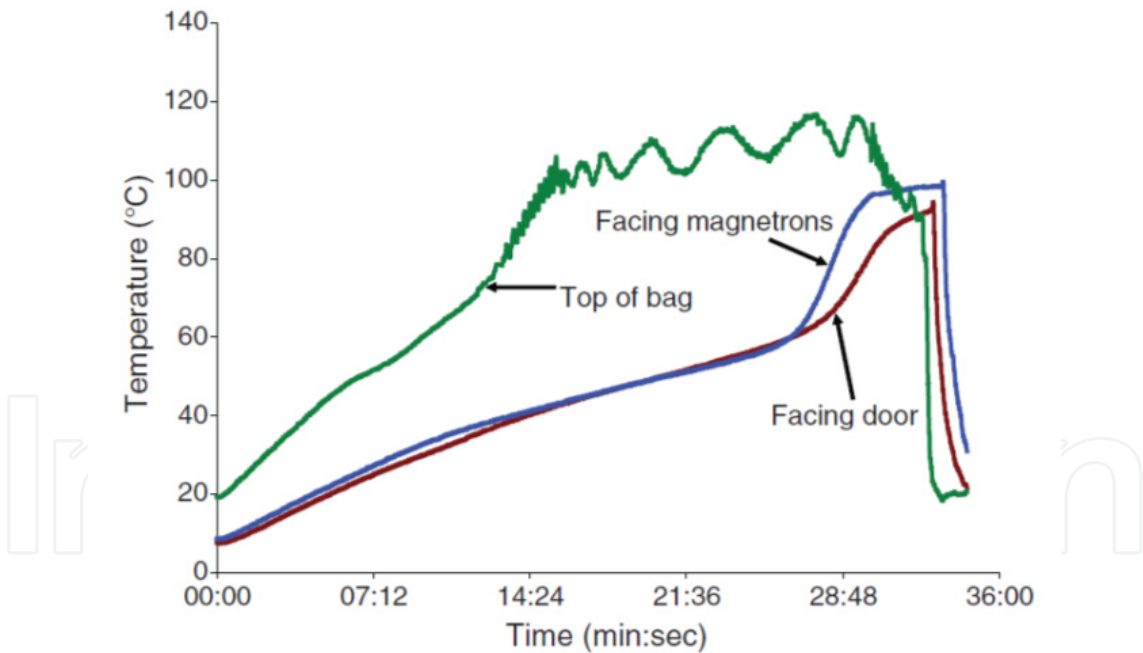


**Figure 14.** Mean temperature of 500 g samples of microwave treated fodder chaff as a function of material density ( $\rho$ ) when heated by a 2.5 kW microwave source operating at 2.45 GHz for 30 seconds

Brodie et al. [103] treated 25 kg samples of lucerne chaff in an experimental 6 kW microwave chamber [31]. The temperature in the air space at the top of the lucerne bags rose to 100 °C in ~12 min and fluctuated above 100 °C for the remainder of the treatment time (Figure 15). The

maximum temperature in the air space was 115 °C. The maximum temperature in the lucerne (99.5 °C) was measured by the probe facing the microwave magnetrons whereas the maximum temperature measured by the probe in the front of the bag, facing the door of the microwave chamber, was only 94 °C.

The temperature in the lucerne increased steadily at a rate of ~2 °C/min of microwave heating time for the first 20–25 min of heating. At this stage there was a sudden increase in heating rate (~6 °C/min) until the temperature stabilised at ~98 °C (Figure 15). The sudden jump in the heating rate after some time of steady heating may be evidence of thermal runaway (Figure 9). Observation of the treated chaff showed no signs of charring; however the chaff was dry and crisp [103]. The onset of thermal runaway dramatically increases the heating efficiency. In this example, the heating rate during thermal runaway is three times higher than during the normal heating phase. Provided charring can be avoided, inducing thermal runaway in the treated chaff may drastically improve treatment efficiency. The onset of thermal runaway is usually quicker when the microwave field intensity is higher (Figure 10) and the thermal conductivity of the material is increased. In the case of fodder chaff, thermal conductivity is proportional to density, which may partially explain why increasing the material density significantly increases the heating rate of the chaff (Figure 14). This needs further exploration.



**Figure 15.** Temperature data from three locations within one 25-kg bag of lucerne being treated for 30 minutes

## 7. Microwave assisted extraction

During microwave assisted extraction (MAE), plant materials such as wood, seeds and leaves are suspended in solvents and the mixture is exposed to microwave heating instead

of conventional heating. Enhanced rates of plant oil extraction have been observed for a range of plant materials. Chen and Spiro [107] examined the extraction of the essential oils of peppermint and rosemary from hexane and ethanol mixtures and found that yields were more than one third greater in the microwave assisted extractions. Saoud *et al.* [108] studied MAE of essential oils from tea leaves and achieved higher yields (26.8 mg/g) than conventional steam distillation (24 mg/g).

