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Review Article

Microwave Technologies as Part of an Integrated Weed Management Strategy: A Review

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Interest in controlling weed plants using radio frequency or microwave energy has been growing in recent years because of the growing concerns about herbicide resistance and chemical residues in the environment. This paper reviews the prospects of using microwave energy to manage weeds. Microwave energy effectively kills weed plants and their seeds; however, most studies have focused on applying the microwave energy over a sizable area, which requires about ten times the energy that is embodied in conventional chemical treatments to achieve effective weed control. A closer analysis of the microwave heating phenomenon suggests that thermal runaway can reduce microwave weed treatment time by at least one order of magnitude. If thermal runaway can be induced in weed plants, the energy costs associated with microwave weed management would be comparable with chemical weed control.

1. Introduction

In 2006, the cost of weeds to Australian agricultural industries, due to management costs or loss of production, was estimated to be about $4 billion annually [1]. Depletion of the weed seed bank is critically important to overcome infestations of various weed species [2]. Mechanical and chemical controls are the most common methods of weed control in cropping systems [3, 4]. The success of these methods usually depends on destroying the highest number of plants during their seedling stage [3] before they interfere with crop production and subsequently set further seed. These strategies must be employed over several years to deplete the weed seed bank.

Burnside et al. [5] reported that viable weed seeds in the soil can be reduced by 95% after five years of consistent herbicide management; however, Kremer [2] pointed out that in spite of achieving good weed control over several years, weed infestations will recur in succeeding years if intensive weed management is discontinued or interrupted. These efforts to deplete the soil seed bank are hindered by the growing list of herbicide−resistant weed biotypes [6].

Interest in nonchemical weed control has been increasing with the spread of these herbicide resistant biotypes [6] and because of environmental concerns over herbicide use [7, 8]. Land managers typically use fire, steaming, flaming, grazing, soil fumigants, mechanical removal, and, to some extent, biological control techniques to manage weeds in the absence of chemical control [9, 10]. Once off mechanical or fire treatments often result in massive recruitment of new seedlings from the seed bank [10, 11], steam treatment has produced poor results [9] and flaming techniques can be dangerous if the weather is unfavourable or the fuel load is too high [10].

2. Radio Frequency and Microwave Treatments

Interest in the effects of high frequency electromagnetic waves on biological materials dates back to the late 19th century [12], while interest in the effect of high frequency waves on plant material began in the 1920s [12]. Many of the earlier experiments on plant material focused on the effect of radio frequencies (RFs) on seeds [12]. In many cases, short exposure resulted in increased germination and vigour of the emerging seedlings [13, 14]; however, long exposure usually resulted in seed death [4, 12, 15].

Davis et al. [16, 17] 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 the study by Davis et al. suggested that both the specific mass and specific volume of the seeds were strongly related to a seed's susceptibility to damage by microwave fields [17]. The association between the seed's volume and its susceptibility to microwave treatment may be linked the "*radar cross-section*" [18] presented by seeds to propagating microwaves. Large radar cross-sections allow the seeds to intercept, and therefore, absorb, more microwave energy.

Barker and Craker [19] investigated the use of microwave heating in soils of varying moisture content (10–280 g water/kg of 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 [20–22]; 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 [23] demonstrated that using microwaves to selectively heat seeds in the soil "*cannot be expected.*" He concluded that seed susceptibility to damage from microwave treatment is a purely thermal effect, resulting from soil heating and thermal conduction into the seeds. This has been confirmed experimentally by Brodie et al. [24].

Experience to date confirms that microwaves can kill a range of weed seeds in the soil [15–17, 19], however, far fewer studies have considered the efficacy of using microwave energy to manage weed plants.

3. Microwave Treatment of Plants

In weed control, microwave radiation is not affected by winds, which extends the application periods compared with conventional spraying methods. Energy can also be focused onto individual plants (Figure 1), without affecting adjacent plants. 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 [25, 26].

Davis et al. [16] 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 several times more susceptible to microwave treatment than honey mesquite plants were.

Figure 1: Selective application of microwave energy to plants in the same pot (left: unaffected; right: 15 second microwave treatment).

Figure 2: A laboratory prototype system based on a modified microwave oven.

Brodie et al. [26] studied the effect of microwave treatment on marsh mallow (*Malva parviflora*) seedlings, using a prototype microwave system based on a modified microwave oven (Figure 2).

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 channeling 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. Three horn applicators, with varying aperture dimension (180 mm by 90 mm; 130 mm by 43 mm; 86 mm by 20 mm), were developed and tested during these experiments. The marsh mallow experiment used the 180 mm by 90 mm horn applicator.

Microwave treatment wilted the leaves and may have ruptured internal structures within the marshmallow plants [26]. This prototype has also been used to study the effect of microwave energy on fleabane (*Conyza bonariensis*) and paddy melon (*Cucumis myriocarpus*) plants. Two horn applicators (130 mm by 43 mm and 86 mm by 20 mm) were used in these experiments.

It was possible to see the plants wilt during relatively short microwave treatments (Figure 3). Stem rupture

Figure 3: Paddy melon (a) immediately after microwave treatment for 15 seconds and (b) 11 days after microwave treatment and fleabane plants (c) immediately after microwave treatment for 15 seconds and (d) 11 days after microwave treatment using the 130 mm by 43 mm aperture horn antenna.

(Figure 4(a)) due to internal steam generation often occurred after the first few seconds of microwave treatment when the small aperture antenna was used. The small aperture antenna occasionally burned through the stems of fleabane plants within a few seconds of treatment (Figure 4(b)). Plant death occurred within 10 days of treatment (Figure 3).

Aperture size profoundly affected the treatment time needed to kill plants, with the smaller aperture antenna needing much less time to provide a lethal dose (Table 1). However, when the data from all treatments was pooled in terms of energy density there was no significant differences between the antenna designs. The small aperture antenna, which focused the microwave energy into a much smaller space on the plants, required much less time to deliver a lethal dose than the large aperture antenna, therefore, the total energy delivered to the plant (microwave output power multiplied by treatment time) was basically the same.

The resulting dose response curves (Figure 5) show that 350 J cm^{-2} of energy was sufficient to kill all three test species and that marsh mallow was less susceptible to microwave damage than fleabane which in turn was less susceptible to damage than paddy melon. The probability of survival for these three species can be described by a simple log-logistic response function [27]:

$$P_{\text{survival}} = \frac{1.0}{1 + (\psi/b)^n}, \tag{1}$$

where Ψ is the applied energy density (J cm^{-2}) and n and b depend on the species of plant (Table 2).

