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Electromagnetic Solutions for the Agricultural Problems

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1. The idea of electromagnetic waves in agricultural applications

1.1 Introduction

In the recent years, interactive relations between various branches of science and technology have improved interdisciplinary fields of science. In fact, most of the research activities take place somewhere among these branches. Therefore, a specialist from one branch usually can propose novel methods, whenever enters a new field, based on his previous knowledge.
Taking a look at the extensive problems in the field of agriculture, an expert in the field of Electromagnetic waves can easily suggest some innovative solutions to solve them. The major suffering problems with which a farmer faces are the damages caused by the harmful pests as well as the product freezing in unexpected cold weather. The promising available biological methods of treatment have decreased the need for new treatment methods effectively. However, some advantages of electromagnetic treatment is still without competitor. The environment-friendly methods we introduce in this chapter are to use electromagnetic waves to kill pest insects without killing the taste or texture of the food they infest.

1.2 Electromagnetic waves in agricultural applications

Electromagnetic waves as tools in the field of agriculture have been used in many applications such as remote sensing, imaging, quality sensing, and dielectric heating in a pre-harvest or post-harvest environment. However, the goal here is to discuss about applications which are directly related to the main electromagnetic wave effect which is warming. Among variable methods applicable in the agriculture section, Radio frequency (RF) power has been known as physical (non-chemical) thermal method. In this method, the general idea is the same as heating food products to kill bacteria. It can be used to disinfest various foods and non food materials including soil. On the other hand, there are applications of using radio frequency to measure soil parameters and soil salinity, as well.

1.3 Pest control and electromagnetic waves

Traditional agricultural producers usually use simple conventional chemical sprays to control pests. Despite the simplicity of use, these chemical fumigants such as Methyl Bromide have many disadvantages such as reducing the thickness of Ozone layer (Tang et al. 2003). Additionally, the probable international ban of methyl bromide for post-harvest treatments will increase the attention to other methods. Three other methods including ionizing radiation, cold treatments and conventional heating has been reviewed in (Wang & Tang, 2001). In ionizing radiation, the main problem is that it is not possible to shut of the radiation after ending the treatment. In addition, although there are still some road blocks to use irradiation effectively and also commercially. Cold treatments are not a complete method due to high price and relatively long required time. The drawback of the conventional heating methods originates from the fact that this kind of heating warms both pest and the agricultural product similarly which may destroy product's quality. To overcome these problems, some modern techniques such as genetic treatments, ultrasonic waves and electromagnetic treatments have been suggested in the literature.

The use of electromagnetic exposure, mainly electromagnetic heating has been started in 1952 by Frings (Frings, 1952) and then Thomas in 1952 (Thomas, 1952) and Nelson from 1966 (Nelson, 1966). But today there are vast applications for electromagentic waves are proposed at least to be an alternate treatment method. Formerly, the electromagnetic wave method was suggested as a post-harvest treatment, but recently, it has been suggested to be used as an in-the-field method for pest control or to prevent the agricultural product from getting freezed (Aliakbarian et al., 2007).

1.4 Challenging problems

Although the effectiveness of using radio waves to kill destructive insects in agricultural products has been known for 70 years, the technique has rarely been applied on a commercial scale because of the technical and market problems. There are at least six challenging problems against the vast implementation of electromagnetic waves use in agricultural applications: high electromagnetic power needed, probable human health effects, probable biological effects on the surrounding environment, finalized price, frequency allocation and system design complexity.

Power problem can be easily solved if the employed frequency is not more than the low-gigahertz range. Based on the fact that high power sources are now available in VHF and UHF frequencies the power problem can be solved.

The problem of price is also an economic topic that should be considered by investors. The enormous detriments of *pests* may motivate large companies in this investment. In addition, RF technology is already used commercially and has existed for about 40 years. Consequently, the machinery that delivers the RF blast will probably be affordable for the industry. However, it is still costly to pay $ 2,000/kW or higher in some bands. Although it is reported that the technology is already commercially applied to food products including biscuits and bakery products in 40 MHz (Clarck, 1997), researches of a team led by J. Tang since 2005 (Flores, 2003(2)) shows that we still need more researches to the economical industrial use of radio waves.

The problem of frequency allocation in some countries is crucial. However, shifting the frequency to the closest ISM bands can solve the frequency allocation problem. The Federal Communications Commission has allocated twelve industrial, scientific and medical, or

ISM, bands starting from 6.7 MHz to 245 GHz. For the outdoor environments, electromagnetic waves are needed for a few days in a year.
Another problem is to design such a proper controllable system to warm up pests uniformly. For example, in a complex environment, if a single power source is used, it will be difficult to cover the whole environment. Thus an array of sources should be designed. Moreover, the frequency of treatment must be selected in such a manner that the absorption of energy by pest be more than other materials available.
Today, electromagnetic wave is known as a potential hazard of health and biological effects such as cancer. It is tried to shield and protect the radiation space from the outside environment. On the other hand, in the outdoor problems, we reduce the hazard lowering the exposure time. Moreover, treatment environments are usually empty of human population. In spite of the health effect, biological effects of electromagnetic exposure should be evaluated to ensure that it does not have a harmful effect on the ecosystem.