Chemat *et al.* [109] studied the extraction of oils from limonene and caraway seeds and found that MAE led to more rapid extraction as well as increased yields. Scanning electron microscopy of the microwave treated and untreated seeds revealed significantly increased rupture of the cell walls in the treated seeds. MAE also led to a more chemically complex extract, which was thought to be a better representation of the true composition of the available oils in caraway seed.

Although less well described in the literature, an alternative approach for utilizing microwave heating of plant based materials has been to treat the materials with microwave energy prior to conventional extraction processes [110]. Microwave preconditioning of sugar cane prior to juice diffusion studies led to significant decreases in colour and significant increases in juice yield, Brix %, purity and Pol % [111]. Microwave treatment significantly reduced the compression strength of the sugar cane samples [111], especially while the cane was still hot from the microwave treatment. This treatment option reduced the compressive strength of the cane to about 18 % of its original strength, implying that much less energy would be required to crush the cane for juice extraction.

Controlled application of microwave heating to green timber [18, 41, 94, 112-114] results in local steam explosions and can directly manipulate both permeability and density with potentially less strength loss than is caused by conventional steam conditioning. This technique does not attempt to dry the wood using microwave energy. Rather, it is used to modify the wood structure to facilitate faster drying in more conventional systems. This technology has the potential to: relieve internal log stresses in susceptible species; substantially accelerate drying; improve preservative treatment and resin uptake; and produce new wood-based products for commercial applications. Application of microwave processing technology has the potential to streamline production and to facilitate conveyor belt automation in the timber industry.

## 8. Microwave assisted pyrolysis and bio-fuel extraction

Three different thermo-chemical conversion processes are possible, depending on the availability of oxygen during the process: combustion (complete oxidation), gasification (partial oxidation) and pyrolysis (thermo-chemical degradation without oxygen). Among these, combustion is the most common option for recovering energy. Combustion is also associated with the generation of carbon oxides, sulphur, nitrogen, chlorine products (dioxins and furans), volatile organic compounds, polycyclic aromatic hydrocarbons, and dust [115]; however gasification and pyrolysis offer greater efficiencies in energy production, recovery of other compounds and less pollution.

Most studies of pyrolysis behaviour have considered lingo-cellulosic materials, which comprise of a mixture of hemicellulose, cellulose, lignin and minor amounts of other organic compounds. While cellulose and hemicelluloses form mainly volatile products during pyrolysis due to the thermal cleavage of the sugar units, lignin mainly forms char since it is not readily cleaved into lower molecular weight fragments [115]. Wood, crops, agricultural and forestry residues, and sewage sludges [116] can be subjected to pyrolysis processes to recover valuable chemicals and energy.

Conventional heating transfers heat from the surface towards the centre of the material by convection, conduction and radiation; however microwave heating is a direct conversion of electromagnetic energy into thermal energy within the volume of the material [20]. In microwave heating, the material is at higher temperature than its surroundings, unlike conventional heating where it is necessary for the surrounding atmosphere to reach the desired operating temperature before heating the material [115]. Consequently, microwave heating favours pyrolysis reactions involving the solid material, while conventional heating improves the reactions that take place in surroundings, such as homogeneous reactions in the gas-phase [115]. In microwave heating, the lower temperatures in the microwave cavity can also be useful for condensing the final pyrolysis vapours on the cavity walls.

Microwave assisted pyrolysis yields more gas and less carbonaceous (char) residue, which demonstrate the efficiency of microwave energy [115]. The conversion rates in microwave assisted pyrolysis are always higher than those observed in conventional heating at any temperature. The differences between microwave heating and conventional heating seems to be reduced with temperature increase, which points to the higher efficiency of microwave heating at lower temperatures [115].

Bio-fuel extraction is facilitated when microwave energy is used to thermally degrade various organic polymers to facilitate extraction of sugars for fermentation [117]. These sugars can then be fermented and distilled to create fuel alcohols. Woody plant materials are commonly subjected to microwave assisted bio-fuel extraction; however other materials such as discharge from food processing industries, agriculture and fisheries can also be processed using these techniques. Other materials that have been subjected to microwave assisted bio-fuel extraction include: soybean residue; barley malt feed; tea residues; stones from Japanese apricots; corn pericarp, which is a by-product from corn starch production; and Makombu (*Laminaria japonica*), which is a kind of brown sea algae.

