Chapter

Microwave Soil Treatment and Plant Growth

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Abstract

Crop yield gaps can be partially overcome by soil sanitation strategies such as fumigation; however, there are fewer suitable fumigants available in the marketplace and growing concerns about chemical impacts in the environment and human food chain. Therefore, thermal soil sanitation has been considered for some time and microwave soil treatment has some important advantages over other thermal soil sanitation techniques, such as steam treatment. It is also apparent that microwave soil sanitation does not sterilize the soil, but favors beneficial species of soil biota making more nutrients available for better plant growth. From these perspectives, microwave soil treatment may become an important pre-sowing soil sanitation technology for high value cropping systems, allowing agricultural systems to better bridge the crop yield gap.

Keywords: microwave pasteurization, agriculture, pathogen control, nutrient, production response

1. Introduction

Crop yield gaps are a significant issue for food security and agricultural sustainability. Crop yield gaps are defined as the differences between optimal yield potential and actual crop yield [1]. Yield potential (Yp) is the yield of a crop cultivar when grown in an environment to which it is adapted, with non-limiting water and nutrient supplies, and with pests, weeds, and diseases being effectively controlled [1]. For example, the impact of weeds on crop yield potential has been widely demonstrated [2] and modeled [3–5]. Noling and Ferris [6] demonstrated that nematodes can reduce alfalfa yields by more than 70%. Similarly, fungi can significantly reduce crop yield potential [7, 8]. The impact of various pathogens on crop yield potential can be demonstrated with some simple models.

According to Noling and Ferris [6], the impact of nematode populations on perennial crops, such as alfalfa, can be described by:

$$Y_{loss} = a\left(1 - e^{-bN}\right) \tag{1}$$

where Y_{loss} is the yield loss, a is the maximum yield loss for the system, b is a population sensitivity parameter for the crop (i.e., damage rate), and N is the nematode population. Therefore, the potential crop yield is described by:

$$Y = Y_o\left[1 - a\left(1 - e^{-bN}\right)\right] \tag{2}$$

where Y_o is the optimal yield.

In a resource limited environment, the rate of population growth is described by:

$$\frac{dN}{d°D} = r\left(\frac{k-N}{k}\right)N \tag{3}$$

where °D is the degree days which are suitable for the growth of the pest or pathogen, k is the maximum sustainable population of the pest or pathogen (i.e., the carrying capacity), and r is the base population growth rate. One Degree Day is determined according to some basis temperature (Tb):

$$°\mathrm{D} \stackrel{\text{def}}{=} \frac{\mathrm{T_{max}} - \mathrm{T_{min}}}{2} - \mathrm{T_b} > 0.0 \tag{4}$$

Equation (3) can be rearranged to become:

$$\frac{dN}{\left(\frac{k-N}{k}\right)N} = r \bullet d°D \tag{5}$$

Integrating both sides of Eq. (5) gives:

$$2\ \tanh^{-1}\left(\frac{2\mathrm{N}}{\mathrm{K}} - 1\right) = \mathrm{r} \bullet °\mathrm{D} + \mathrm{C} \tag{6}$$

Therefore, Eq. (6) becomes:

$$N = \frac{K}{2}\left[1 + \tanh\left(\frac{r \bullet °D}{2} + \frac{C}{2}\right)\right] \tag{7}$$

To evaluate the constant of integration (C), it is appropriate to choose a boundary condition on the problem. It is noted that at the start of any study (i.e., when °D = 0 for this study period), the population will have some starting population value "No." Substituting this into Eq. (7) and setting °D = 0 gives:

$$\mathrm{No} = \frac{\mathrm{K}}{2}\left[1 + \tanh\left(\frac{\mathrm{C}}{2}\right)\right] \tag{8}$$

or:

$$\mathrm{C} = 2 \bullet \tanh^{-1}\left(\frac{2 \bullet \mathrm{No}}{\mathrm{K}} - 1\right) \tag{9}$$

Therefore,

$$N = \frac{K}{2}\left[1 + \tanh\left(\frac{r \bullet °D}{2} + \tanh^{-1}\left(\frac{2 \bullet No}{K} - 1\right)\right)\right] \tag{10}$$

Using data from Noling and Ferris [6] as a guide, the population of *Meloidogyne hapla* nematodes in their study would increase as shown in **Figure 1**. When these population models are applied to the crop yield model in Eq. (2), the apparent crop yield decline is similar in form to that presented in Noling and Ferris [6], as shown in **Figure 2**.