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. [28] 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^{-2} at the point of exposure. Temperature increases of only 4°C, when compared with control seedlings, were measured in the 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 and paddy melon have revealed that a very short (less than 5 seconds) pulse of microwave energy, focused onto the plant stem, was sufficient to kill these plants (Table 1).

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.

4. Simultaneous Heat and Moisture Diffusion during Microwave Heating

In his studies on textiles, Henry (1948) showed that a change in external temperature or humidity (or both), "*results in*

(a) (b)

Figure 4: (a) Ruptured stem of a paddy melon plant and (b) a severed stem of fleabane plant; both occurred after only a few seconds of microwave treatment using the 86 mm by 20 mm aperture horn antenna.

Table 1: Mean survival percentages for fleabane and paddy melon during microwave treatment experiments (unpublished data).

Species	Antenna design	Treatment time (s)					
		0	5	10	15	30	60
Fleabane	130 mm by 43 mm aperture horn antenna	100^a	100^a	100^a	60^b	0^c	0^c
	86 mm by 20 mm aperture horn antenna	100^a	70^b	0^c	0^c	0^c	0^c
Paddy melon	130 mm by 43 mm aperture horn antenna	100^a	100^a	100^a	60^b	0^c	0^c
	86 mm by 20 mm aperture horn antenna	100^a	0^c	0^c	0^c	0^c	0^c
LSD ($P < 0.05$)							16

means with different superscripts are significantly different to one another.

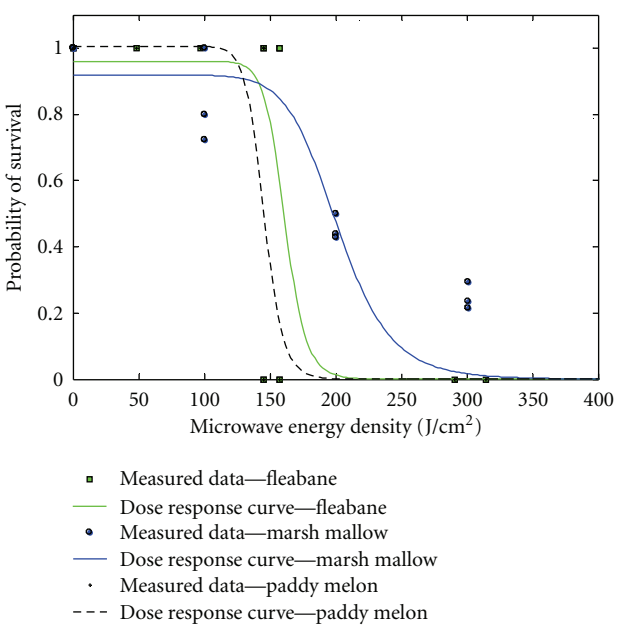

Figure 5: Microwave dose response curves for fleabane, marsh mallow and paddy melon plants.

a coupled diffusion of moisture and heat which is mathematically analogous in many respects to a pair of coupled vibrations." The combined process is equivalent to the independent diffusion of two quantities, each of which is a linear function of moisture vapor concentration and temperature [30, 31].

Table 2: Log-logistic dose response parameters for marsh mallow, fleabane and prickly paddy melon.

Species	Response parameter		
	b (J cm^{-2})	n	R^2
Marsh mallow	201.5	10	0.92
Fleabane	161.2	20	0.82
Paddy melon	145.3	20	0.90

Henry [30] states that "*the diffusion constants appropriate to these two quantities are always such that one is greater and the other less than either of the diffusion constants which would be observed for the moisture or heat, were these not coupled by the interaction.*" The slower diffusion coefficient of the coupled system is less than either of these independent diffusion constants, but never by more than one half [30]. The faster diffusion coefficient is always many times greater than either of these independent diffusion constants [30].

Henry [30] states that similar reasoning should be applied in the case where either moisture or heat are released or absorbed inside the material in a way that is independent of the diffusion process. Microwave heating is quite independent of any diffusion processes; therefore, Henry's assumptions are valid for microwave heating, so simultaneous heat and moisture diffusion should occur [29].

Considerable evidence exists for rapid heating and drying during microwave processing [32–34]. Therefore, the faster diffusion wave dominates microwave heating in moist materials [29] such as plant tissues. Effectively, volumetric

microwave heating, generates a wave of hot moisture that rapidly propagates through the material, resulting in a faster than would be expected heat transfer through the heated object. A slow heat and moisture diffusion wave should also exist; however, observing this slow wave during microwave heating may be difficult and no evidence of its influence has been seen in the literature so far.

Rapid dehydration may be linked to the unique temperature distribution inside plant stems induced by microwave heating.

5. Temperature Distributions Associated with Microwave Heating

Horn antennas (Figure 6) are very popular for microwave communication systems [35]. 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 electric field distribution in the aperture of a horn antenna, fed from a wave-guide propagating in the TE_{10} mode, is described by:

$$\vec{E} = E_o \cos\left(\frac{\pi}{a}x\right) \cdot \hat{y}\,(\mathrm{V\,m^{-1}}), \tag{2}$$

In the case of a cylindrical object, such as a plant stem, the microwave's electric field distribution [36] can be described by:

$$E = \tau E_o \frac{I_o(\beta r)}{I_o(\beta r_o)} \cdot \cos\left(\frac{\pi}{a}x\right) \tag{3}$$

The resulting temperature distribution can ultimately be derived [36]:

$$\begin{aligned} T = {} & \frac{n\omega\varepsilon_o\kappa''\tau^2E_o^2\left(e^{4\beta^2\gamma t}-1\right)}{4k\beta^2 I_o(2\beta r_o)} \\ & \times\left[\frac{4\alpha\gamma t}{[J_o(\alpha r_o)I_o(\beta r_o)]^2}e^{-r^2/4\gamma t} + I_o(2\beta r)\right. \\ & \left. + \left\{2\beta I_1(2\beta r_o) + \frac{h}{k}I_o(2\beta r_o)\right\}(r_o - r)e^{-(r_o-r)^2/4\gamma t}\right] \\ & \cdot \cos\left(\frac{\pi}{a}x\right). \end{aligned} \tag{4}$$

Unlike conventional heating, microwave heating produces its highest temperature in the core of the plant stem (Figure 7), whereas conventional heating has the highest temperature at the surface and the coolest temperature in the core. This high core temperature may lead to irreversible cavitations in the water filled Xylem tissue [37], which ultimately leads to permanent wilting and death of the plant. In extreme cases, there may also be cell rupture due to localised pressure waves created by these cavitations and the generation of steam inside the cells. The temperature inside the plant's stem from (4) depends on the strength of the microwave's electric field (E) and the dielectric loss factor (κ'') of the plant material.