## 9. Conclusion

Microwave and radio frequency heating have many potential applications in the agricultural and forestry industries. This chapter has discussed a few of these, but there are many more that have not been included. The purpose of this chapter was to encourage practitioners within the microwave engineering and agricultural and forestry industries to explore the many possibilities of applying microwave heating to address many problems and opportunities within the primary industries.

## Nomenclature

$\Omega$ = combined temperature and moisture vapour parameter

$a_v$ = air space fraction in the material

$b$ = Microwave drying constant to be determined experimentally

$C$ = thermal capacity of the composite material ( $\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$ )

$D_a$ = vapor diffusion coefficient of water vapor in air ( $\text{m}^2 \text{ s}^{-1}$ )

$E$ = electric field associated with the microwave ( $\text{V m}^{-1}$ )

$E_o$ = magnitude of the electric field external to the work load ( $\text{V m}^{-1}$ )

$E_m$ = Microwave energy (J)

$f$ = complex wave number of the form  $f = \alpha + j\beta$

$h$ = convective heat transfer at the surface of a heated object ( $\text{W m}^{-1} \text{ K}^{-1}$ )

$i_o(x)$  = modified spherical Bessel function of the first kind of order zero

$I_o(x)$ = modified Bessel function of the first kind of order zero

$j_o(x)$  = spherical Bessel function of the first kind of order zero

$J_o(x)$  = Bessel function of the first kind of order zero

$i_1(x)$  = modified spherical Bessel function of the first kind of order one

$I_1(x)$ = modified Bessel function of the first kind of order one

$k$ = thermal conductivity of the composite material ( $\text{W m}^{-1} \text{ } ^\circ\text{C}^{-1}$ )

$L$ = latent heat of vaporization of water ( $\text{J kg}^{-1}$ )

$M_v$ = moisture vapor concentration in the pores of the material ( $\text{kg m}^{-3}$ )

$MC$ = Moisture content ( $\text{kg kg}^{-1}$  dry matter)

$MC_i$ = Initial moisture content ( $\text{kg kg}^{-1}$  dry matter)

$MC_f$ = Final moisture content ( $\text{kg kg}^{-1}$  dry matter)

$n$  = constant of association relating water vapor concentration to internal temperature of a solid

$p$  = constant of association relating internal temperature of a solid to water vapor concentration

$q$ = volumetric heat generated by microwave fields ( $\text{W m}^{-3}$ )

$r$ = radial distance from the centre of a cylinder or sphere (m)

$r_o$ = external radius of the cylinder or sphere (m)

$t$ = heating time (s)

$T$ = temperature ( $^\circ\text{C}$ )

$W$ = thickness of the slab (m)

$x$ = linear distance across the aperture of a horn antenna (m)

$z$ = linear distance from the surface of a slab (m)

$\Gamma$ = internal reflection coefficient

$\alpha$  = real part of the complex wave number  $f$

$\beta$ = imaginary part of the complex wave number  $f$

$\delta$ = phase shift of microwave fields at the surface of a material

$\epsilon_o$ = electrical permittivity of free space

$\gamma$ = combined diffusivity for simultaneous heat and moisture transfer

$\kappa'$  = relative dielectric constant of the material



$\kappa''$  = dielectric loss factor of the material

$\lambda$  = wave length inside a material (m)

$\rho$  = composite material density ( $\text{kg m}^{-3}$ )

$\rho_s$  = density of the solid material ( $\text{kg m}^{-3}$ )

$\sigma$  = constant of association relating moisture vapor concentration to moisture content in a solid

$\tau$  = transmission coefficient for incoming microwave

$\tau_v$  = tortuosity factor

$\omega$  = angular frequency ( $\text{rad s}^{-1}$ )