2. Theory of electromagnetic selective warming

2.1 Introduction

There are various ideas about the mechanism of pest control using electromagnetic waves. Most of the researchers believe that the waves can only warm up the pests. This belief originates from the fact that these insects are mostly composed of water. Normally, the water percentage in their body is more than the other materials present in the surrounding environment. On the other hand, there are some claims expressing that not only do the electromagnetic waves heat the pest, but also they can interfere with their bodys' functionality with their none-thermal effects. (Shapovalenko et al., 2000). Fig.1 represents a practical tests of electromagnetic exposure which shows pests running away from the antenna. Their escape may be due to heating effect or due to some other colfict to their dody. Although attraction is also reported, a reapetable test has not been verified. However, none-thermal effects of electromangetic waves on living tissue has been confirmed (Geveke & Brunkhorst, 2006).
The imaginary part of the dielectric constant can be used to heat up a material remotely using radio waves. However the main goal is not just to heat a material (*i.e.* a flower) in the indoor or outdoor environment since it can be done using a heater or 2.4 GHz microwave source. The mission, here, is to warm a material while the surrounding materials are not affected. This can be done using the difference between the imaginary parts of the dielectric constants of two different material at a specified frequency. Taking into account that the dielectric constant of each material is frequency-dependent, there can be an appropriate frequency for which the electromagnetic energy is absorbed by the pest while the product or plant don't absorb the energy at this frequency. Concequently, this process will not affect the quality of the agricultural products, specially important for the products which are sensitive to the temperature increase.

Fig. 1. Repelling in response of *Sunne* pest to electromagnetic exposure

2.2 Electromagnetic heating

Dielectric materials, such as most plants, can store electric energy and convert electric energy into heat. Each material has a complex permittivity (ε) in general. According to measurements, usually this value is noticeably frequency dependent. The imaginary part (ε″) of this value is responsible for absorption of electromagnetic waves in each material. Eq.1 shows the general form of the first Maxwell's equations considering (ε″).

$$\begin{aligned} \nabla \times H &= j\omega\varepsilon' E + J = j\omega\varepsilon' E + \sigma E \\ &= j\omega(\varepsilon' - j\frac{\sigma}{\omega})E = j\omega(\varepsilon' - j\varepsilon'')E \end{aligned} \tag{1}$$

As a consequence, total power absorption in a specific material is achieved if the second part of the equation is integrated over the material volume as follows.

$$P_{Loss} = \int_v E.JdV = \int_v \sigma |E|^2 dV = \omega \int_v \varepsilon'' |E|^2 dV \tag{2}$$

The basic idea is to use ε'' to warm up the selected materials which are located far from an electromagnetic source. On the other hand, the E-field distribution inside the absorbing material highly depends on the shape of absorber and surrounding scatterers, compared to wavelength and also the source of excitation. For instance, regarding the distribution of a cluster of walnuts inside an oven, the resulted electromagnetic wave inside one of them is a function of its shape, the shape and the position of other walnut as external scatterers and the oven and its exciting antenna as the source. Hence, not only the total absorbed energy resulted from (2) is important, but also the uniformity of the electromagnetic field distribution is crucial. If the dimensions of the exposed object are electrically small, we can assume the E-field distribution inside the object is uniform. For bigger objects, the penetration of the wave inside the object, i.e. skin depth, can be calculated using (3) depending on frequency used and the dielectric properties of the sample under test, especially conductivity.

$$\delta = \frac{1}{\sqrt{\pi \mu_o}} \sqrt{\frac{1}{\sigma \mu f}} \tag{3}$$

Wherein, δ is the skin depth in meter, f is frequency in Hz, μ is relative permeability, σ is conductivity ($S \cdot m^{-1}$). and μ_o is $4\pi \times 10^{-7}$. The increase in the temperature of a material by absorbin the electromagnetic energy can be expressed in Eq. (4) as stated in (Nelson, 1996)

$$\rho C \frac{\Delta T}{\Delta t} = 55.63 \times 10^{-12} f E^2 \varepsilon'' \tag{4}$$

where C is the specific heat capacity of the material ($J.kg^{-1}.°C^{-1}$), ρ is the density of the material (kg.m-3), E is the electric field intensity ($V.m^{-1}$), f is the frequency (Hz), ε'' is the dielectric loss factor (farad/m) of the material, Δt is the time duration (s) and ΔT is the temperature rise in the material (°C).

Thus, if the goal is to absorb as much as the energy to the victim, the optimized solution is to maximize P_{loss} or simply $\varepsilon''(f)$ in a predefined structure.

Thus, it is essential to measure the dielectric constant of the material. Fig.2 shows the measured dielectric constant and loss factor of tissue of fresh Navel Orange in terms of frequency measured at different temperatures (Nelson, 2004). The figure indicates that the dielectric constant relatively depends on the temperature of the material.

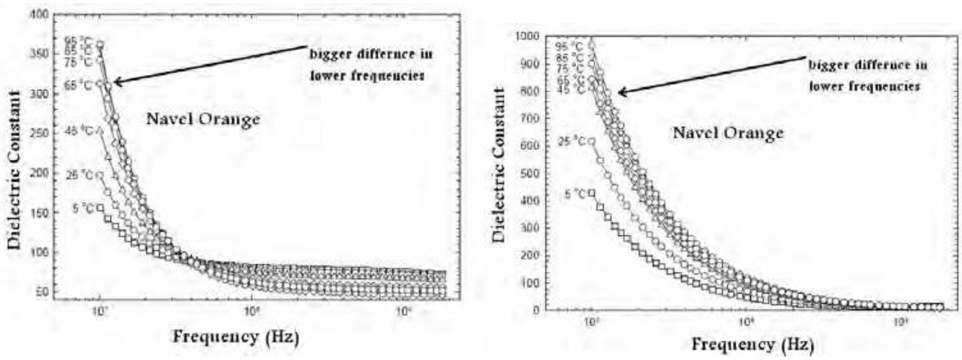


Fig. 2. Dielectric constant of fresh Navel Orange in different temperatures (Nelson, 2004)