Different crops require differing numbers of degree days to reach maturity. For example, maize requires between 800 and 2700 degree days while barley requires between 1290 and 1540 degree days. Using the data presented in **Figure 2** to

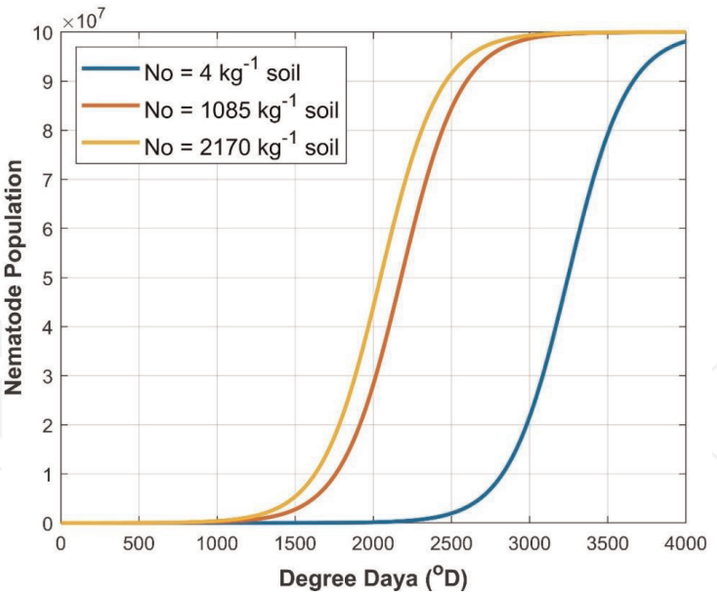

Figure 1.
Population growth in Meloidogyne hapla *nematodes as a function of degree days, based on the initial inoculum of the soil (calculated from Eq. (10)).*

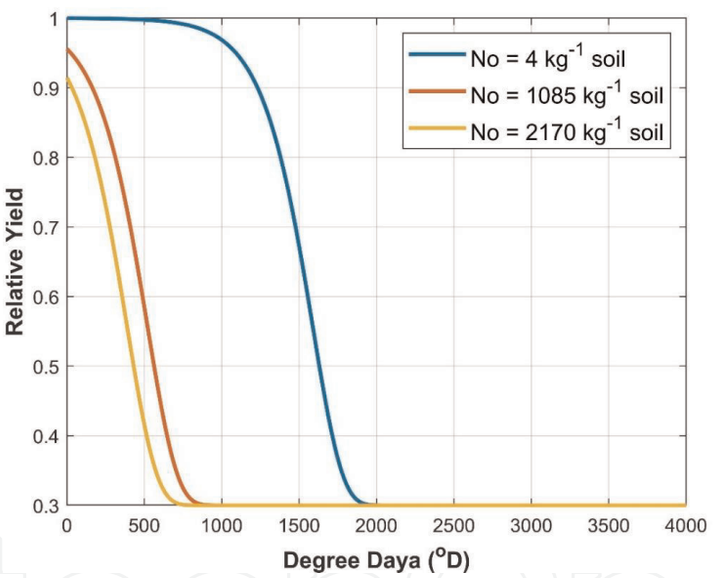

Figure 2.
Crop yield potential for Alfalfa affected by Meloidogyne hapla *nematodes as a function of degree days, based on the initial inoculum of the soil (calculated from Eq. (2)).*

illustrate the importance of the impact of pathogens and pests on crop yield, if a crop requiring 1500 growing degree days to mature is exposed to an initial *Meloidogyne hapla* nematode population of 1085 individuals kg^{-1} of soil, the yield potential would be 0.3 at the end of crop maturation; however, if the crop was exposed to an initial population of only 4 individuals kg^{-1} of soil because of some pre-sowing soil sanitation strategy, the crop yield potential would be approximately 0.7. Therefore, pre-sowing soil sanitation could provide a crop yield increase (compared with untreated soil) of: $\frac{(0.7-0.3)}{0.3} \times 100 = 133\%$.

Although this may appear to be a significant crop yield increase, the pre-sowing soil sanitation is simply bridging a little more of the crop yield gap by treating the soil to remove crop inhibiting organisms before sowing the crop. In fact, the modeling suggests that the crop growing on the sanitized soil may still not have reached its full crop yield potential.

2. Soil sanitation

Many soilborne plant pathogens flourish during the crop growing season and survive between seasons, either in the soil or above-ground, by means of resting structures, such as propagules that are either free or embedded in infected plant debris. Soil sanitation aims to reduce or eliminate the pest population from all sources, thus breaking the continuity of survival in time and space between crops. Soil sanitation (e.g., by fumigation or heating) is a routine procedure in many agricultural systems [9].

3. Fumigation

Soilborne diseases, plant-parasitic nematodes, and weeds can be devastating, and preplant soil fumigation is commonly relied upon to mitigate the risk of crop loss [10]. Methyl bromide has been widely used for soil sanitation in the past; however, because of its ozone depleting impacts it has been included in the 1987 Montreal Protocol as a substance whose use should be reduced and eventually eliminated. Under the Montreal Protocol exemptions were granted for substances (like Methyl Bromide) where no economic alternative existed [11]. Even so, especially in the Strawberry runner industry, alternative treatments have been investigated and found to be wanting [12, 13]. Most alternative treatments involve other fumigants, such as Metam sodium or chloropicrin [14], or thermal processes, such as solarization or applying steam.