## Author details

Graham Brodie

*Melbourne School of Land and Environment, University of Melbourne, Australia*

## 10. References

- [1] Commonwealth Department of Transport and Communications (1991) Australian Radio Frequency Spectrum Allocations. Canberra: Commonwealth Department of Transport and Communications
- [2] Ayappa K G, Davis H T, Crapiste G, Davis E J and Gordon J (1991) Microwave heating: An evaluation of power formulations. *Chemical Engineering Science*. 46: 1005-1016.
- [3] Antti A L and Perre P (1999) A microwave applicator for on line wood drying: Temperature and moisture distribution in wood. *Wood Science and Technology*. 33: 123-138.
- [4] Hasna A, Taube A and Siores E (2000) Moisture Monitoring of Corrugated Board During Microwave Processing. *Journal of Electromagnetic Waves and Applications*. 14: 1563.
- [5] Zielonka P and Dolowy K (1998) Microwave Drying of Spruce: Moisture Content, Temperature and Heat Energy Distribution. *Forest Products Journal*. 48: 77-80.
- [6] Bond E J, Li X, Hagness S C and Van Veen B D (2003) Microwave imaging via space-time beamforming for early detection of breast cancer. *IEEE Transaction on Antennas and Propagation*. 51: 1690-1705.
- [7] Nelson S O (1972) Insect-control possibilities of electromagnetic energy. *Cereal Science Today*. 17: 377-387.
- [8] Nelson S O and Stetson L E (1985) Germination responses of selected plant species to RF electrical seed treatment. *Transactions of the ASAE*. 28: 2051-2058.
- [9] Arrieta A, Otaegui D, Zubia A, Cossio F P, Diaz-Ortiz A, delaHoz A, Herrero M A, Prieto P, Foces-Foces C, Pizarro J L and Arriortua M I (2007) Solvent-Free Thermal and Microwave-Assisted [3 + 2] Cycloadditions between Stabilized Azomethine Ylides and Nitrostyrenes. An Experimental and Theoretical Study. *Journal of Organic Chemistry*. 72: 4313-4322.

- [10] Nelson S O (2003) Microwave and radio-frequency power applications in agriculture. In: Folz D C, Booske J H, Clark D E and Gerling J F editors. Third World Congress on Microwave and Radio Frequency Applications. Westerville, OH: The American Ceramic Society. pp. 331-340
- [11] Chu J L and Lee S (1993) Hygrothermal stresses in a solid: Constant surface stress. *Journal of Applied Physics*. 74: 171-188.
- [12] Henry P S H (1948) The diffusion of moisture and heat through textiles. *Discussions of the Faraday Society*. 3: 243-257.
- [13] Crank J (1979) *The Mathematics of Diffusion*. Bristol: J. W. Arrowsmith Ltd.
- [14] Vos M, Ashton G, Van Bogart J and Ensminger R (1994) Heat and Moisture Diffusion in Magnetic Tape Packs. *IEEE Transactions on Magnetics*. 30: 237-242.
- [15] Fan J, Luo Z and Li Y (2000) Heat and moisture transfer with sorption and condensation in porous clothing assemblies and numerical simulation. *International Journal of Heat and Mass Transfer*. 43: 2989-3000.
- [16] Fan J, Cheng, X., Wen, X., and Sun, W. (2004) An improved model of heat and moisture transfer with phase change and mobile condensates in fibrous insulation and comparison with experimental results. *International Journal of Heat and Mass Transfer*. 47: 2343-2352.
- [17] Brodie G (2007) Simultaneous heat and moisture diffusion during microwave heating of moist wood. *Applied Engineering in Agriculture*. 23: 179-187.
- [18] Torgovnikov G and Vinden P (2003) Innovative microwave technology for the timber industry. In: Folz D C, Booske J H, Clark D E and Gerling J F editors. *Microwave and Radio Frequency Applications: Proceedings of the Third World Congress on Microwave and Radio Frequency Applications*. Westerville, Ohio: The American Ceramic Society. pp. 349-356
- [19] Brodie G (2010) Wood: Microwave Modification of Properties. In: Heldman D R editor. *Encyclopedia of Agricultural, Food and Biological Engineering*. London: Taylor & Francis. pp. 1878 - 1881
- [20] Metaxas A C and Meredith R J (1983) *Industrial Microwave Heating*. London: Peter Peregrinus.
- [21] Brodie G (2008) The influence of load geometry on temperature distribution during microwave heating. *Transactions of the American Society of Agricultural and Biological Engineers*. 51: 1401-1413.
- [22] Vriezinger C A (1998) Thermal runaway in microwave heated isothermal slabs, cylinders, and spheres. *Journal of Applied Physics*. 83: 438 -442.
- [23] Van Remmen H H J, Ponne C T, Nijhuis H H, Bartels P V and Herkhof P J A M (1996) Microwave Heating Distribution in Slabs, Spheres and Cylinders with Relation to Food Processing. *Journal of Food Science*. 61: 1105-1113.