2.2 Differential heating

The dielectric constant parameter for materials as a whole and for agricultural products specifically varies with frequency. For instance, ε'' of water has a peak in 24 GHz frequency. The absorption frequency of water may help us in warming the water in the insects' bodies but probably all of the other water-composed materials in the nearby environment absorb the energy as well. Thus, to be more efficient and safe, the electromagnetic wave should have a frequency which maximizes the difference between temperature increment in pest on one side and the agricultural products on the other side. This goal can be reached by using the frequency dependent character of the dielectric constants of the two materials. Using (4), the function in (5) represents a goal function which should be maximized in the volume of an electrically small object.

$$\begin{aligned} Goal(f) &= \frac{(\Delta T_{pest}(f) - \Delta T_{Orchid}(f))}{\Delta t} \\ &= \frac{\alpha f E^2_{pest}(f)\varepsilon''_{pest}(f)}{\rho_{pest} C_{pest}} - \frac{\alpha f E^2_{Orchid}(f)\varepsilon''_{Orchid}(f)}{\rho_{Orchid} C_{Orchid}} \\ \alpha &= 55.63 \times 10^{-12} \end{aligned} \tag{5}$$

Using the assumption that specific heat capacities of the both materials are equal, goal function is reduced to (6).

$$Goal(f) = \frac{\alpha f}{\rho C}\left(E^2_{pest}(f)\varepsilon''_{pest}(f) - E^2_{Orchid}(f)\varepsilon''_{Orchid}(f)\right) \tag{6}$$

If we simply suppose that electric field is equal in pest and agricultural product regions, the goal function is reduced to (7)

$$Goal(f) = \frac{\alpha f E^2}{\rho C}(\varepsilon''_{pest}(f) - \varepsilon''_{Orchid}(f)) \tag{7}$$

Therefore, approximately, it can be stated that we are searching for a frequency at which the difference between ε″ (f) of the agricultural material and pest is the most possible value. In order to solve this problem, we are going to measure the effective permittivity of the agricultural products to find the optimum frequency in which the difference between ε″ of the pest and the agricultural product is the largest.

The above discussion assumes that the target object is a small one in terms of heat convection, while it is not the case almost all of the time. Therefore, to predict the temperature in a practical three dimensional domain, Maxwell equations and Navier-Stokes equations should be solved simultaneously in the presence of all products. Navier-Stokes equations are nonlinear partial differential equations describes the temperature and gas distribution in an environment. The combined equation can help us to predict the real situation inside a silo.

In conclusion, taking a look at equations (4) and (7), we can find out that there are two approaches based on maximum energy transfer and maximum differential heating which does not necessarily happen at the same frequency.

2.3 Measurement of the dielectric constant (Wang et al., 2003)

There are many methods for the measurement of the dielectric properties of materials. The best one for arbitrarily shaped materials is the open-ended coaxial probe which ended at the material under measurement with full contact. Using the method, we can measure the properties in a wide range of frequencies using reflection data. The more accurate one is the transmission line method, but it is necessary to fill a part of transmission line with the samples accurately. In order to measure very low loss materials, cavity method can be used. In this method, the sample is inserted in a cavity and the change in the reflection coefficient and the resonance frequency shift is measured. Using accurate perturbation formulas, the dielectric constant can be calculated in one fixed frequency. Many experimental data has been released for several foods and agricultural products (Wang et al., 2003) but yet few works has been done on pest's properties. The measurement results shows that the properties highly depends on frequency, temperature, moisture content and also state of the moisture, namely frozen, free or bound.

3. Proposed treatments

The proposed treatments can be categorized from different aspects. Here, we divide the applications in two categories of post-harvest and pre-harvest treatments. On the other hand, the vast range of frequencies from low RF to microwave and millimeter waves can be used which is mentioned.

The applications of electromagnetic waves in agriculture are not known without Tang and Wang's works. For many years, they have tried to replace fumigation with radio frequency treatment for export fruit quarantine applied on cherries and apples in Washington, citruses in Texas, and also walnuts and almonds in California (Flores et al., 2003(1)).

3.1. Post-harvest treatment

3.1.1. Walnuts treatment in ISM band

Keeping in mind that the two third of world nuts are supplied by US, the importance of quality improvement will be clear. The dielectric loss factors of nuts' pests are much higher than those of the nuts illustrated in Fig.3 (Wang & Tang, 2001). Within a 3 minutes of treatment, the Codling moth, which infests the walnuts, is killed due to the high absorption of energy compared to the walnut (Ikediala et al., 2000). On the other hand, the shell and the air inside it act as an insulator and protect the walnut from convectional heating, while the electromagnetic wave selects the victim inside the walnut to transfer the energy. The speed of temperature increase is approximately 10 times the hot air method.