Klose et al. [14] showed that weed seeds and soil pathogens exhibit a logistic dose-response to a commercial soil fumigant formulation of 1,3-dichloropropane (1,3-D; 61%) and chloropicrin (33%). It has been shown elsewhere [15] that a more physically meaningful representation of logistic dose responses can be described by:

$$S = a \bullet erfc[b(D - c)] \tag{11}$$

where S is the surviving portion of the population, erfc(x) is the Complementary Gaussian Error Function, D is the fumigant dose (μmol kg^{-1}), and a, b and c are constants that are determined experimentally. Equation (11) is based on an underlying normally distributed population susceptibility to some treatment; therefore, the cumulative effect (mortality) in the population becomes the integral of the normal distribution function, which is described by the Gaussian Error Function, and population survival, which is the whole population minus the mortality rate, is therefore described by the Complementary Gaussian Error Function. Therefore, it is anticipated that the crop yield response to varying doses of pre-sowing soil fumigation treatment should also have a Gaussian Error form, as a function of applied pre-sowing fumigant dose.

Growing concern over the use of excessive chemicals in agriculture, with adverse effects on on-farm and off-farm environments, has prompted a search for alternative soil sanitation options. Soil heating has provided some similar pest and pathogen control to chemicals.

4. Soil heating

The fatal impacts of high temperatures on botanical and zoological specimens have been studied in detail for over a century [16]. In particular, a thoroughly

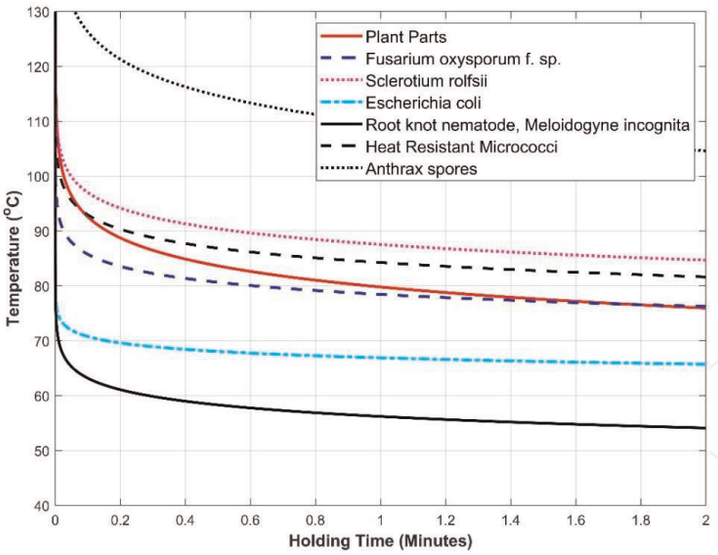

Figure 3.
Lethal temperature/time functions for several important pathogenic organisms.

demonstrated empirical relationship between lethal temperature and temperature holding time has been developed by Lepeschkin [17]:

$$T = 79.8 - 12.8 \bullet \log_{10} Z \tag{12}$$

where T is the lethal temperature (°C), and Z is the lethal temperature holding time, in minutes [16]. Individual relationships for different species of plants and pathogens [9, 17, 18] have been developed over time (**Figure 3**). Ultimately, heat can provide similar lethal effects to chemicals and therefore has been used in soil sanitation processes for some time.

5. Steam treatment

It has been demonstrated that steam soil treatment is as effective as some soil fumigants at reducing pre-sowing soil pathogen loads [19]; however, if the steam is applied to the surface of the soil (i.e., not injected), effective treatment is shallow compared with conventional soil fumigation techniques. This is due to limitations of heat being transferred from the steam into the soil. The governing equation for heat transfer from a hot fluid (air, water or steam) with a temperature of T_f into a solid, such as soil, with an initial temperature of T_s, is expressed as:

$$\frac{q}{A} = h\left(T_s - T_f\right) \tag{13}$$

where q is the heat flow (W), A is the cross sectional area through which the heat passes (m^2), and h is the convective heat flow coefficient of the soil's surface [20]. When studying thermodynamic processes, temperatures are usually expressed in absolute (Kelvin) values.

The convective heat flow coefficient depends on a number of other parameters and conditions [21]. For example, the convective heat flow coefficient for a vertical surface where natural convection achieves turbulent fluid flow conditions over the surface is given by [21]:

$$h = \frac{k}{L}\left\{0.825 + \frac{0.387Ra_L^{1/6}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{9/16}\right]^{8/27}}\right\} \tag{14}$$

where k is the thermal conductivity of the heating fluid (W m^{-1} K^{-1}), Pr is the Prandtl number, and L is the characteristic length of the object being heated (m).