- [24] Ohlsson T and Risman P O (1978) Temperature distributions of microwave heating - spheres and cylinders. *Journal of Microwave Power and Electromagnetic Energy*. 13: 303-310.
- [25] Manickavasagan A, Jayas D S and White N D G (2006) Non-Uniformity of Surface Temperatures of Grain after Microwave Treatment in an Industrial Microwave Dryer. *Drying Technology*. 24: 1559-1567.
- [26] Setiady D, Tang J, Younce F, Swanson B A, Rasco B A and Clary C D (2009) Porosity, Color, Texture, and Microscopic Structure of Russet Potatoes Dried Using Microwave Vacuum, Heated Air, and Freeze Drying *Applied Engineering in Agriculture*. 25: 719-724.
- [27] Higgins T R and Spooner A E (1986) Microwave drying of alfalfa compared to field-and oven-drying: Effects on forage quality. *Animal Feed Science and Technology*. 16: 1-6.
- [28] Adu B and Otten L (1996) Microwave heating and mass transfer characteristics of white beans. *Journal of Agricultural Engineering Research*. 64: 71 -78.
- [29] Nelson S O (1987) Frequency, moisture, and density dependence of the dielectric properties of small grains and soybeans. *Transactions of the American Society of Agricultural and Biological Engineers*. 30: 1538-1541.
- [30] Kiranoudis C T, Maroulis Z B, Tsami E and Marinos-Kouris D (1993) Equilibrium moisture content and heat of desorption of some vegetables. *Journal of Food Engineering*. 20: 55-74.
- [31] Harris G A, Brodie G I, Ozarska B and Taube A (2011) Design of a Microwave Chamber for the Purpose of Drying of Wood Components for Furniture. *Transactions of the American Society of Agricultural and Biological Engineers*. 54: 363-368.
- [32] Walde S G, Balaswamy K, Velu V and Rao D G (2002) Microwave drying and grinding characteristics of wheat (*Triticum aestivum*). *Journal of Food Engineering*. 55: 271-276.
- [33] Velu V, Nagender A, Prabhakara Rao P G and Rao D G (2006) Dry milling characteristics of microwave dried maize grains (*Zea mays* L.). *Journal of Food Engineering*. 74: 30-36.
- [34] Carter C A, Chalfant J A, Goodhue R E, Han F M and DeSantis M (2005) The Methyl Bromide Ban: Economic Impacts on the California Strawberry Industry. *Review of Agricultural Economics*. 27: 181-197.
- [35] Wang S, Tang J, Cavalieri R P and Davis D C (2003) Differential heating of insects in dried nuts and fruits associated with radio frequency and microwave treatment. *Transactions of the ASAE*. 46: 1175-1182.
- [36] Nelson S O (2001) Radio-frequency and microwave dielectric properties of insects. *Journal of Microwave Power and Electromagnetic Energy*. 36: 47-56.
- [37] Headlee T J (1931) The difference between the effect of radio waves on insects and on plants. *Journal of Economic Entomology*. 24: 427-437.

- [38] Headlee T J and Burdette R C (1929) Some Facts Relative to the Effect of High Frequency Radio Waves on Insect Activity. *Journal of the New York Entomological Society*. 37: 59-64.
- [39] Nelson S O (1996) Review and assessment of radio-frequency and microwave energy for stored-grain insect control. *Transactions of the ASAE*. 39: 1475-1484.
- [40] Nzokou P, Tourtellot S and Kamdem D P (2008) Kiln and microwave heat treatment of logs infested by the emerald ash borer (*Agrilus planipennis* Fairmaire) (Coleoptera: Buprestidae). *Forest Products Journal*. 58: 68.
- [41] Torgovnikov G and Vinden P (2009) High-intensity microwave wood modification for increasing permeability. *Forest Products Journal*. 59: 84-92.
- [42] Plaza P J, Zona A T, Sanshis R, Balbastre J V, Martinez A, Munoz E M, Gordillo J and Reyes E d l (2007) Microwave disinfestation of bulk wood. *Journal of Microwave Power and Electromagnetic Energy*. 41: 21-36.
- [43] Brodie G I (2008) Innovative wood drying: Applying microwave and solar technologies to wood drying. Saarbruecken, Germany: VDM Verlag. 120 p.
- [44] Pimentel D, Lach L, Zuniga R and Morrison D (2002) Environmental and economic costs associated with non-indigenous species in the United States. In: Pimentel D editor. *Biological invasions: economic and environmental costs of alien plant, animal, and microbe species*. Boca Raton; USA: CRC Press Inc. pp. 285-303
- [45] Riley J R (1992) A millimetric radar to study the flight of small insects. *Electronics & Communication Engineering Journal*. 4: 43-48.
- [46] Meissner T and Wentz F J (2004) The Complex Dielectric Constant of Pure and Sea Water From Microwave Satellite Observations. *IEEE Transactions on Geoscience and Remote Sensing*. 42: 1836-1849.
- [47] Ellison W J, Lamkaouchi K and Moreau J M (1996) Water: a dielectric reference. *Journal of Molecular Liquids*. 68: 171-279.
- [48] Torgovnikov G I (1993) *Dielectric Properties of Wood and Wood-Based Materials*. Berlin: Springer-Verlag.
- [49] Jackson A and Day D (1989) *Wood Worker's Manual*. Sydney: William Collins Sons & Co. Ltd.
- [50] Lewis V R and Haverty M I (1996) Evaluation of six techniques for control of the western drywood termite (Isoptera: Kalotermitidae) in structures. *Journal of Economic Entomology*. 89: 922-934.
- [51] Lewis V R, Power, A. B., and Haverty, M. I. (2000) Laboratory evaluation of microwaves for control of the western drywood termite. *Forest Products Journal*. 50: 79-87.
- [52] Tirkel A Z, Lai J C S, Evans T A and Rankin G A (2011) Heating and Provocation of Termites Using Millimeter Waves. *Progress in Electromagnetic Research Symposium (Online)*. 7: 27-30.

