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Use of Microwaves for Disinfection of Farmland: a Feasibility Study

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This work focuses on the heat transfer dynamics in agricultural soils when exposed to microwave (MW) fields, in order to disinfect them and to eliminate dangerous organisms without using pesticides. The work managed with the design of a horn antenna, with fixed feeding power, to be used to irradiate the superficial layer of soils for a fixed depth. The soil was approximated with a transmission line model, i.e. a lumped electrical model. By this model, after evaluating the relevant physical parameters such as the dielectric constant (as a function of the soil water content), it was possible to evaluate the power absorption and, finally, the increase in temperature and its profile as a function of the irradiation time. The latter information, strictly connected to the heat transfer process, demonstrated the feasibility of the methodology here proposed to achieve difficult conditions for microbial and pathogens life and so an effective disinfection of the treated farmland.

1. Introduction

Recently the scientific community's interest in biological agriculture has widely increased. "Bio-Agriculture" means precise cultivation methods, excluding the use of chemical products such as herbicides and pesticides. In recent times the use of electromagnetic (EM) waves, especially microwaves (MW), for soil disinfection from pathogen agents has been taken into account. Microwaves are important because lead to an increase in the rotational energy of molecules, especially those of water, which possess an electric dipolar moment with angular frequency equal to that of MW (Fanti et al., 2016), and for this reason they are widely diffused in chemical (Desogus et al., 2016) and biochemical processes (Fanti et al., 2015), particularly with aqueous solutions (Casu et al., 2016). As bacteria and microorganisms are mainly composed of water, the energy transfer, i.e. the temperature increase, can be exploited to inhibit or eliminate them, creating intolerable environmental conditions (Nelson, 1996). On the other hand, microwave effects on bacteria have been showed in the literature (Carta and Desogus, 2010), and also non-thermal effects (Carta et al., 2006).
Microwaves have often been proposed as an enhancing factor in environmental remediation (Carta and Desogus, 2013), and also in the soil treatment for the elimination of chemical pollutants (Acierno et al., 2003), but, at our knowledge, it cannot be found in the literature any testing and analysis of soil disinfection with in situ MW applications (Baghdadi et al., 2008). The main studies on the soil response to MW irradiation were conducted using radar remote sensing, taking into account the surface roughness (Ulaby et al., 1978), also developing semiempirical backscattering models (Ulaby et al., 1982) and using inversion techniques (Ulaby et al., 1986). Also other authors focused on the passive response of soil to MW (Schmugge et al., 1986), and a reliable and accurate review of them was done by Das and Paul (2015). Moreover, these analyses exploited free-space techniques, as done by Hallikainen et al. (1985) and by Valbonesi and Bisceglia (2015), or driving structures, e.g. waveguides or horn antennas (Helszajn, 2000). Moreover, the studies on soil irradiation ranged from the determination of the electric parameters, i.e. the quantification of electric permittivity of several soil layers taking into account the content of water (Wang and Schmugge, 1978) or moisture (Fung,

1994), to the frequency response of the soil (Hallikainen et al., 1985), but also the prediction and prevention of possible hydrological phenomena in areas with risk through satellite and georadar detection (Guattari et al., 2015). Regarding agricultural soils, nowadays the problem of the elimination of pathological agents (algae, fungi and fungine roots, viruses, nematodes, protozoa) is perceived as fundamental, especially for the quality of the cultivated products. Since many biological species can be pathogenic, the agricultural soil should be disinfected without affecting the organic nutrients. Aim of this work is to assess the feasibility of the use of high-power microwaves to disinfect the soil. The MW use seems to be promising since it does not affect organic substances if the temperature is suitably controlled to prevent overheating. The chosen exposure system consists of a pyramidal horn antenna feed by a waveguide, similar to a literature device (Helszajn, 2000), often used for this kind of studies, as mainly done by Hallikainen et al. (1985) and much more recently Bebawi et al. (2007), but herein designed according to the approach described by Simone et al. (2015) using the PSO algorithm for the rectangular feeding waveguide (Simone et al., 2016).