The Rayleigh number (Ra_L) in Eq. (14) is also based on a complex relationship between temperature and the physical properties of the fluid. It is given by [21]:

$$Ra_L = \frac{g\beta}{\nu\alpha}(T_s - T_\infty)L^3 \tag{15}$$

where g is the acceleration due to gravity; β is the thermal expansion coefficient of the fluid; υ is the kinematic viscosity of the fluid medium; α is the thermal diffusivity of the fluid medium; and L is the characteristic length of the surface.

Finally, the Prandtl number used in Eq. (14) is a relationship between the fluid's viscous and thermal diffusion rates given by [21]:

$$Pr = \frac{\nu}{\alpha} \tag{16}$$

where v is the kinematic viscosity (m^2 s^{-1}) and α is the thermal diffusivity (m^2 s^{-1}).

Close examination of these equations shows that the convective heat transfer coefficient is dependent on the temperature differential between the fluid and the surface of the soil (see **Figure 4**) and the apparent surface area of the heat transfer interface. Injecting the steam into the soil through hollow tines effectively increases the surface area of the heat transfer interface between the cool soil and hot steam.

Semi-commercial steam soil sanitation systems have been in operation for some time [13, 19]. They are functional, though their application is limited, because they are energy expensive and difficult to use due to their large and heavy operation systems. Soil heat treatment may be better achieved through direct heating of the soil.

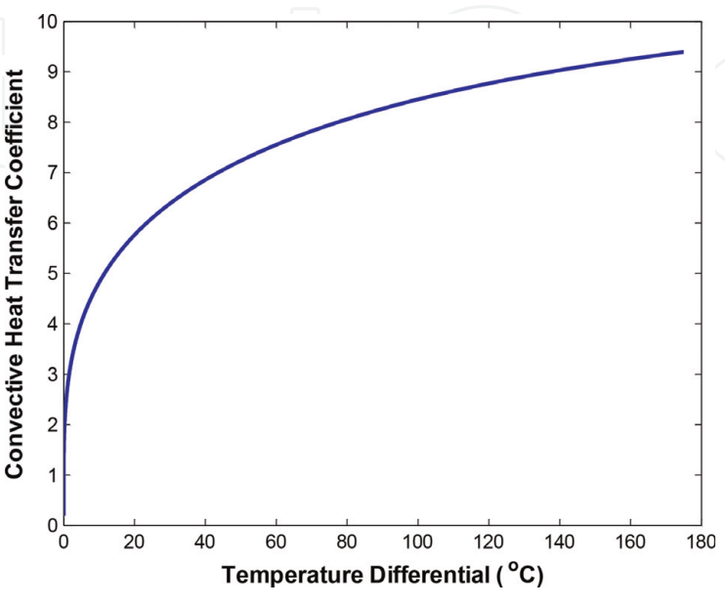

Figure 4.
Convective heat transfer coefficient (h) for air as a function of temperature differential between an object and the air.

6. Microwave soil heating

Microwaves are non-ionizing electromagnetic waves (**Figure 5**) with a frequency of about 300 MHz to 300 GHz and the wavelength range of 1 m to 1 mm [23]. Biological and agricultural systems are electro-chemical in nature [24] and a mixture of organic and dipole molecules, i.e., H_2O, arranged in different geometries [25, 26].

Interest in the study of the interactions of ultra-high frequency electromagnetic energy with complex biological system dates back to the nineteenth century [27]. The interactions of microwave energy with living systems are characterized at atomic, molecular, cellular and subcellular level [24].

The basic consideration in measuring the influence of microwave irradiation on living systems is the determination of the induced electromagnetic field and its spatial distribution. The bio-effects of microwave treatments can be described solely by differences in temperature profile between microwave and conventionally heated systems [28]. The energy of microwave photon at 2.45 GHz is 0.0016 eV [29]. This is not enough energy to break the structure of organic molecules [30]. The basic interactive mechanism of microwave energy with biological system/materials is inducing torsion on polar molecules, i.e., H_2O, Proteins and DNA, by induced electric field [31]. Oscillations in this torsion occur 2.45 billion times/second for 2.45 GHz waves. These oscillations manifest as internal kinetic energy in the material, which is heat.

Microwave (electromagnetic) heating has major advantages over conventional heating techniques. Some of these include: rapid volumetric heating as opposed to surface heating only, precise control, rapid start up and shut down [32], and in the case of soil, having a lighter apparatus than a steam generator to avoid soil compaction issues.

Many of the earlier experiments on plant material focused on the effect of radio frequencies [33] on seeds [27]. In many cases, exposure to low energy densities resulted in increased germination and vigor of the emerging seedlings [34, 35]; however, exposure to higher energy densities usually resulted in seed death [27, 36, 37].