- [53] Halverson S L, Burkholder W E, Bigelow T S, Nordheim E V and Misenheimer M E (1996) High-power microwave radiation as an alternative insect control method for store products. *Journal of Economic Entomology*. 89: 1638-1648.
- [54] Park D, Bitton G and Melker R (2006) Microbial inactivation by microwave radiation in the home environment. *Journal of Environmental Health*. 69: 17-24.
- [55] Devine A A, Grunden A M, Krisiunas E, Davis D K, Rosario G, Scott S, Faison S and Cosby W M (2007) Testing the Efficacy of a Combination of Microwave and Steam Heat for Log Reduction of the Microbial Load Following a Simulated Poultry Mass Mortality Event. *Applied Biosafety*. 12: 79-84.
- [56] DAFF (2006) Weeds. Australian Department of Agriculture, Fisheries and Forestry
- [57] Kremer R J (1993) Management of Weed Seed Banks with Microorganisms. *Ecological Applications*,. 3: 42-52.
- [58] Batlla D and Benech-Arnold R L (2007) Predicting changes in dormancy level in weed seed soil banks: Implications for weed management. *Crop Protection/Weed Science in Time of Transition*. 26: 189-197.
- [59] Bebawi F F, Cooper A P, Brodie G I, Madigan B A, Vitelli J S, Worsley K J and Davis K M (2007) Effect of microwave radiation on seed mortality of rubber vine (*Cryptostegia grandiflora* R.Br.), parthenium (*Parthenium hysterophorous* L.) and bellyache bush (*Jatropha gossypifolia* L.). *Plant Protection Quarterly*. 22: 136-142.
- [60] Ark P A and Parry W (1940) Application of High-Frequency Electrostatic Fields in Agriculture. *The Quarterly Review of Biology*. 15: 172-191.
- [61] Tran V N (1979) Effects of Microwave Energy on the Strophiole, Seed Coat and Germination of Acacia Seeds. *Australian Journal of Plant Physiology*. 6: 277-287.
- [62] Tran V N and Cavanagh A K (1979) Effects of microwave energy on *Acacia longifolia*. *Journal of Microwave Power*. 14: 21-27.
- [63] Davis F S, Wayland J R and Merkle M G (1971) Ultrahigh-Frequency Electromagnetic Fields for Weed Control: Phytotoxicity and Selectivity. *Science*. 173: 535-537.
- [64] Davis F S, Wayland, J. R. and Merkle, M. G. (1973) Phytotoxicity of a UHF Electromagnetic Field. *Nature*. 241: 291-292.
- [65] Wolf W W, Vaughn C R, Harris R and Loper G M (1993) Insect radar cross-section for aerial density measurement and target classification. *Transactions of the American Society of Agricultural and Biological Engineers*. 36: 949-954.
- [66] Barker A V and Craker L E (1991) Inhibition of weed seed germination by microwaves. *Agronomy Journal*. 83: 302-305.
- [67] Haller H E (2002) Microwave Energy Applicator. United States Patent 20020090268A1,
- [68] Clark W J and Kissell C W (2003) System and Method for In Situ Soil Sterilization, Insect Extermination and Weed Killing. United States Patent 20030215354A1,
- [69] Grigorov G R (2003) Method and System for Exterminating Pests, Weeds and Pathogens. United States Patent 20030037482A1,