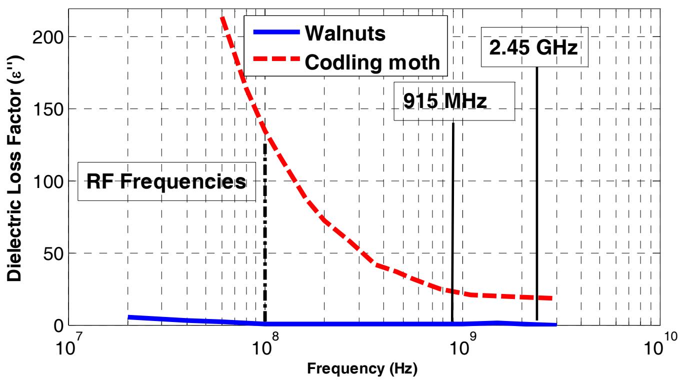


Fig. 3. Difference between the loss factor of codling moth and walnut (Wang & Tang, 2001)

Thus, the idea of combined methods is raised to remove some of the disadvantages of each one of them. If the RF heating is combined with hot air (Wang et al, 2002), the temperature drop during the holding period will be reduced and surface heating will be improved as well. The schematic of the system is described in Fig.4. 6 kW RF power in 27 MHz is supplied by an oscillator circuit, but the gap between electrodes is adjusted to expose 0.8 kW to the samples under treatment. From the other side, hot air is supplied using a tray drier.

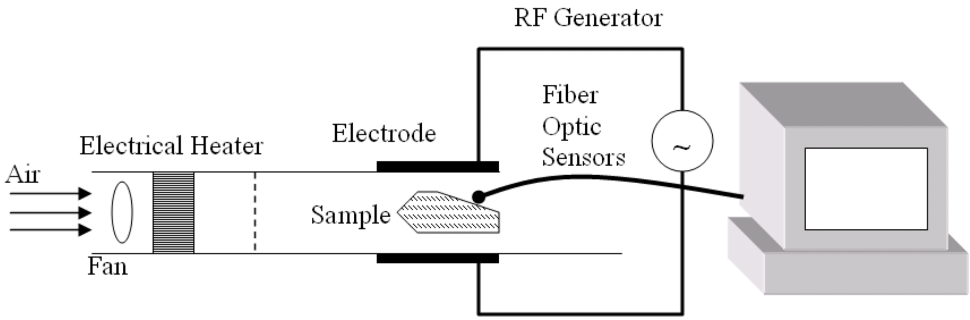


Fig. 4. Schematic of 27 MHz combined RF and hot air prototype

As another example of combined methods (Wang, 2001), RF heating can be combined with chemical fumigation. After fumigation, in-shell walnuts are washed and dried. During this process, walnuts are dropped into storage bins a number of times which may cause walnuts' shells to be cracked. With the use of RF waves to heat and dry the walnuts, we can effectively reduce damages, treatment time and required space. Yet, there are many practical problems such as the problem of different moisture content in walnuts. Moist material (basically water) has high dielectric constant. One of the reasons of the different moisture content is the different bleaching operations based on the customer (Wang et al, 2006). For example in US, 3% hypochlorite is used for Spain export while 6% hydrogen peroxide for Germany which are absorbed differently by the walnuts' tissues. Moreover, the absorption depends on the condition of the walnuts such as to be opened, closed, or cracked. A scaled pilot system is designed and implemented in 27 MHz (Wang, 2006). To overcome the problems of cost and quality, some solutions such as walnut orientation and intermittent mixing of the walnuts are suggested.

3.1.2 Thermal and none-thermal treatment of fruit Juice using low-frequency waves. (Geveke & Brunkhorst, 2006)

This work is to some extent similar to post-baking applications (Clarck, 1997) because both of them concerns food processing application rather than agriculture. On the other hand, this example is exceptional due to the use of none-thermal effects of electromagnetic waves. Use of radio waves to make safer fruit juices has been worked out by researchers for many years but has not been commercialized yet due to economical reasons. Conventional pasteurization is done using different heating techniques, but they can affect the nutrient composition and flavour of the fruit and vegetable juices. The new method is totally different. The radio frequency electric fields inactivate bacteria in apple juices without

heating them. According to Geveke and Brunkhors's work, the method has been used half century ago for pasteurization purposes but this is the first time that they could inactivate bacteria of fruit juice using this technique successfully.
However, using the combined method, namely the use of moderate heat in addition to the none-thermal method, has much greater effects than those of the either processes has alone. They have built a specially designed treatment to apply high-intensity radio frequency electric fields to apple juice. The schematic of the device shown in Fig.5 illustrates the juice flow passing the RF part in the center. It also highlights how it is tried to reduce required RF power to converge the juice flow into a narrow line. Current simulation is done using Quick field finite element software.

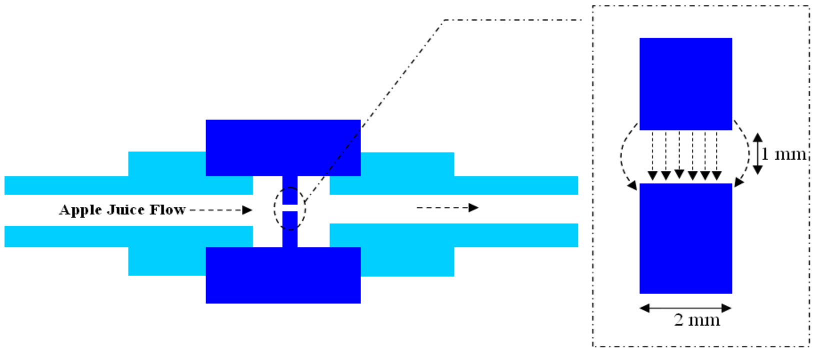


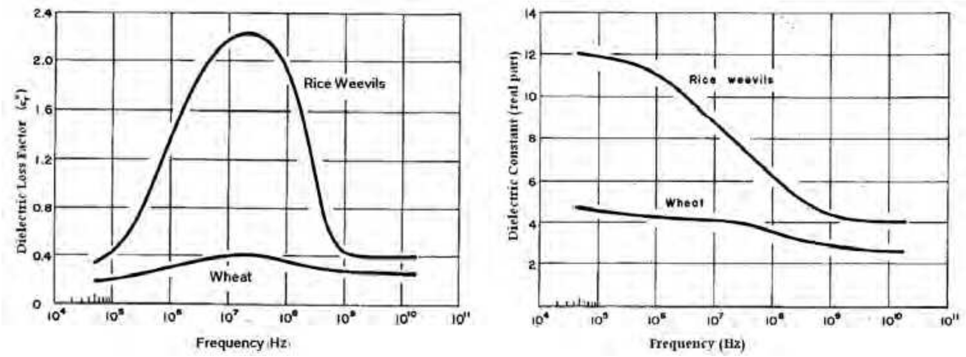
Fig. 5. Schematic of the treatment device for apple juice bacteria inactivation