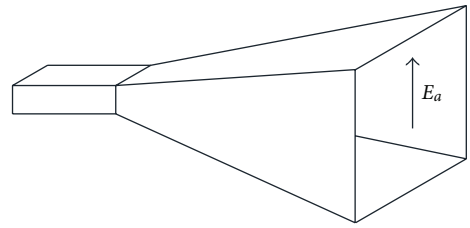

Figure 6: A typical horn antenna showing the orientation of the electrical field component of the microwave energy in the antenna's aperture.

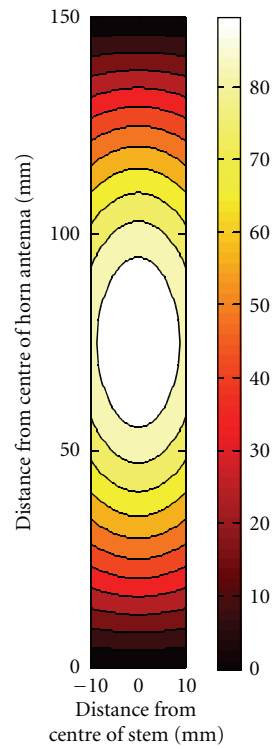

Figure 7: Temperature distribution in the longitudinal cross-section of a 10 mm thick plant stem created by a horn antenna projecting microwave energy into the stem (note: the temperature scales is in °C).

6. Determining the Electric Field Strength

Simulating microwave field strength requires the solution of Maxwell's electromagnetic equations in three dimensions when complex boundary conditions are imposed onto the system by the microwave device and the material that is being treated. This is a very complex problem for which there are no exact solutions; however, several techniques can be employed to solve Maxwell's equations, including computer simulations such as the finite difference time domain (FDTD) technique, proposed by Yee [38]. The FDTD

method is a simple and elegant way to transform the differential forms of Maxwell's equations into difference equations. Yee used an electric field grid (Figure 8), which was offset both spatially and temporally from a magnetic field grid to calculate the present field distribution throughout a complex microwave system based on the past field distributions in the system. These simulation then proceeds in a leap-frog fashion to incrementally march the electric and magnetic fields forward in time.

An FDTD program, written using MatLab, was used by Brodie, et al. [26] to study the field distributions associated with different horn antennas that may be used for weed management. The modelled space consisted of a magnetron source, mounted in short wave guide, feeding the horn antenna. A 50 mm air gap, followed by a 50 mm thickness of plant material, followed by a 200 mm thickness of soil, was layered in front of the horn antenna. The resulting FDTD algorithm takes about one hour to simulate 0.4 nanoseconds of real time, so investigating several design options is a very slow process.

Because the field strength in the mouth of the antenna with the 86 mm by 20 mm aperture (Figure 9(b)) is many times greater than that created by the antenna with the 130 mm by 43 mm aperture (Figure 9(a)), the heating rate (4) and lethal effect of this small aperture antenna was many times faster than the antenna with the larger aperture. This explains the shorter treatment time needed to kill fleabane and paddy melon plants when using this antenna (Table 1).

The success of using numerical simulations such as the FDTD technique depends on having accurate mathematical models for the dielectric properties of the various components of the simulated space.

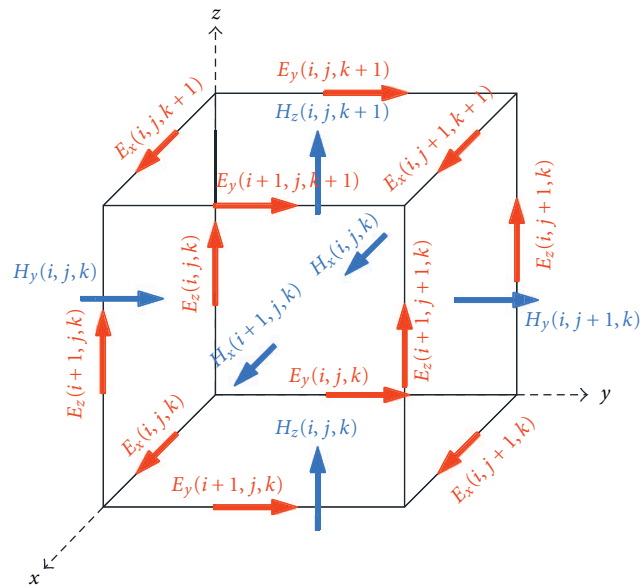

Figure 8: Single cell from the computational space used to compute Maxwell's equations using FDTD technique.

7. Dielectric Properties of Plant Materials

Ulaby and El-Rayes [39] studied the dielectric properties of plant materials at microwave frequencies. Plants with high moisture content have higher dielectric constants (Figure 10) and will therefore, interact more with the microwave fields, rendering them more susceptible to microwave damage. Generally, plants with a more upright and rigid structure have more cellulosic material in their cell structure and therefore, have a lower water content than prostrate vines and climbers [37]. Therefore, differences in moisture content may explain the differing susceptibilities of paddy melon, fleabane and marsh mallow.

It has been well documented that the dielectric properties of most materials are temperature and moisture dependent [40–45]. Equation (4) was used in an iterative calculation, where the new dielectric properties were recalculated after 1 second of microwave heating, based on the temperature and moisture content of the plant stem under investigation. Moisture loss was assumed to have a linear relationship with microwave heating time, based on previous experimental work [46]. This results in nonlinear heating responses and sudden jumps in temperature when there is no change in the applied microwave power (Figure 11). The sudden jump in temperature for the 15 mm diameter stem (Figure 11) is the result of "thermal runaway."

Vriezinga has studied this phenomenon and concluded that thermal runaway is caused by (1) the specific characteristic of the dielectric loss factor of water, which decreases with increasing temperature [43]; (2) resonance of the electromagnetic waves within the irradiated medium due changes in the electromagnetic wavelength inside the irradiated medium as the dielectric properties change during heating [43, 44]. Resonance will only occur when the object's dimensions are similar to 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 11), while the smaller stems are too narrow to allow field resonance.

8. Thermal Runaway

Thermal runaway during microwave heating manifests itself as a sudden jump in temperature over a very short time. It is linked to the temperature and moisture dependence of the dielectric properties of the heated material. In some cases this can result in the material absorbing more microwave energy as it is heated, which in turn leads to faster heating and greater absorption. The net result is a sudden and uncontrolled jump in temperature, depending on the strength of the electromagnetic fields and the heating time.