- [70] Nelson S O (1996) A review and assessment of microwave energy for soil treatment to control pests. *Transactions of the ASAE*. 39: 281-289.
- [71] Brodie G, Botta C and Woodworth J (2007) Preliminary investigation into microwave soil pasteurization using wheat as a test species. *Plant Protection Quarterly*. 22: 72-75.
- [72] Brodie G, Harris G, Pasma L, Travers A, Leyson D, Lancaster C and Woodworth J (2009) Microwave soil heating for controlling ryegrass seed germination. *Transactions of the American Society of Agricultural and Biological Engineers*. 52: 295-302.
- [73] Brodie G, Hamilton S and Woodworth J (2007) An assessment of microwave soil pasteurization for killing seeds and weeds. *Plant Protection Quarterly*. 22: 143-149.
- [74] Connor F R (1972) *Antennas*. London: Edward Arnold.
- [75] Brodie G, Ryan C and Lancaster C (2012) Microwave technologies as part of an integrated weed management strategy: A Review. *International Journal of Agronomy*. 2012: 1-14.
- [76] Brodie G, Pasma L, Bennett H, Harris G and Woodworth J (2007) Evaluation of microwave soil pasteurization for controlling germination of perennial ryegrass (*Lolium perenne*) seeds. *Plant Protection Quarterly*. 22: 150-154.
- [77] Brodie G, Ryan C and Lancaster C (2012) The effect of microwave radiation on Paddy Melon (*Cucumis myriocarpus*). *International Journal of Agronomy*. 2012: 1-10.
- [78] Bigu-Del-Blanco J, Bristow J M and Romero-Sierra C (1977) Effects of low-level microwave radiation on germination and growth rate in corn seeds. *Proceedings of the IEEE*. 65: 1086-1088.
- [79] Helsel Z R (1992) Energy and alternatives for fertilizer and pesticide use. In: Fluck R C editor. *Energy in Farm Production*. New York: Elsevier. pp. 177-201
- [80] Hülsbergen K J, Feil B, Biermann S, Rathke G W, Kalk W D and Diepenbrock W (2001) A method of energy balancing in crop production and its application in a long-term fertilizer trial. *Agriculture, Ecosystems & Environment*. 86: 303-321.
- [81] Mari G R and Chengying J (2007) Energy Analysis of various tillage and fertilizer treatments on corn production. *American-Eurasian Journal of Agricultural and Environmental Science*. 2: 486-497.
- [82] Mari G R and Changying J (2007) Energy analysis of various tillage and fertilizer treatments on corn production. *American-Eurasian Journal of Agricultural and Environmental Science*. 2: 486-497.
- [83] Langner H-R, Böttger H and Schmidt H (2006) A Special Vegetation Index for the Weed Detection in Sensor Based Precision Agriculture. *Environmental Monitoring and Assessment*. 117: 505-518.
- [84] Heap I M (1997) The occurrence of herbicide-resistant weeds worldwide. *Pesticide Science*. 51: 235-243.
- [85] Hill J M and Marchant T R (1996) Modelling Microwave Heating. *Applied Mathematical Modeling*. 20: 3-15.



- [86] Vriezinga C A (1996) Thermal runaway and bistability in microwave heated isothermal slabs. *Journal of Applied Physics*. 79: 1779 -1783.
- [87] Vriezinga C A (1999) Thermal profiles and thermal runaway in microwave heated slabs. *Journal of Applied Physics*. 85: 3774 -3779.
- [88] Vriezinga C A, Sanchez-Pedreno S and Grasman J (2002) Thermal runaway in microwave heating: a mathematical analysis. *Applied Mathematical Modelling*. 26: 1029 -1038.
- [89] Ulaby F T and El-Rayes M A (1987) Microwave Dielectric Spectrum of Vegetation - Part II: Dual-Dispersion Model. *IEEE Transactions on Geoscience and Remote Sensing*. GE-25: 550-557.
- [90] El-Rayes M A and Ulaby F T (1987) Microwave Dielectric Spectrum of Vegetation-Part I: Experimental Observations. *Geoscience and Remote Sensing, IEEE Transactions on*. GE-25: 541-549.
- [91] Zielonka P, Gierlik G, Matejak M and Dolowy K (1997) The comparison of experimental and theoretical temperature distribution during microwave wood heating. *Holz als Roh- und Werkstoff*. 55: 395-398.
- [92] Jerby E, Dikhtyar V, Aktushev O and Groszlick U (2002) The microwave drill. *Science*. 298: 587-589.
- [93] Jerby E, Aktushev, O., and Dikhtyar, V. (2005) Theoretical analysis of the microwave-drill near-field localized heating effect. *Journal of applied physics*. 97: 034909-1 - 034909-7.
- [94] Torgovnikov G and Vinden P (2010) Microwave Wood Modification Technology and Its Applications. *Forest Products Journal*. 60: 173–182.
- [95] Vinden P, Torgovnikov G and Hann J (2010) Microwave modification of Radiata pine railway sleepers for preservative treatment. *European Journal of Wood and Wood Products*. 1-9.
- [96] Moriwaki S, Machida M, Tatsumoto H, Kuga M and Ogura T (2006) A study on thermal runaway of poly(vinyl chloride) by microwave irradiation. *Journal of Analytical and Applied Pyrolysis*. 76: 238 -242.
- [97] Diprose M F, Benson F A and Willis A J (1984) The Effect of Externally Applied Electrostatic Fields, Microwave Radiation and Electric Currents on Plants and Other Organisms, with Special Reference to Weed Control. *Botanical Review*. 50: 171-223.
- [98] Bird S, Brown W and Rowe J (2001) *Safe and Effective Grain Feeding for Horses*. Barton, ACT, Australia: Rural Industries Research and Development Corporation
- [99] Dong S, Long R, Zhang D, Hu Z and Pu X (2005) Effect of microwave treatment on chemical composition and in sacco digestibility of wheat straw in yak cow Asian-Australasian Journal of Animal Sciences. 18: 27-31.
- [100] Sadeghi A A and Shawrang P (2006) Effects of microwave irradiation on ruminal degradability and in vitro digestibility of canola meal. *Animal Feed Science and Technology*. 127: 45-54.