The juice has been exposed to electrical field strengths of up to 20 kilovolts per centimeter and frequencies in the range of 15 to 70 kilohertz for 0.17 ms period, using a 4-kilowatt power supply. Based on the experiments, frequency increase as well as field strength and temperature increment enhances the inactivation. However, exposure above 16 Kilovolts intensity does not improve the inactivation performance and so do not the frequencies of more than 20 KHz. The experiment on different drinks in 18 MHz and intensity of 0.5 Kilovolts/cm does not show any none-thermal effect.

3.1.3 Indoor differential warming for wheat (Nelson & Tetson, 1974)

It is a key advantage if we can warm the infecting insects while not affecting the products. This decreases the undesirable effects of waves on the products especially when they can not tolerate temperature increment. As stated in the previous subchapters, this localized differential warming is based on the possible considerable difference between dielectric loss factors of the insects' body and products. Considering the fact that the insect objects are different in biological and physiological nature, they have different dielectric constants. The shapes and sizes are also different. Thus it is rather difficult to find a single optimized frequency for the differential warming.
Nelson (Nelson & Tetson, 1974) believes that treatment of the affected products with the lower frequency bands, namely 11-90 MHz, is much better and more efficient than those of the microwave bands such as 2450 MHz, meaning that pest can be controlled in lower

temperatures and using less power in the lower bands rather than microwave band. The complex dielectric constant of one kind of rice weevils and a kind of wheat in a wide range of frequencies are compared in Fig.6. It can be seen from the Fig.6 (a) that the band between 5 MHz and 100 MHz is the best option for differential heating.



(a) (b)

Fig. 6. (a) Dielectric loss factor of rice weevil and wheat versus frequency (b) Dielectric constant of rice weevil and wheat versus frequency (Nelson & Tetson, 1974) © 1974 IEEE

The theory is also confirmed by measurements done in different frequencies shown in Fig.7. In this figure, insect mortality in terms of temperature is shown for two different bands of 39 MHz and 2450 MHz and different durations, 1 and 8 days. It is obvious that complete mortality for 39 MHz frequency is achieved with less temperature around 50^{o} degrees compared to more than 80^{o} degrees for 2450 MHz. Thus, it shows that the complete mortality is delayed to be achieved in higher frequencies. The point which is not mentioned is that how long does is take to increase the temperature to the required level. Moreover, for a fair claim of differential heating, the magnitude of RF power and the resulted temperature of exposed wheat should also be mentioned.

In some cases, during the treatment, while the temperature increases, the frequency of maximum absorption (relaxation frequency) shifts to higher frequencies as shown in Fig.8. This is due to a change in the biological tissue of the insects. In another word, the dielectric loss factor depends on the temperature. Consequently, it may be more efficient to change the frequency of exposure during the treatment. This can be done using a sweeper starting from the lower up to the upper frequency bound.

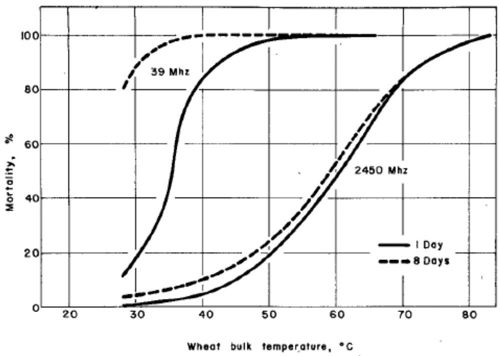


Fig. 7. Mortalities of adult rice weevils in different frequencies in terms of temperature (Mofidian et al., 2007) © 1974 IEEE

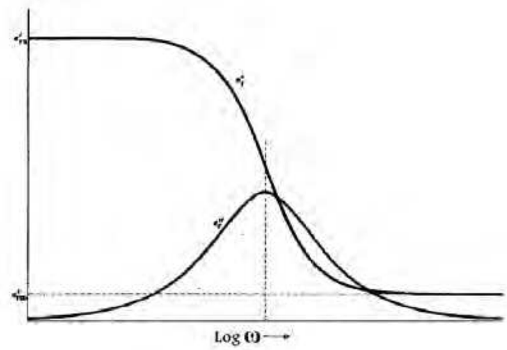


Fig. 8. Dispersion and absorption curves based on the Debye relaxation process for polar molecules (Mofidian et al., 2007) © 1974 IEEE

3.1.4 Millimeter wave pest killer (Halverson et al., 1998)

A practical device for stored-grains has been designed by Halverson presented in (Halverson et al., 1998). He has tried to assess the effectiveness and financial side of controlling stored-grain insects with microwave energy in millimeter wave and microwave band using the free-water relaxation frequency. It is worth pointing out that the crucial bottleneck of using these bands, which is the development of high-power microwave oscillators with tolerable price, has already been solved.