The transfer of microwave energy into a material also depends on the transmission coefficient of the material's surface, which depends on the dielectric properties of the material. Therefore, as the dielectric properties decrease due to moisture loss (Figure 10) and temperature dependence during microwave heating, more energy enters the material due to increased transmission across the material's surface,

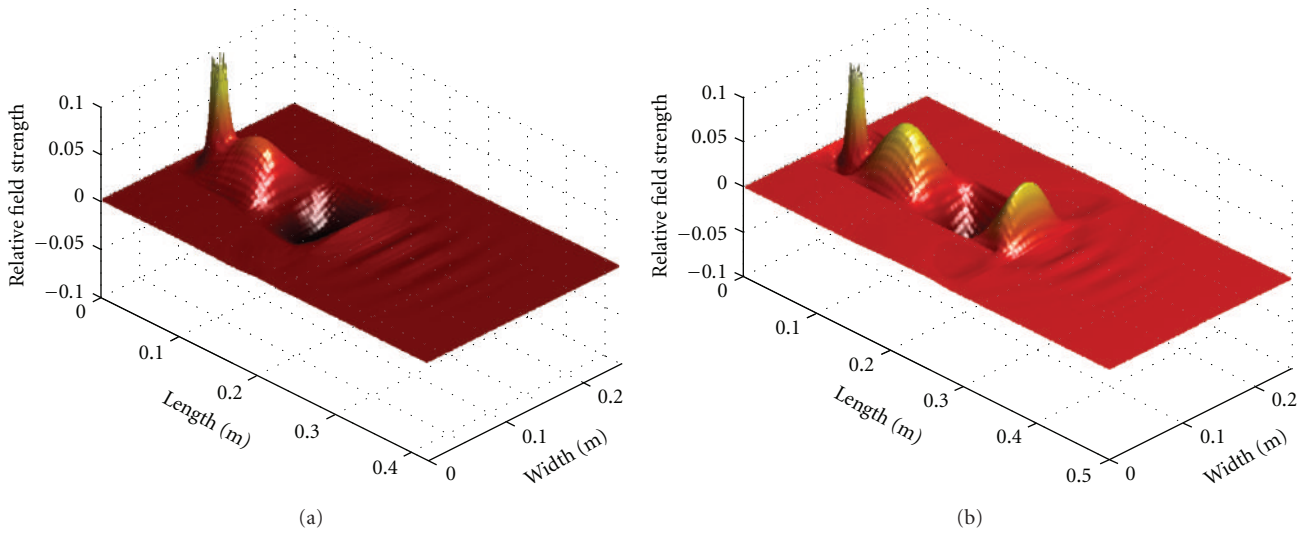

Figure 9: Comparison of microwave fields for (a) the 130 mm by 43 mm aperture horn antenna and (b) the 86 mm by 20 mm aperture horn antenna.

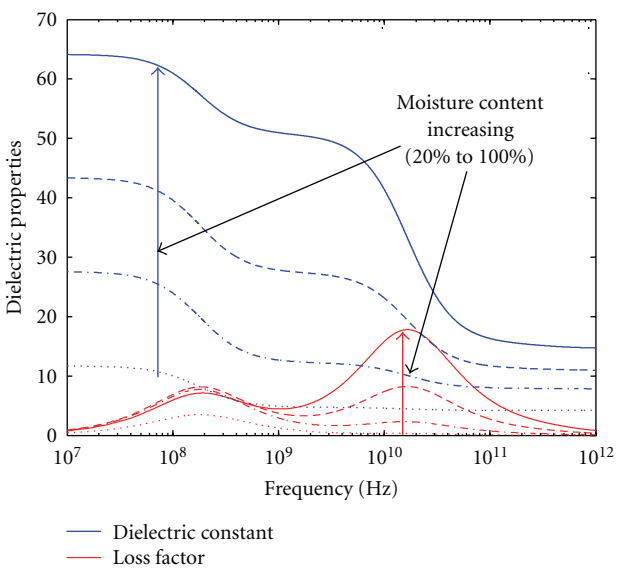

Figure 10: Dielectric properties of leaf material as a function of frequency and gravimetric moisture content based on models developed by Chuah et al. [63].

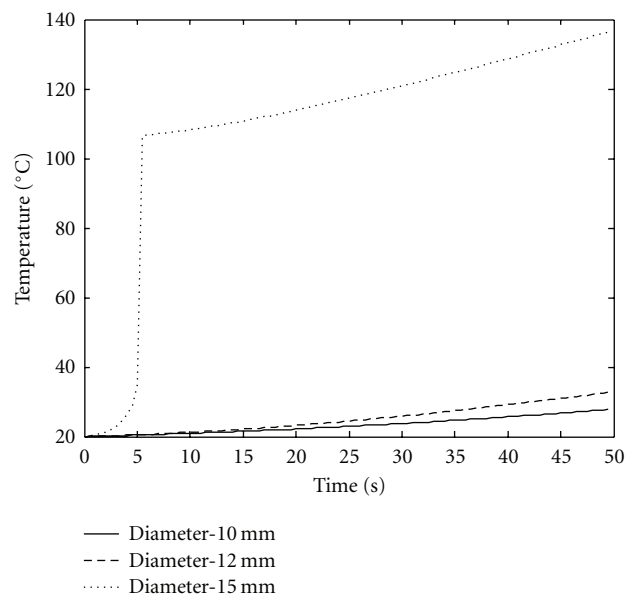

Figure 11: Temperature response, at constant microwave power density, in the centre of a plant stem as a function of plant stem diameter, calculated using (4) and assuming constant moisture loss from a moisture content of 0.87 to 0.10 during microwave heating.

which leads to faster heating, which leads to more energy transfer and so on.

Thermal runaway can also be caused by resonance [43] of the electromagnetic waves within the object. As dielectric properties decrease with increasing temperature and moisture loss (Figure 10), the wavelength inside the material will increase. At a certain temperature, the wavelength will fit exactly within the dimensions of the heated object, causing resonance [43]. Exactly at that moment the temperature will suddenly rise. Because heating and drying rates are dependent on the microwave field intensity, thermal runaway is strongly dependent on the intensity of the microwave's electric field (Figure 12).

In most cases, thermal runaway is a problem during microwave heating. It usually leads to undesirable destruction of the microwave heated material [47]; however, it has been very effectively used in some applications.