- [101] Sadeghi A A and Shawrang P (2006) Effects of microwave irradiation on ruminal protein and starch degradation of corn grain. *Animal Feed Science and Technology*. 127: 113-123.
- [102] Sadeghi A A, Nikkhaha A and Shawrang P (2005) Effects of microwave irradiation on ruminal degradation and in vitro digestibility of soya-bean meal. *Animal Science*. 80: 369-375.
- [103] Brodie G, Rath C, Devanny M, Reeve J, Lancaster C, Harris G, Chaplin S and Laird C (2010) The effect of microwave treatment on lucerne fodder. *Animal Production Science*. 50: 124-129.
- [104] McLeod M N and Minson D J (1978) The accuracy of the pepsin-cellulase technique for estimating the dry matter digestibility in vivo of grasses and legumes. *Animal Feed Science and Technology*. 3: 277-287.
- [105] McLeod M N and Minson D J (1980) A note on Onozuka 3S cellulase as a replacement for Onozuka SS (P1500) cellulase when estimating forage digestibility in vitro. *Animal Feed Science and Technology*. 5: 347-350.
- [106] McCleary B V, Gibson T S and Mugford D C (1997) Measurement of total starch in cereal products by amyloglucosidase-alpha-amylase method: Collaborative study. *Journal of Aoac International*. 80: 571-579.
- [107] Chen S S and Spiro M (1994) Study of microwave extraction of essential oil constituents from plant materials. *Journal of Microwave Power and Electromagnetic Energy*. 29: 231-241.
- [108] Saoud A A, Yunus R M and Aziz R A (2006) Yield study for extracted tea leaves essential oil using microwave-assisted process. *American Journal of Chemical Engineering*. 6: 22-27.
- [109] Chemat S, Aït-Amar H, Lagha A and Esveld D C (2005) Microwave-assisted extraction kinetics of terpenes from caraway seeds. *Chemical Engineering and Processing*. 44: 1320-1326.
- [110] Miletic P, Grujic R and Marjanovic-Balaban Z (2009) The application of microwaves in essential oil hydro-distillation processes. *Chemical Industry and Chemical Engineering Quarterly*. 15: 37-39.
- [111] Brodie G, Jacob M V, Sheehan M, Yin L, Cushion M and Harris G (2011) Microwave modification of sugar cane to enhance juice extraction during milling. *Journal of Microwave Power and Electromagnetic Energy*. 45: 178-187.
- [112] Vinden P and Torgovnikov G (1996) A method for increasing the permeability of wood. University of Melbourne Patent PO 0850/96,
- [113] Vinden P and Torgovnikov G (2000) The physical manipulation of wood properties using microwave. In *Proceedings of International Conference of IUFRO*. pp. 240-247
- [114] Torgovnikov G and Vinden P (2005) New microwave technology and equipment for wood modification. In: Schulz R L and Folz D C editors. *Microwave and Radio*

- Frequency Applications: Proceedings of the Fourth World Congress on Microwave and Radio Frequency Applications. Arnold MD: The Microwave Working Group. pp. 91-98
- [115] Fernandez Y, Arenillas A and Menendez J A (2011) Microwave heating applied to pyrolysis. In: Grundas S editor. Advances in Induction and Microwave Heating of Mineral and Organic Materials. Rijeka, Croatia: InTech. pp. 723-752
- [116] Dominguez A, Menendez J A, Inguanzo M and Pis J J (2005) Investigations into the characteristics of oils produced from microwave pyrolysis of sewage sludge. Fuel Processing Technology. 86: 1007 -1020.
- [117] Tsubaki S and Azuma J-i (2011) Application of microwave technology for utilization of recalcitrant biomass. In: Grundas S editor. Advances in Induction and Microwave Heating of Mineral and Organic Materials. Rijeka, Croatia: InTech. pp. 697-722