Another problem in using these bands is the poor penetration depth compared to low RF. The skin depth in a dense medium, mentioned in Equation (3), is inversely proportional to the frequency and the conductivity. Conductivity (σ) is also directly related to loss factor (ε'') according to Equation (1). Thus, a good compromise should be done between volume percentage of the gain in a mixture of air and grain when mass product rolls in. This calculation can help us to estimate the efficiency of maximum penetration of the energy into the flowing products. The 3 dB attenuation depth of energy (or similarly penetration depth) is then calculated using Equation (8) (Halverson & Bigelow, 2001).

$$\delta = 0.3466/(2\pi f\sqrt{\mu\varepsilon_o\varepsilon_r\cos(\tfrac{1}{2}\arctan(-\tfrac{\varepsilon_r}{\varepsilon_r'}\pm 2\pi)+\tfrac{\pi}{2})}) \tag{8}$$

And the ε_r of the mixture is calculated using Equation (9).

$$\varepsilon_r^{1/3} = \nu_2\varepsilon_{grain}^{1/3} + \nu_1\varepsilon_{air}^{1/3} \tag{9}$$

which υ_1 and υ_2 are the ratios of the volume of the air and infested product respectively. He has made several one-way path attenuation measurements on controlled air-grain mixtures of flowing soft white wheat, hard red wheat, and rice over a range of 18 to 50 GHz. Fig. 9. shows the semi-schematic for test fixture which performed attenuation tests. The grains are coming down from the hopper and the scalar network analyzer measures the insertion loss of receiver to transmitter link. The measurement results of maximum and minimum penetration depth for the three products, soft while wheat (SWW), hard red wheat (HRW) and rice, shown in Table 1, illustrate that the highest penetration depth occurs in the range of 18 to 26.5 GHz compared to that of the 26.5-40 GHz and 33-50 GHz frequency bands.

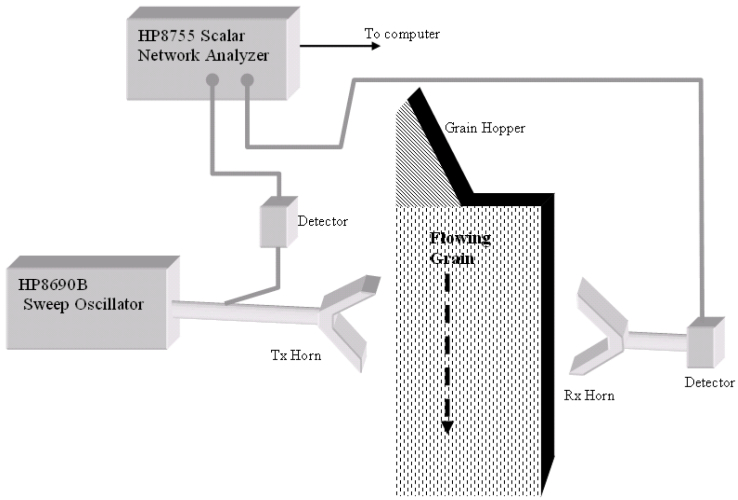


Fig. 9. Semi-schematic diagram of the one-way path attenuation measurement (Halverson et al., 1998).

Using measurement results, he designed the finalized version of his microwave/millimeter apparatus patented in 2001. The schematic of the device has been described in details in the patent (Halverson & Bigelow, 2001).

Grain	f (GHz)	L-3dB max (cm)	L-3dB min(cm)
HRW	18 to 26.5	501.39	75.70
	26.5 to 40	34.76	8.78
	33 to 50	101.95	13.68
SWW	18 to 26.5	139.66	35.48
	26.5 to 40	84.26	7.96
	33 to 50	100.94	12.36
Rice	18 to 26.5	180.97	46.34
	26.5 to 40	61.54	9.57
	33 to 50	131.26	10.22

Table 1. Maximum and minimum penetration depth corresponding to estimated attenuation (Halverson et al., 1998)

3.1.5 Microwave-protected silo (Mofidian et al., 2007)

The prototype system described here has used a bigger microwave oven to control insects of stored wheat. A 2.44 GHz magnetron source has been used to affect two kinds of existing harmful insects, *Sitophilus granarius* and *Tribolium*. This frequency band has been tried before (Andreuccetti, 1994) as the commercial high power low-price technology exists.

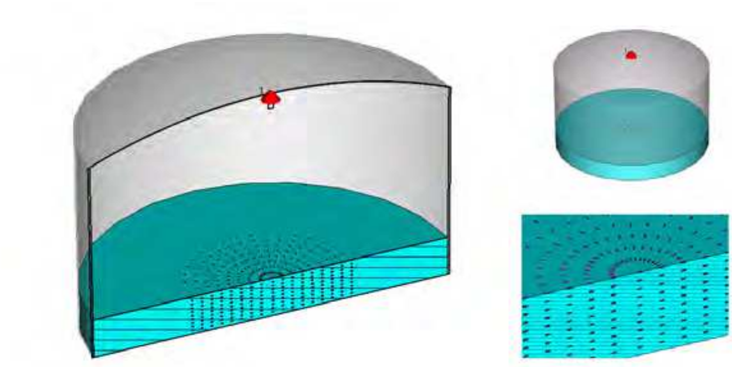
Most stored-product pests are killed within few minutes having temperature of 50^{o} C or more shown in Table 2 (Mofidian et al., 2007). On the other hand, there are possible methods such as cutting down the insects' activities using a lower temperature increment which requires a lower power as well.