Internal steam pressure, induced by thermal runaway, may cause stem rupture (Figure 4(a)) in the paddy melon plants and severing of the fleabane plants, if sufficient microwave field intensity can be focused onto the plants. Total treatment time, and therefore, total applied microwave energy, could be reduced by at least an order of magnitude (Figure 11), if thermal runaway can be induced in weed

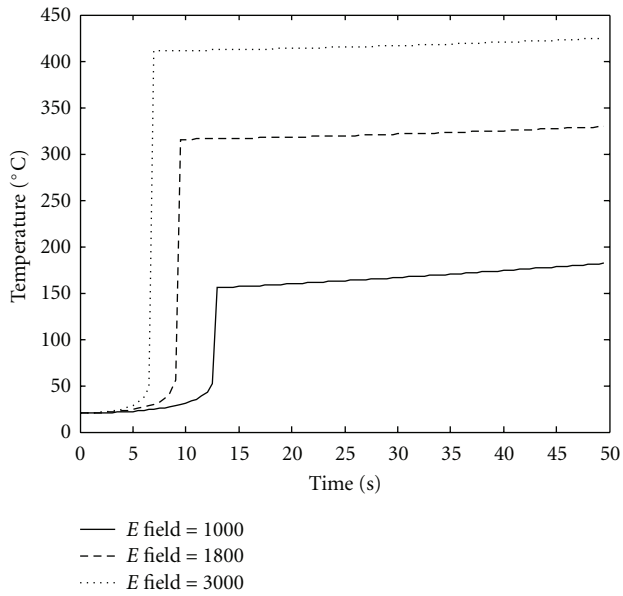

Figure 12: Theoretical influence of microwave field strength over thermal runaway in a plant stem of 16 mm diameter based on calculations using (4).

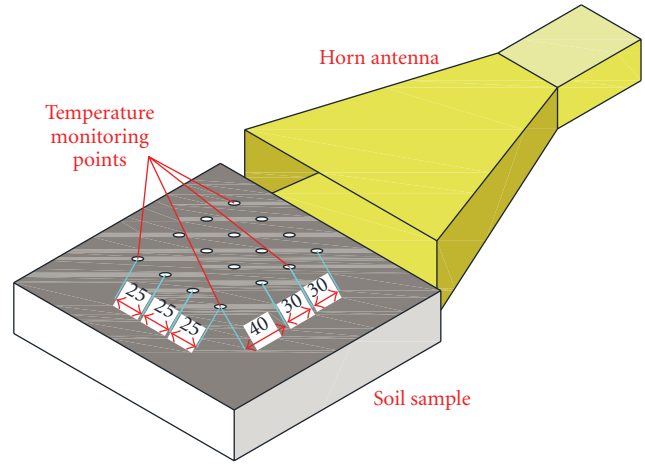

Figure 13: Schematic of thermometer placement during temperature measurement experiment.

plants during microwave treatment. For example, extrapolating the data presented in Figure 11, it takes approximately 100 seconds for the 10 mm diameter stem to reach 40°C; however, the 15 mm diameter stem reaches 40°C in 5 seconds under the same applied microwave power. Therefore, the energy required to achieve this temperature rise in the 15 mm diameter stem is only 5% of the energy needed to heat the 10 mm diameter stem. The same may also be true in microwave treatment of seeds in the soil.

9. Temperature Profile in Soil

FDTD modeling of the system with a thin layer of plant material over the top of a soil substrate revealed that the microwave energy easily penetrated the plant layer and propagates into the soil (Figure 9). It was therefore, appropriate to explore the effect that microwave energy may have on the soil. Based on earlier work [36], the expected temperature distribution in the soil is described by

$$T = \frac{n\omega\varepsilon_o\kappa''\tau^2E_o^2\cdot\left(e^{4\gamma\beta^2t}-1\right)}{4k\beta^2} \cdot\left[e^{-2\beta z}+\left(\frac{h}{k}+2\beta\right)z\cdot e^{-z^2/4\gamma t}\right]\cdot\cos\left(\frac{\pi}{a}x\right). \quad (5)$$

In an experiment using an Orthic, Basic Rudosol [48], Brodie et al. [26] confirmed the temperature distribution that could be expected in the soil from microwave heating using a horn antenna. The soil was crushed, mixed thoroughly, and passed through a 2 mm sieve to ensure homogeneity and uniform response to the microwave fields. The soil was air dried to constant weight. Samples of approximately 2.3 kg were placed into a 20 cm by 20 cm plastic dish to a depth of 5 cm. Temperatures were measured using sixteen 120°C thermometers placed into the soil in the arrangement shown in Figure 13. Samples were heated using the experimental prototype microwave system for 150 seconds at full power. Thermometers were inserted into the soil immediately after heating was completed.

The hottest place in the heating pattern was along the centre line of the antenna and between 2 cm and 5 cm below the surface. Figure 14 compares the expected temperature profile in the soil to the average soil temperature profile measured during these experiments. The temperature profiles are similar, although not quite the same.

10. Soil's Response to Microwave Treatments

The interaction between microwave energy and soil depends on the soil texture and moisture content. Soil moisture has three main effects on microwave heating:

(1) moisture increases the reflectivity of the soil surface [49], reducing the amount of microwave energy that penetrates into the soil [50];

(2) on the other hand, moist soil more readily absorbs microwave energy to create heat [50]. Therefore, while there is less total microwave energy entering the soil, the presence of moisture enhances the total microwave heating effect;

(3) moisture is also a heat-diffusing agent, rapidly transporting the heat through the soil profile as hot water and vapour is forced through the soil particles by a propagating pressure wave created by the microwave heating [29].

The soil texture, which depends on the distribution of particle sizes in the soil mixture, determines the heating rate due to microwave irradiation (Table 3). Dry clay/loam soils heat more rapidly than dry sandy soils [51]. This could be due to several factors, but the most likely explanation may involve bound water on the soil particles. Usually these

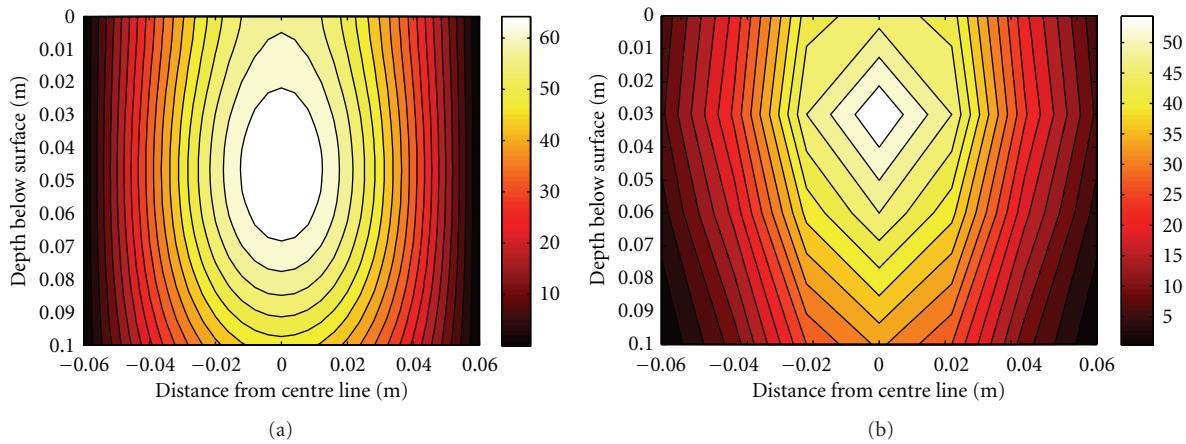

Figure 14: Comparison of expected soil temperature profile (a) with measured soil temperature profile (b) for the 750 W prototype microwave unit after 150 seconds of heating (note: the temperature scales is in °C).