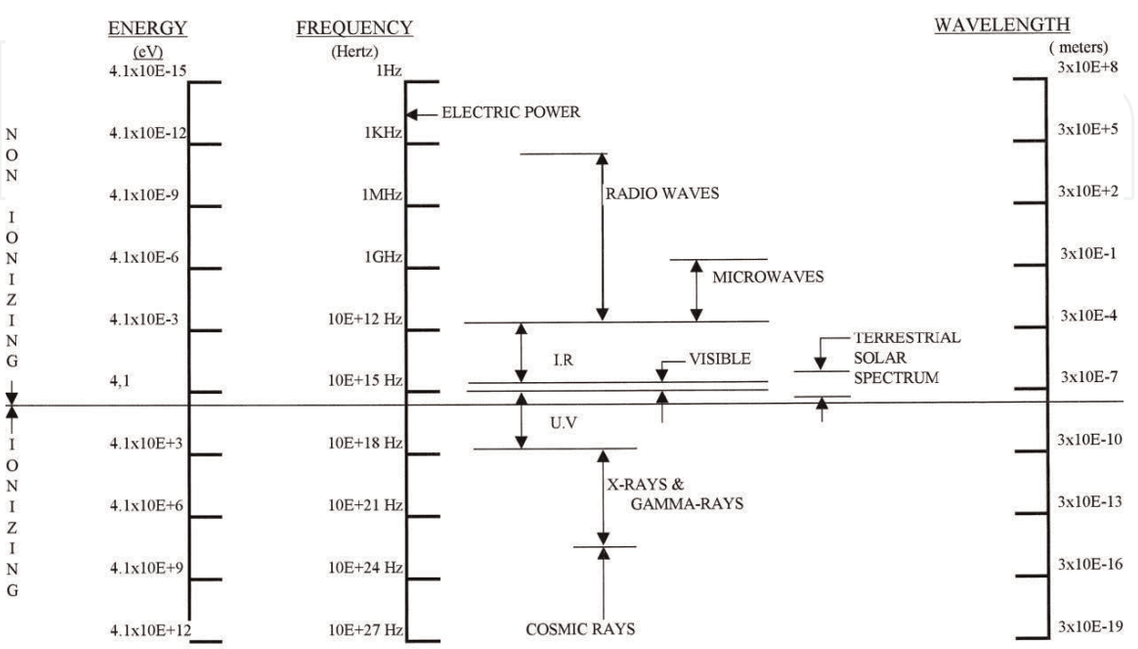

Figure 5.
The electromagnetic spectrum (adapted from [22]).

Davis et al. [38, 39] were among the first to study the lethal effects of microwave heating on weed 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 in each seed. In addition, they 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. The association between the seed's volume and its susceptibility to microwave treatment may be linked to the "*radar cross-section*" [40] presented by seeds to propagating microwaves. Large radar cross-sections allow the seeds to intercept, and therefore absorb, more microwave energy.

Ferriss [8] conducted experiments on soil samples with moisture contents between 7 and 37% (wet/dry-weight) and showed that treatment in a microwave oven for 150 seconds eliminated populations of *Pythium*, *Fusarium* and all nematode species, except *Heterodera glycines* in the soil samples. Compared with autoclaving or Methyl bromide (MB) treatment, he found that microwave treatments released less nutrient into the soil solution but had less effect on soil *prokaryotes* and resulted in less recolonization of the soil by *Fusarium* and other fungi after treatment. Similar observations were made by Mattner and Brodie [41] during a preliminary experiment in soils growing strawberry runners at Toolangi, Victoria.

Speir et al. [42] examined the effect of microwave energy on low fertility soil (100 randomly selected cores at a depth of 50 mm), microbial biomass, nitrogen, phosphorus, and phosphatase activity. They reported that an increase in microwave treatment duration (90 seconds) dramatically increased the nitrogen level in the soil by a factor of approximately 10 times (106 μg N g^{-1}) compared with untreated soil (9–10 μg N g^{-1}), but available phosphorus concentration declined as treatment time increased. Furthermore, relevant to soil productivity, Gibson et al. [43], demonstrated that shoot and root growth of birch (*Betula pendula*) significantly increased in microwave irradiated soil. Their experiment evaluated the effect of microwave treatment of soil supplemented with two mycorrhizas on birch seedlings. Shoot growth progressively increased with irradiation duration, with the highest dry shoot weight of 84 mg coinciding with the highest irradiation duration (of 120 seconds) compared to non-irradiated soil which resulted in 25 mg of growth. This result was achieved with no mycorrhizal supplementation. In addition, a recent study reported that microwave (915 MHz; different power × duration) soil treatment increased the dissolved organic carbon (+1.6-fold compared with the control), inorganic phosphorus (+1.2-fold compared with the control), and nitrate content in soil [44]. In addition, they grew the pregerminated seeds of *Medicago truncatula* Gaertn. in microwave treated soil and found that its dry biomass accumulation significantly increased in response to soil heating (75–80°C), compared with the untreated control soils.