2. Physics soil properties

Soil is defined as a mixture of fragmented and eroded minerals, of decomposing organic matter and a certain amount of water and air. Four are the main soil components, which are listed in Table 1. These features, i.e. its composition, establish the texture of soil, which is an important characteristic identifying how the ground under analysis retains water or moisture, the amount of which is a relevant parameter influencing the dielectric constant. Soil is a porous medium, and typically, for farmland, porosity is around 70 %. Such pores can be filled with water or air. If they contain mainly the latter, the soil is dry or sandy; on the other hand, if they are mainly filled in by the former, the soil can be classified as clayey, i.e. saturated soil. Water can be found in pores in different states: vapour, free-and bound-water, depending on the soil composition, which influences the affinity between water molecules and solid surfaces. Hence it is possible to define the field capacity (FC) as a function of the water content (humidity) in the soil, which varies depending on the ground porosity, as stated by the expression of Wang and Schmugge (1978):

$$FC = 25.1 - 0.21 \cdot S + 0.22 \cdot C \qquad (1)$$

where S and C are the percentual amount of sand and clay, respectively. From FC the volumetric amount of water (m_v) can be obtained, dividing the water fractional volume by the soil bulk density (Behari, 2005).
Another relevant material for the soil characteristics is peat, which is an organic formation mainly composed by vegetal residues impregnated by water, sunk in an acid environment, so that they cannot completely decompose. However, peat may include many different kinds of organic materials, e.g. insects or animals remains. Moreover, such kind of material is highly porous, with variable texture (similar to clay or gravel), depending on its porosity (46 - 84 %) (Ayalew et al., 2007), and extremely wet, these listed conditions allow the proliferation of several microorganism populations, namely pathogens and parasites.

3. Electromagnetic model

3.1 Antenna design

To irradiate the soil, we designed a horn antenna with pyramidal base, composed by a waveguide and fixed aperture dimensions. The radiation system was fed with an available power P_{MW} at a frequency of 2.45 GHz and it exhibited 10 dB gain. The behavior and response of our antenna was analyzed using a Finite Element Method software for high frequencies EM problems. The horn was placed at the distance of 0.95 m from the soil surface, and produced a Poynting vector modulus $S_i = P_{MW}/A_1$ over the irradiated area A_1 of 0.72 m^2.

3.2 Dielectric constant of soil

In order to establish the soil behavior under MW exposition, it was necessary to determine the value of its relative dielectric constant (ε) for humidity ranging from 0 ÷ 10 (dry soil) to 30 ÷ 40 % (wet soil), and also 50 ÷ 90 % (peat). To quantify such physical parameter (both the real and the imaginary parts, ε' and ε"), we exploited the empirical model of the following Eq(2) developed by Hallikainen et al. (1985):

$$\varepsilon' (\text{or } \varepsilon'') = (a_0 + a_1 \cdot S + a_2 \cdot C) + (b_0 + b_1 \cdot S + b_2 \cdot C) \cdot m_v + (c_0 + c_1 \cdot S + c_2 \cdot C) \cdot m_v^2 \qquad (2)$$

in which aj, bj and cj are fitting parameters and j refers to the component by the percentual amount of which the parameter must be multiplied (0 for none, 1 for sand, 2 for clay). Of course, the soil behavior under radiation could also be measured using frequency domain (Mazzarella and Panariello, 1991) or time domain (Costanzo et al., 2013) reflectometry.

Table 1: Classification of soil granulometric classes (diameter size in mm) (Soil Conservation Service, 1987)

Clay	Silt	Sand					Gravel
		Very fine	Fine	Medium	Coarse	Very coarse	
< 0.002	0.002÷0.05	0.05÷0.1	0.1÷0.25	0.25÷0.5	0.5÷1.0	1.0÷2.0	2.0÷50.0

3.3 Equivalent circuit model of soil through analytical transmission line model

To evaluate electrical parameters when soil is irradiated, we modeled it with a lumped parameter model, approximating it to a transmission lines system, as shown in Figure 1. Since soil is composed of several layers of different texture and moisture (Hillel, 1998), and considering the antenna as a power source, every layer i is considered as a line with impedance Z_i, length L_i and propagation constant k_i. These values depend on the dielectric constant and can be calculated using the following expressions (Guattari et al., 2015):

$$k_i = \beta_0 \Big/ \sqrt{\varepsilon_i} \tag{3}$$

$$Z_i = Z_0 \Big/ \sqrt{\varepsilon_i} \tag{4}$$

where β_0 is the propagation constant of vacuum. The input impedance of the soil is different from the free-space one, so that a suitable matching network is required. Since the required bandwidth is very small, we used, in our model, the simple network of Figure 1b.