Table 3: Average heating rate for air dry soil samples (°C per second).

Soil type	Microwave power level	
	2 kW	4 kW
Clay	0.66^{a}	1.33^{c}
Loam	0.53^{b}	0.80^{d}
Sand	0.30^{e}	0.68^{a}
LSD ($P < 0.05$)		0.09

Means with different superscripts are significantly different to each other [51].

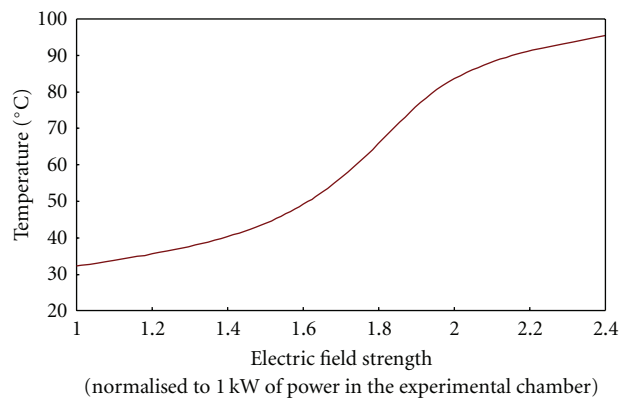

Figure 15: Temperature versus applied microwave field strength (in clay/loam soil after 25 seconds of heating time) [26, 51].

moisture layers on the soil particles are several molecules thick, even when the soil is "dry" [52, 53]. Microwaves interact with this bound water to create heat.

Clay soil is made up of smaller particles than sandy soil; consequently, they have more surface area per unit volume of soil for water to bind to. Therefore, there will be more water in a given volume of dry clay soil than in the same volume of sandy soil, resulting in faster microwave heating.

Experiments by Cooper and Brodie [54] confirmed that treating soil using microwave heating has no effect on soil pH, nitrate, phosphate, potassium, and sulphate availability; however, increasing microwave treatment significantly reduced both the nitrite concentration and the number of colonizing bacteria in the soil [54]. This may affect the growth of plants that are grown in the soil after microwave treatment; however, this was beyond the scope of the current investigation.

Many composite materials that include water as part of their mix have nonlinear responses to increasing microwave field strength [36, 55]. Figure 15 shows the response of dry clay/loam soil when the strength of microwave field is varied. There seems to be a saturation effect as the field strength (microwave power) is increased. The implication is that increasing microwave power beyond some optimal limit will not result in significant improvements in heating effect.

11. Seed Survival

Seed survival depends on the soil temperature, seed size, and whether the seeds have imbibed water or not [4, 51]. Microwave treatment of moist soil can inhibit grass seed germination to a depth of at least 5 or 6 cm, provided the soil around the seeds reaches 65°C to 80°C, depending on the type of seed [26].

Seed size influences the susceptibility of seeds to microwave treatment [25]. Figure 16 shows that wheat seeds, with an average mass of 41.7 mg each, are more susceptible than wild oats seeds, with an average mass of 7.2 mg. Wild oats are more susceptible than ryegrass seeds, which have an average mass of only 2.1 mg each.

12. Effect of Microwave Energy on Soil Biota

Ferriss [56] reported that microwave treatment reduced populations of soil microorganisms with increasing treatment time, however these effects decreased with increasing amounts of soil, and decreased with increasing soil water

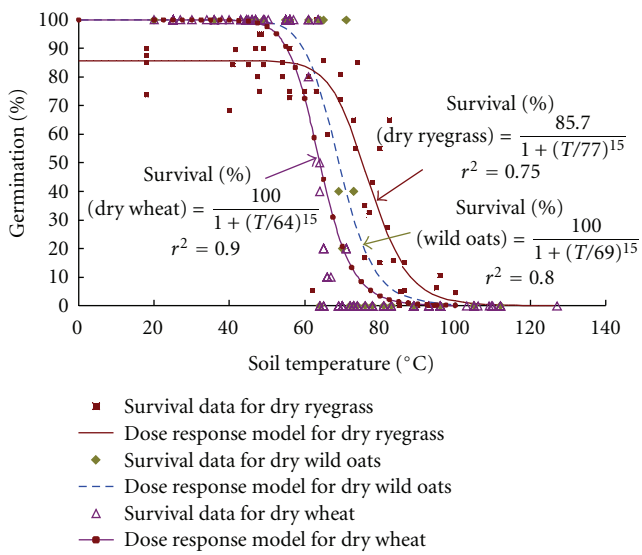

Figure 16: Dose-response curve for soil temperature versus seed survival percentage for wheat, wild oats, and perennial ryegrass seeds in dry sandy soil [24, 51].

content between 16 and 37% (wt. water/dry wt. soil). No pronounced effect of soil type was noted in their experiments, which is unexpected given the data in Table 3. Treatment of 1 kg soil, at 7% to 37% water content, for 150 s in a 653 W microwave oven, operating at 2.45 GHz, eliminated populations of *Pythium*, *Fusarium,* and all nematodes except *Heterodera glycines*. Marginal survival of *Rhizoctonia*, cysts of *H. glycines* and *mycorrhizal* fungi, was observed in some treated soils. Treatment of 4 kg of soil for 425 s gave comparable results [56].

In an experiment using the prototype microwave system described earlier (Figure 2), Cooper and Brodie [54] discovered that microwave treatment reduced soil bacterial populations by 78% in the top 2 cm of soil after 16 min of microwave treatment; however, populations at 10 cm depth were not significantly affected by treatment. Therefore, the soil was not sterilized and bacteria could regenerate after treatment.

13. Microwave Treatment Can Promote Seed Germination

In experiments to control Annual bluegrass (*Poa annua*) using microwave soil pasteurization, it was discovered that microwave heating actually stimulated bluegrass seed germination in some lightly treated plots (unpublished data). Using microwave energy to stimulate seed germination in certain acacia species has been observed before [13, 57].

The main concern with this phenomenon is that it may be possible to apply enough energy to kill weed plants, but the energy level in the soil below may be sufficient to stimulate seed bank germination. This could result in a worse weed problem if follow-up treatments are not applied. Clearly, microwave treatment of some species may need to be carefully investigated.

14. Important Considerations

Care must be taken, because individuals within the population can resist low levels of microwave treatment. Failure to kill all individuals in the population will eventually lead to "thermal resistance" within the population.