Since then there has been ongoing research interest in microwave soil treatment and weed management. **Table 1** lists a subset of the papers that have been published on these and related topics. The consensus from these studies is that: microwave treatment can kill plants; moderate microwave treatment can break dormancy in some hard-seeded species; and high energy microwave treatment can sanitize soil.

Typically, responses of weed seeds and soil biota are both energy and depth dependent, because of the absorption of microwave energy with soil depth. The relationships between applied microwave energy and seed or biota survival at different depths are given by:

$$S = a \bullet \operatorname{erfc}\left[b \bullet \left(\Psi \bullet e^{-2cd} - f\right)\right] \tag{17}$$

where Ψ is the microwave energy density at the soil surface (J cm^{-2}), d is the depth in the soil (m) and a, b, c, and f are constants to be determined

Paper title	Reference
Douglas- fir tree seed germination enhancement using microwave energy	[45]
Microwave processing of tree seeds	[46]
Increasing legume seed-germination by VHF and microwave dielectric heating	[47]
Effects of low-level microwave radiation on germination and growth rate in corn seeds	[48]
Effects of microwave energy on the strophiole, seed coat and germination of acacia seeds	[35]
The effect of microwave-energy on germination and dormancy of wild oat seeds	[49]
The effect of externally applied electrostatic fields, microwave radiation and electric currents on plants and other organisms, with special reference to weed control	[50]
Control of field weeds by microwave radiation	[51]
Effect of microwave irradiation on germination and initial growth of mustard seeds	[52]
Inhibition of weed seed germination by microwaves	[53]
A possibility of correction of vital processes in plant cell with microwave radiation	[54]
Microwave irradiation of seeds and selected fungal spores	[7]
Response surface models to describe the effects and phytotoxic thresholds of microwave treatments on barley seed germination and vigor	[55]
Energy efficient soil disinfestation by microwaves	[56]
Microwave effects on germination and growth of radish (*Raphanus sativus* L.*)* seedlings	[57]
Report on the development of microwave system for sterilization of weed seeds: stage I – feasibility	[58]
Design, construction and preliminary tests of a microwave prototype for weed control	[59]
Thermal effects of microwave energy in agricultural soil radiation	[60]
Influence of low-frequency and microwave electromagnetic fields on seeds	[61]
An improved microwave weed killer	[62]
Observations on the potential of microwaves for weed control	[63]
Plant response to microwaves at 2.45 GHz.	[64]
Germination inhibition of undesirable seed in the soil using microwave radiation	[65]
Effect of microwave radiation on seed mortality of rubber vine (*Cryptostegia grandiflora* R. Br.), parthenium (*Parthenium hysterophorus* L.) and bellyache bush (*Jatropha gossypiifolia* L.)	[36]
Effects of microwave treatment on growth, photosynthetic pigments and some metabolites of wheat	[66]
Microwave seed treatment reduces hardseededness in *Stylosanthes seabrana* and promotes redistribution of cellular water as studied by NMR relaxation measurements	[67]
Effect of microwave fields on the germination period and shoot growth rate of some seeds	[68]
Germination of *Chenopodium album* in Response to Microwave Plasma Treatment	[69]
Work conditions for microwave applicators designed to eliminate undesired vegetation in a field	[70]

Table 1.
Literature addressing the application of microwave technology to seed and weed treatment.

experimentally. This is illustrated by the relationships for weed seeds and bacteria in (**Figures 6** and 7).

Unlike in the case of chemical soil fumigants, microwave soil treatment does not sterilize the soil. Although there is a general reduction in soil bacteria after