4. Soil biological environment

Soil is a living medium, in fact, thanks to water and air circulating in pores, and also to nutrients, it represents a favorable environment for life. Bacteria, fungi, plants and animals, e.g. invertebrates and small vertebrates, find suitable conditions to survive and reproduce, creating a fragile interacting dynamic system (Mitscherlich and Marth, 1984). Each of them has a specific role, function and position in the soil matrix, but it is necessary to distinguish between pathological and risky agents (nematodes, fungi and parasites), and favorable organisms, e.g. earthworms. These biological entities are mainly composed by water, ranging from 80 to 90 %. The study by Komarova et al. (2008) underlined that MW exert a lethal influence on bacteria, due to the increase in temperature and to the bioeffects of non-ionizing radiations, even if MW are applied to soils (Vela and Wu, 1979), but the explanation of the latter remains, in part, still unclear (Vela et al., 1976). Actually, some harmful agents are able to withstand high temperatures, even for long times of exposition. Experimental findings show that the treatment efficiency is strictly related to the exposure time, therefore, to reach the lethal temperature, such information should be related to power levels, so that future in situ actions can be designed and undertaken (Valbonesi and Bisceglia, 2015). We assumed, in this study, that the temperature of 60 °C must be reached for about 30 min in a layer about 3 cm thick (this thickness was chosen according to the information from Soil Survey Division Staff, 1993). Since the temperature, for a constant MW power, would increase with time, the fixed value can be maintained for a few minutes by a suitable reduction of the horn power or turning off the generator.

5. Methods and model

The moisture values used in the present work were acquired from a measurement campaign performed on Sardinian farmland using TDR (Time Domain Reflectometry) probe and gravimetric measures. Hence, data on the superficial layer of soil were directly exploited. The texture of analyzed soils is shown in Table 2. In order to evaluate the actual heating of the soil, we need to solve the following heat equation:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot \left(k \nabla T \right) + P \tag{5}$$

where ρ is the soil (bulk) density, ranging from 200 to 1,800 Kg m^{-3}, c is its specific heat, ranging from 800 to 3,300 J Kg^{-1} K^{-1}, k the thermal conductivity, ranging from 0.01 to 4 W m^{-1} K^{-1} (Coppola et al., 2007) (both c and k are relative to the soil considered as a pseudo homogeneous medium), T is the temperature (in K), t is time (in s), and P is the specific heat power (in W m^{-3}) generated within the volume by the MW power source. Since both the electromagnetic and the thermal properties of the soil are temperature-dependent, Eq(5) is non-linear. In order to assess the feasibility of the proposed approach, we decided to solve a simplified linear and one dimensional model. With reference to Figure 1, let be z ≥ 0 the soil semi-space coordinate. Then, the generated EM power is:

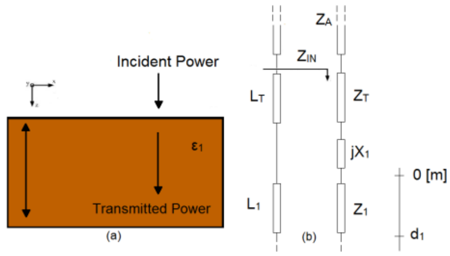

Figure 1: (a) first layer of the soil; (b) equivalent transmission line model with an incident plane wave on first layer and quarter-wave dielectric slugs impedance matching

$$P(z) = P(0)e^{-2\alpha_E z}, \text{ with } P(0) = 2\alpha_E S_i \tag{6}$$

where α_E is the imaginary part of the dielectric constant (Hallikainen et al., 1985) and is one of the main indicators of the feasibility of the technique here proposed. The power is produced only in the upper layer of the soil and then heat transfers toward the deepest layers (and in atmosphere), so the other relevant parameters are k and the average convection coefficient at the soil surface, h_c, considering that the heat power exchange with air (q_A) is given by the following expression, in which T_A is the air temperature:

$$q_A = h_c \cdot (T(0) - T_A) \tag{7}$$

The convection coefficient depends essentially on the air properties and, for the soil free surface, is around 2 W m^{-2} K^{-1}. However, if necessary, this value can be reduced by covering the soil with a layer of a smooth material; moreover, if an insulating material (e.g. polystyrene foam, which is transparent to the EM waves) is chosen for the cover, the heat flux to air can be further reduced (down to 0.5 W m^{-2} K^{-1}). On the contrary, the heat exchange with air can be significantly increased using forced convection, of more than one order of magnitude.