Mortality, as a general rule, depends on the duration that insects are exposed. However, during heat treatment, temperature can be different within structural profile of a storing facility. Hence, the essential time which insects are exposed to the lethal temperature can differ depending on their location within the facility. This is one of the main problems of the electromagnetic exposure systems.

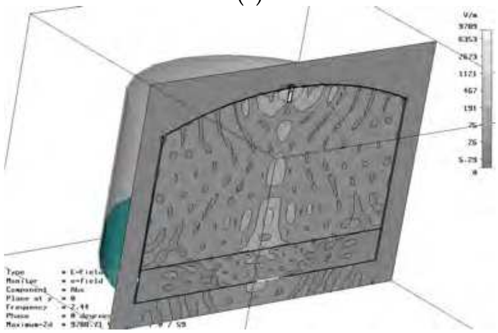
Temprature(°C)	**Effect**	**Zone**
50-60	Death in minutes	Lethal
45	Death in hours	Lethal
35	Development stops	Suboptimum
33-35	Development slows	Suboptimum
25-33	Maximum rate of development	Optimum
13-25	Development slows	Suboptimum
3-13	Death in days (unacclimated) movement stops	Lethal
-5 to -10	Death in weeks to months if acclimated	Lethal
-25 to -15	Death in minutes, insects freeze	Lethal

Table 2. Response of stored product insects to various temperature zones

The practical scaled system was designed similar to a real wheat storing silo. The system has been modeled in CST Microwave Studio 5 shown in Fig.11 with more than 1 meter diameter and 70 centimeters height. The exposed wheat is located at the bottom of the silo and the insects are inserted in middle areas of wheat-filled section. As can be seen in the Fig.11, the exciting monopole antenna is positioned at the top of the silo's lid below the microwave source.



(a)



(b)

Fig. 11. Design and simulation of the silo structure using CST software (a) defined structure (b) simulated E-field (Mofidian et al., 2007) © 2007 IEEE

The simulation of the structure has been done using 2.44 GHz normalized microwave source. The resulted E-field in the simulated silo is illustrated in Fig.11(b). It is obvious that the power density is concentrated in the center part of the system, approximately ten times higher than near the wall. Therefore, we expect that the wheats located in the center of the bulk absorb much more power in comparison to the other areas. Fig. 12 presents the constructed system of the silo and the exciting circuit including 220/2000 volt transformer, voltage rectifier, antenna and the 600 watt magnetron with its feeding circuit.

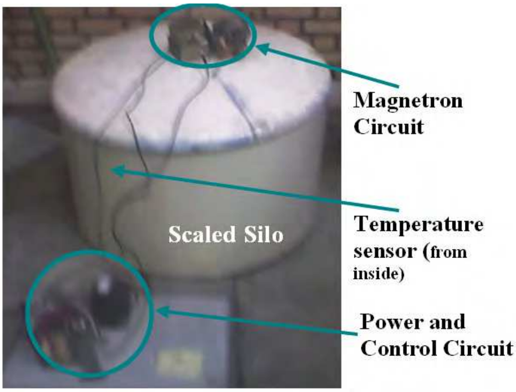


Fig. 12. The constructed scaled Silo using a 2.44 GHz source (Mofidian et al., 2007) © 2007 IEEE

Regarding the comparison of mortality rate between larvae and adults, it is evident that larvae are more susceptible than adults to high temperatures as larvae's mortality is more than adult's which can be seen in Fig.13 in terms of different exposed times. The susceptibilities of both insects are depicted in Fig.14. having similar behavior although *Sitophilus granarius* is quite more outstanding than *Tribolium*. The low mortality rate for 10-minute and 20-minute tests caused by the none-uniform distribution of the field. In the high intensity part, the pests are burnt while they are still alive in the low intensity parts. To improve the performance, the system antenna can be restructured using an array antenna. Obviously, we can reach a complete mortality of insects by increasing the exposure time or the power magnitude as well.

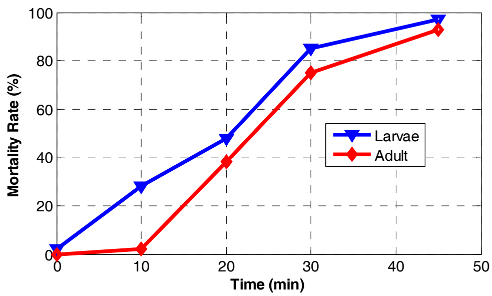


Fig. 13. Comparison between larvae and adults mortality rate of *Tribolium and Sitophilus Granarius* exposed to microwave radiation (2.44 GHz) in terms of exposed time

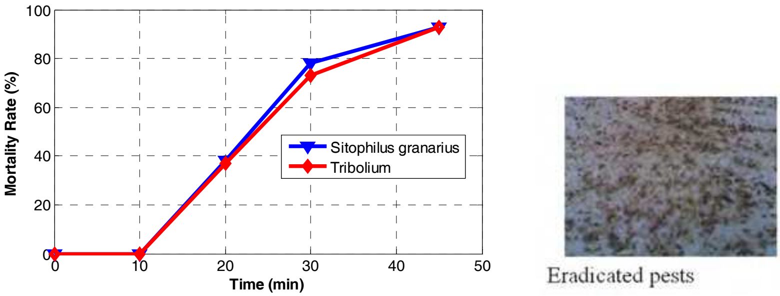


Fig. 14. Comparison between mortality rate of adult *Tribolium* and *Sitophilus Granarius* exposed to microwave radiation (2.44 GHz) in terms of exposed time

3.2. Pre-harvest treatment

3.2.1 Disinfection of soil (Lagunas-Solar, 2006)

Lagunas-Solar (Lagunas-Solar, 2006), at UC Davis, has used lower bands of the RF spectrum (few kHz to < 10 MHz) to disinfest the soil from pests. New RF systems has been designed and engineered based upon solid state electronics. A conceptual schematic of the system is illustrated in Fig.15. Its test is said to be relatively efficient for the control of fungi, nematodes and can compete with the other methods specially fumigation such as methyl bromide.