Microwave treatment will not be as cheap as chemical treatments; however, its mechanism for killing weeds and their seeds is different to chemical treatments. This can deal with herbicide resistant individuals in the weed population. Microwave treatment also deals directly with the seed bank rather than waiting for the seeds to germinate. This may reduce the number of treatments that are needed to deplete the seed bank in badly infested areas.

15. Energy Comparisons

Although Figures 16 and 17 present dose responses to soil temperature, it is useful to interpret this data in terms of applied energy. The amount of energy needed to attain a certain temperature in the soil depends on the soil type (Table 3) and moisture content. Sand has the poorest response to microwave energy, so it can be regarded as the worst case scenario for microwave treatment.

Based on energy calculations for plants and seeds on the surface of sandy soil, dry seeds require much higher energy densities to kill them than moist seeds, plants and most bacteria (Figure 18). As mentioned earlier, seed size influences their susceptibility to microwave damage, with larger seeds being more susceptible than smaller seeds.

The most susceptible plant that has been studied so far was prickly paddy melon. Its dose response curve (Figures 6 and 18) indicates that 100% control of paddy melon should be achieved using 200 J cm^{-2} (or 20 GJ ha^{-1}) of microwave energy. This is an order of magnitude higher than the embodied energy (2.2 GJ ha^{-1}) associated with published chemical plant protection data [58–60].

Based on existing data, phenomena such as thermal runaway, and the nonlinear temperature/ microwave field strength relationships ((4) and (5)) discussed in this paper, it is difficult to discuss "scale up." If thermal runaway can be induced in plant tissues, treatment time, and the associated treatment energy may be drastically reduced (Figure 11) for a small increase in applied microwave field density. This may result in a system that is comparable to conventional chemical weed control, in terms of its embodied energy and costs. This can only be explored by further research using a more powerful prototype system.

16. Further Reductions in Energy Using Infrared Weed-Detecting Technologies

Several technologies have been developed to better manage weeds in the special case of fallowed paddocks. These include the adoption of "weed seeker" technologies that are based on differences in the spectral properties of weeds and soil [61].

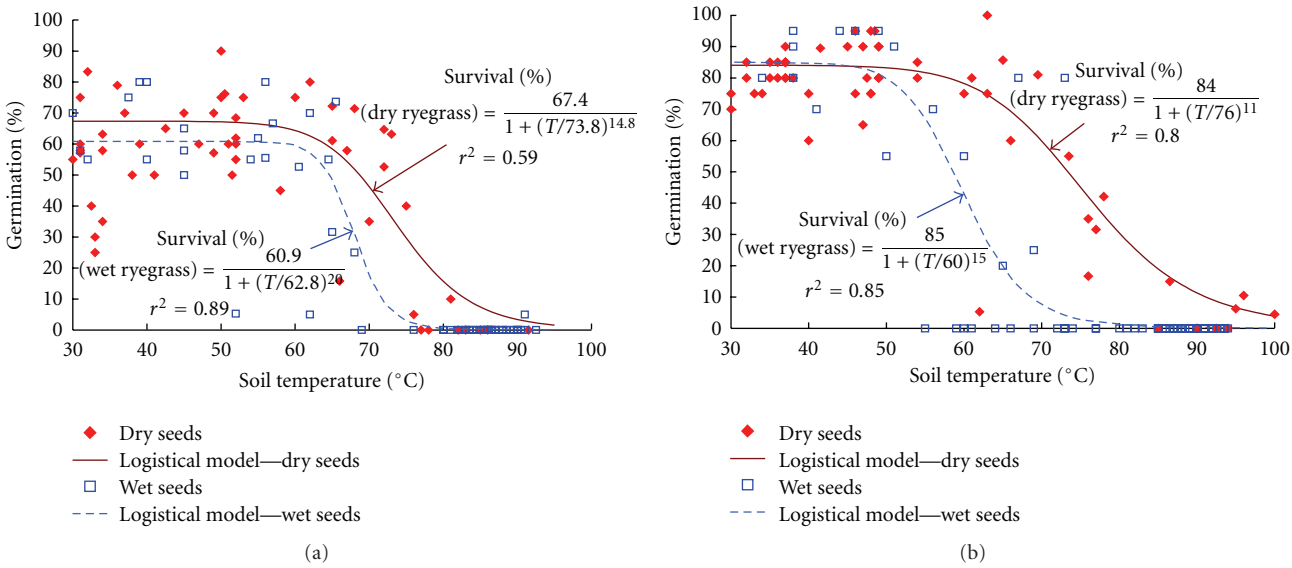

Figure 17: Dose response curve for soil temperature versus seed survival percentage for (a) annual ryegrass (*Lolium rigidum*) and (b) perennial ryegrass (*Lolium perenne*) seeds [51].

The reflectance value of green vegetation is very low in the red optical range around 670 nm; however, weeds strongly reflect incident irradiation in the near infrared range (NIR) [61]. Soil has only a small difference between reflectance in the red and in the near infrared range.

Sensors based on visible and infrared cameras monitor changes in reflectance to trigger the application of a short burst of herbicide to the ground at the weed's location. This system can be adapted to turn on a microwave generator at the appropriate time to irradiate a detected weed, rather than having the microwave system generating microwave energy all the time. Depending on the growth stage and level of infestation, this strategy should greatly reduce the energy requirements for microwave weed management on broad acre enterprises.

Most of the experiments that contributed to the presented data (Figures 16, 17, and 18) were conducted during the winter, due to logistical and educational constraints on the activities of the researchers. Therefore, the soil samples cooled rapidly after treatment, because of the low ambient temperature and the small soil sample mass involved in the experiments. Dahlquist et al. [62] demonstrated that temperatures as low as 40–50°C were 100% lethal to some seed populations if they were exposed to these temperatures for several hours.

This suggests that summer weed seed management, using microwave energy, may require much less energy than at other times of the year. Two factors contribute to this hypothesis: firstly, the soil temperature will not require as much energy to raise it to lethal temperatures, and, secondly, if treatment is applied earlier in the day, soil temperatures may be maintained at a relatively high value through the day because of solar radiation. This has yet to be explored experimentally.

17. Technological Concerns about Using Microwave Treatment

Microwave treatment needs a finite amount of time to heat weed plants to a sufficiently high temperature to kill the plant. This will determine the travel speed of the microwave equipment during weed treatment. Focused microwave energy requires a very short treatment time to kill weed plants (Table 1). This suggests that a field prototype needs to create a narrowly focused strip of microwave energy that travels across the ground at a reasonable speed. It would also be very useful to have two or more microwave sources focused onto the same strip in order to enhance the heating effect and reduce the time needed to treat a plant. When using multiple microwave sources, diffraction interference from the two sources must be avoided. This can be achieved by polarizing the microwave fields at right angles to one another.