6. Results and discussion

We considered a horn power of 8 kW with S_i=11 kW m^{-2} and an initial air and soil temperature of 20 °C. For a dry soil, α_E can be around 6÷8 m^{-1}, so that the EM power is dissipated quite uniformly in the layer of interest (2÷3 cm depth from the surface). In this case the heating is near independent from the thermal parameters of the soil, but P(0) is very low (around 150 kW m^{-3}) and so about 7 - 8 min would be necessary to reach the temperature of 60 - 65 °C in the whole layer of interest (see Figure 2). However, since the temperature field is almost uniform, an increase of the MW power would reduce the heating time without overheating, which could damage the soil nutrients. A larger value of α_E, around 15 m^{-1} (i.e., a wetter soil) would produce a faster heating of the surface but would require a low k value (near to the lower end of its possible range). This could seem strange, since it is the heat diffusion that now increases the temperature of the lower portions of the useful soil. But the same effect is also responsible of the heat loss toward the deepest layers, where we do not need a disinfection. On the other hand, since such a value of α_E easily leads to surface overheating, h_c should be carefully chosen. Even larger values of α_E (near to 30 m^{-1}, typical of very wet soils) allow a quick heating, but a longer time is required to heat the lower layers, and the surface can easily reach 100 °C. From this discussion it follows that, using a proper horn power, we can reach the required temperatures for dry and slightly wet soils, preventing the surface overheating. However, for a given farmland soil, an optimization is needed to get the best water content and h_c value to reduce the overall disinfection time. This optimization, at first, could be done by a linear model, then it must be refined by a coupled EM-thermal non-linear one.

7. **Conclusions**

The results here presented show that MW heating can be a viable method to disinfect the upper layer of agricultural soils. However, a suitable optimization must be done, to select the optimal sets of parameters and among them the water content of the soil. Since this can be modulated by irrigation, a suitable protocol must be derived, depending on the initial soil characteristics, external temperature and air motion conditions. The higher air temperature, the better temperature distribution versus depth and time. In other words, for higher air temperatures, a more uniform optimal temperature distribution is reached in a shorter time.

Table 2: Collected soil texture data of some Sardinian farmlands (Montaldo et al., 2008; 2013)

Fields	Coordinates (WGS84 GD)		Soil Texture (%)		
	Longitude	Latitude	Sand	Silt	Clay
A – Silt loam	9.16691920436652	39.7029696452146	29.0	50.1	20.9
E – Clay loam	9.22181049758689	39.6876325325612	22.4	50.6	27.0
F – Loam	9.22368411780198	39.6900166394511	29.3	48.5	22.2
G – Silt	9.21743569879174	39.7317365306478	5.9	90.8	3.3
H – Silty clay loam	9.15900027986903	39.6883121736779	17.7	52.0	30.3

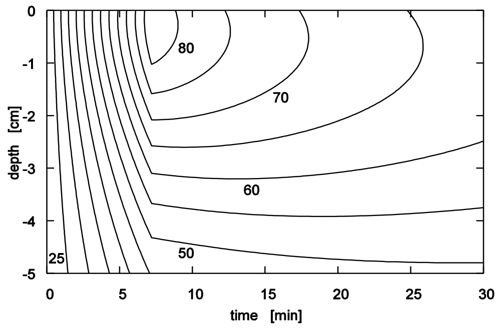

Figure 2: Soil temperature as a function of depth and time of irradiation (ρ=1,200 kg m^{-3}; c=1200 J kg^{-1} K^{-1}; k=0.5 W m^{-1} K^{-1}; h_c=2.0 W m^{-2} K^{-1}; S_i=11 kW m^{-2}; MW irradiation stopped after 7.2 min; temperatures in °C)

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