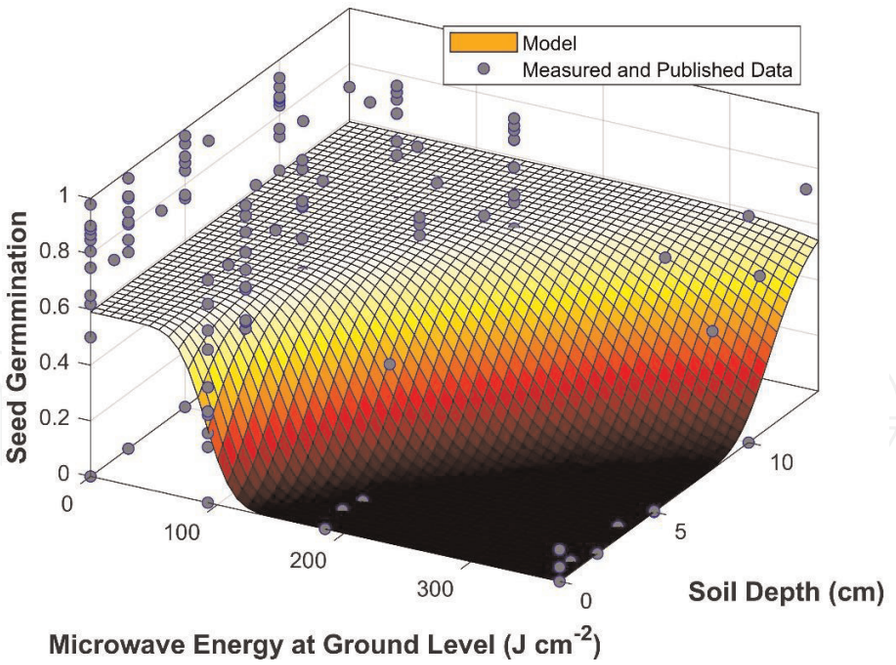

Figure 6.
Response of multiple species of weed seeds as a function of applied microwave energy and soil depth [71].

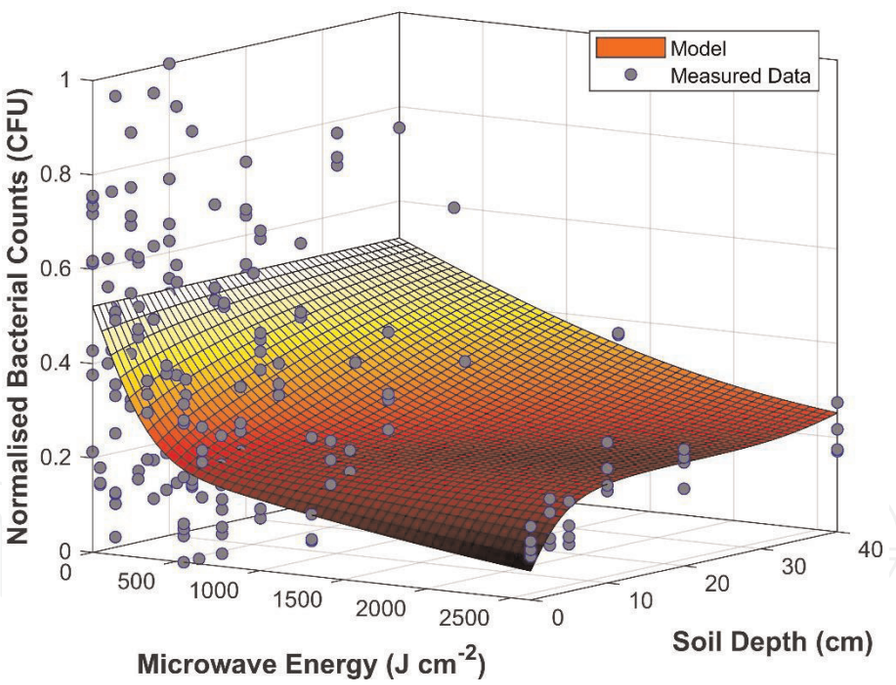

Figure 7.
Response of soil bacteria as a function of applied microwave energy and soil depth [71].

microwave treatment (**Figure 7**), Khan et al. [72] demonstrated that immediately after microwave soil treatments, the relative abundance of *Firmicutes* increased while the relative abundance of *Proteobacteria* decreased significantly. They also showed that the relative abundances of beneficial soil microbes (*Micromonosporaceae*, *Kaistobacter* and *Bacillus*) were significantly higher, as soils recovered from high heating intensities induced by microwave soil treatment, compared with untreated soils.

There is also considerable evidence that microwave soil treatment releases more nitrogen sources in the soil for the crop growth [73]. This may be due to the resilience of nitrifying bacteria and archaea to microwave soil heating. Khan et al. [72] showed that microwave soil treatment did not significantly affect ammonia oxidizing bacteria or ammonia oxidizing archaea. Vela et al. [74] also demonstrated that nitrifying bacteria in the soil were resilient to 40 kJ cm^{-2} of microwave energy at the soil surface; which is 70 times higher than the energy densities used during experimental work undertaken by the current authors.

7. Crop responses

Fully replicated pot and field plot experiments have been undertaken over an extended period of time by the authors to better understand the impact of pre-sowing microwave soil treatment on crop growth. In all cases, the experiments had at least 5 experimental replicates and in many cases, they used 10 experimental replicates. Experiments were undertaken to explore the effect of pre-sowing microwave soil treatments on plant growth and yield of wheat (*Triticum* spp.), rice (*Oryza sativa*), maize (*Zea mays*), canola (*Brassica napus*), processing tomatoes and strawberry runners. In most cases the potted experiments were repeated two or three times and in some cases the field experiments were also repeated. Microwave energy was applied to the soil in pots or in situ using a trailer mounted microwave prototype system with 4 individual 2 kW microwave generators (see **Figure 8**).