Another important consideration, when using a microwave system in conjunction with a weed sensing technology is the time delay between the application of power to a magnetron and the generation of microwave energy. This delay of about 2 and 3 seconds may be overcome by mounting the sensor well in front of the microwave generator or by keeping the energization current running through the cathode of the magnetron, but only applying the high voltage needed to generate microwaves between the anode and cathode of the magnetron tube when treatment is required. This has yet to be explored experimentally.

18. Conclusions

The potential use of microwave energy as a weed management tool has been explored for some time. Experimental

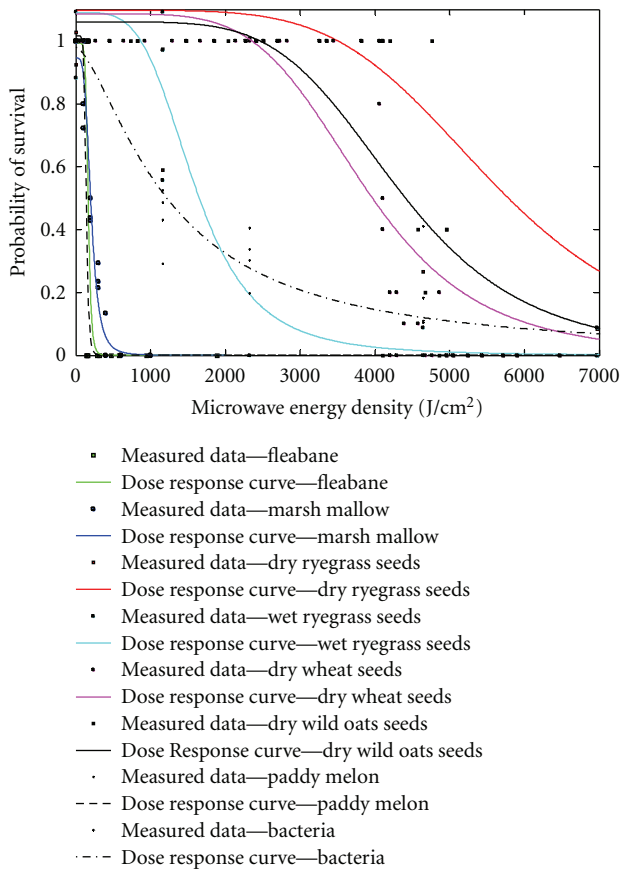

Figure 18: Microwave energy dose response curves for seeds (dry and moist), plants, and bacteria.

evidence demonstrates its effectiveness at killing weeds and their seeds, yet the technology has not been fully commercialised. The main reason for this is the energy requirements needed to treat broad acre cropping enterprises. Chemical weed control is still the cheapest option for weed management on most farming systems. Unfortunately there is a growing population of chemical resistant weed biotypes and chemical weed management may become ineffective in the future. For this reason, microwave weed control systems should be explored as part of an integrated weed management strategy.

Most microwave weed control experiments have focused on managing seed banks. Some experiments have been done on weed plants, but they have been conducted using microwave systems which broadcast their energy over a relatively large area rather than concentrating the energy into a small space on the weed plants. This reduces the efficacy of microwave treatment, prolongs the exposure time need to kill the plants and precludes the onset of thermal runaway in the plant tissue. Thermal runaway, if it can be induced in the plant stems, could vastly reduce treatment time (Figure 11) for a given microwave power level, thus reducing the energy needed to treat weeds by an order of magnitude. This would make microwave weed control comparable in energy terms with conventional chemical weed treatment. The integration of microwave treatment systems with weed sensing technologies would also reduce treatment energy.

In conclusion, microwave energy can be used to manage weeds and their seeds. Energy requirements are an important consideration, but these may be addressed by using novel microwave applicators to focus the microwave energy into a very narrow strip to induce thermal runaway in the plant tissue. Further energy savings may be achieved by integrating microwave treatment systems with weed sensing technology.

Soil pasteurization is more effective in moist soils. Figure 17 shows a typical temperature response curve for ryegrasses (*Lolium spp.*) seeds in sandy soil. Clearly, dry seeds (dormant seeds in dry soil) are much less susceptible to microwave-induced damage than imbibed seeds.

Nomenclature

Ψ: Microwave energy density (J/cm^2)
a: Width of the horn antenna (m)
E_o: Peak strength of the electric field in the aperture of the horn antenna (V m^{-1})
E: The electric field (V m^{-1})
H: The magnetic field (Webers m^{-1})
μ: The magnetic permeability of the medium (Henrys m^{-1})
ε^*: The complex dielectric permittivity (Faradays m^{-1})
J_c: The current density due to the conductivity of the material (A m^{-1})
J_s: The current density associated with any current sources inside the space of interest (A m^{-1})
λ_o: Wavelength of an electromagnetic wave in free space (m)
h: Convective heat transfer coefficient at the surface of the material (W m^{-1} K^{-1})
$I_o(x)$: Modified Bessel Function of the first kind of order zero
$J_o(x)$: Bessel Function of the first kind of order zero
k: Thermal conductivity of the material (W m^{-1} K^{-1})
m_c: Initial masses of the control samples (kg)
m_m: Initial masses of the microwave treated samples (kg)
n: Magnitude ratio for the coupling between heat and moisture diffusion
r_o: Outer radius of a cylindrical object heated by microwaves (m)
t_h: Microwave heating time for experiment (s)
x: Horizontal coordinate measured from the centre line of the horn antenna's aperture (m)
$\triangle m_c$: Changes in mass of the control samples (kg)
$\triangle m_m$: Changes in mass of the microwave treated samples (kg)

$\triangle T_C$: Change in temperature of the control samples (K)
$\triangle T_m$: Change in temperature of the microwave treated samples (K)
α: Wave phase constant (m^{-1})
β: Wave attenuation factor (m^{-1})
ε_a: Complex dielectric constant of air
ε_w: Complex dielectric constant of water
ε_s: The nondispersive residual component of the dielectric properties due to the hydrocarbon molecules in the plant material
v_{fw}: The volume fraction of free water in the plant material
ε_{fw}: The dielectric properties of free water
v_b: The volume fraction of bound water in the plant material
ε_{bw}: The dielectric properties of bound water
M: Gravimetric moisture content of the leaf material
f: Frequency (GHz)
γ: Combined heat and moisture diffusion coefficient
κ'': Dielectric loss factor of the heated material
τ: Transmission coefficient for the transfer of microwave energy into the material
ω: Angular frequency of the microwaves (Rad s^{-1}).

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