The crops were planted within hours of the microwave treatment, once the soil had returned to ambient temperature. Plant growth rate, final plant height, and crop yield showed significant increases with increasing microwave energy (**Table 2**). In the potted trials and in one wheat field trial, hand weeded controls were included in the experiments to determine whether crop growth response was simply due to less weed competition.

Pre-sowing microwave soil treatment was found to have significant beneficial effects on subsequent crop growth. Most crops showed a typical Gaussian Error Function response to increasing microwave soil treatment dosage (**Figure 6**), as would be expected if the pre-sowing soil treatment were acting as a soil fumigant (**Figure 9**).

Figure 8.
Prototype 4 by 2 kW microwave weed killer in a strawberry runner field at Toolangi, Victoria.

Microwave treatment	Control	Hand weeded	Microwave energy (J cm^{-2})			LSD (P = 0.05)	Change from hand weeded/ control (%)
			136	318	545		
Pot trials							
Canola pod yield (g pot^{-1})	0.27^{a}	0.56^{a}	0.36^{a}	1.25^{b}	1.95^{c}	0.55	250%
Wheat grain yield (g pot^{-1})	0.66^{a}	0.67^{a}	0.68^{a}	0.75^{a}	1.25^{b}	0.3	87%
Rice grain yield (g pot^{-1})	40.0^{a}	41.3^{a}	43.3^{a}	59.0^{ab}	64.0^{b}	18.9	55%
Maize (g pot^{-1})	5.3^{a}	6.6^{a}	__	10.3^{ab}	12.8^{b}	4.8	92%
Field trials							
Rice (t ha^{-1}) – Dookie Year 1 (2015/2016)	7.5^{a}	__	__	__	10.1^{b}	2	35
Rice (t ha^{-1}) – Dookie Year 2 – (2016/2017) - crop was cold affected at panicle initiation	2.1^{a}	__	__	__	3.9^{b}	1.3	84
Rice (t ha^{-1}) – Old Coree – (2016/2017)	7.7^{a}	__	__	__	9.1^{b}	1.2	19
Wheat (t ha^{-1})	5.7^{a}	6.6^{ab}	__	__	7.8^{b}	1.4	18
Tomato (t ha^{-1})	64.1^{a}	65.2^{a}	__	__	89.6^{b}	24.7	37
Strawberry runner production (daughter plants m^{-2})	6970^{a}	__	__	__	8445^{b}	670	21

Means with different superscript letters (i.e. a, b, c etc) are statistically different from one another at a probability of 0.05.

Table 2.
Summary of pot and field trial crop yields in response to microwave soil treatment.

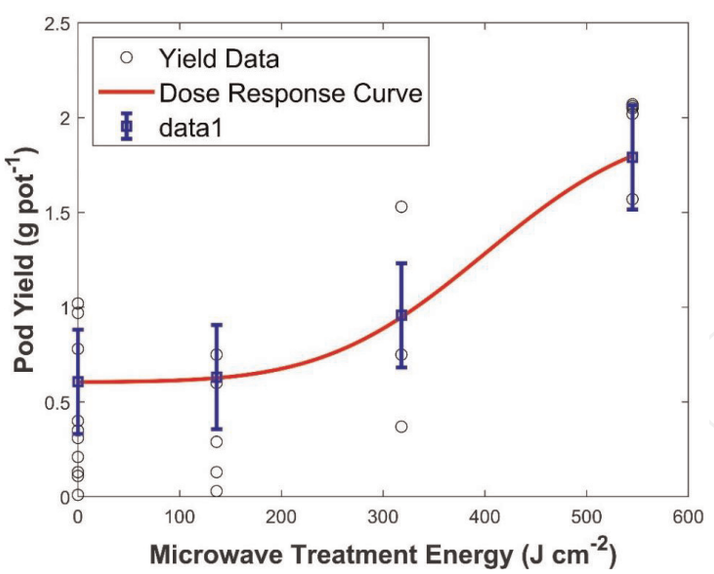

Figure 9.
Canola pod yield response to increasing microwave treatment.

8. Conclusions

Pre-sowing microwave soil treatment acts as a soil sanitation technology and results in significant increases in crop yield, as would be expected from other soil sanitation techniques. Microwave treatment has some major advantages over other soil sanitation techniques in that it is purely thermal in nature and allows immediate

access to the site once the soil has cooled to ambient temperatures. Unlike, other thermal treatment systems, such as steam treatment, microwave systems can be light and highly controllable, reducing other impacts on the soil such as compaction.

Also, unlike other soil sanitation techniques, it is evident that microwave treatment does not sterilize the soil, but favors beneficial species of soil biota making more nutrients available for better plant growth. From these perspectives, microwave soil treatment may become an important pre-sowing soil sanitation technology for high-value cropping systems, allowing agricultural systems to better bridge the crop yield gap.

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