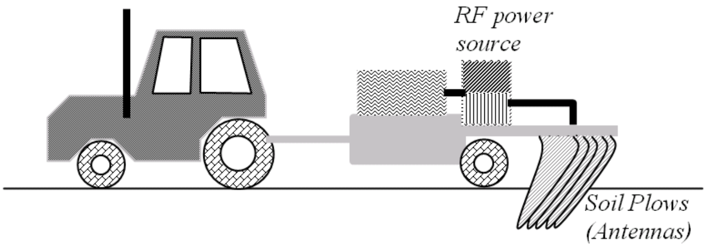


Fig. 15. Schematic for a Portable RF-Soil processing system.

The principle of the working is based on the relatively high electrical conductivity and heat capacity of the agricultural soils. Therefore, the RF oscillator of the system can transfer the energy to the soil, make it warm efficiently, and then it will retain the energy for a while. One of the biggest challenges for the efficient implementation of the system is the large volume (and mass) of soils and consequently the required energy. To save the energy inside the soil, some kind of covers on top can be used.

Using lower frequencies, the RF waves can easily penetrate the soil but do not affect the soil itself. Then, the absorbed energy in pests, mites, and mico-organisms annihilate them. Lagunas-Solar states that the using microwave frequencies may also cause permanent changes in the soil in contrary to the RF lower frequency waves' effects which are always reversible. Fig.16 shows the exposure time required for the soil to reach 60 degrees for different kind of soils. A comparison of soil disinfection using three methods is shown in Table.(2)

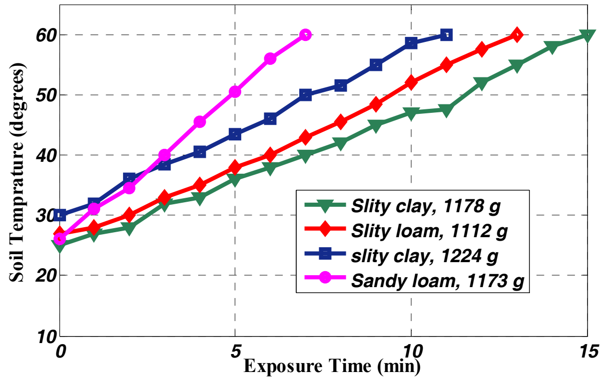


Fig. 16. Soil temperatures vs RF exposure time resulted from a 500 W test (Lagunas-Solar, 2006).

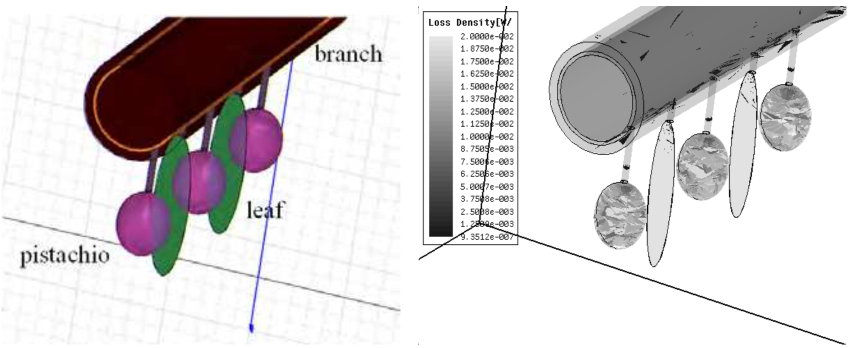
3.2.2 Pre-emptive attack (Aliakbarian et al., 2004),(Aliakbarian et al., 2007)

'Sunne' pest or '*Eurygaster integriceps*', shown in Fig.1, is the most destroying sap-sucking bug of wheat in the middle east, central and east Europe and North Africa in about twenty countries. The most injures in wheat production in these regions is due to this pest. The proposed idea is to use electromagnetic exposure to control *Sunne* pest in winters before their migration and attack to wheat farms, not to kill them with heat. The method is based on interfering the biological organization of *Sunne* pests in their life period.

The lifetime of the *Sunne* pests is only one year. By the end of March, groups of *Sunne* pests start to migrate to wheat farms and hurt their widest harm to flourishing wheat in 15 to 30 days. Also they start reproducing and then they come back to mountains until the next year. Furthermore, they have a winter sleep when they are in mountains and use their stored energy until the next year. *Sunne* pest can fly about 30 kilometers to the farms and so all of their winter shelters are known and are smaller than wheat farms. Traditional method of spraying poison to kill them in the winter is unsuccessful because they take crucibles as their shelters during these days. *Sunne* pests, like many other insects, are too sensitive to temperature variations and hence they don't attack to warmer regions. In addition, *Sunne* pests are more sensitive to temperature variations in the period of sleep in winter and the variation of climate temperature in this period usually causes an immense damage on them. The reason is that they have *diapause* phenomenon in this time which does not allow them to reproduce and nourish, so it makes them resist against coldness in order to save their energy during winter. As a consequence, if we can heat them up to about 12 to 15 degrees they will wake up and their *diapause* will be broken. Consequently, they should fly, reproduce, and move but not eat because they don't have any food. These activities result in shedding their energy with impunity and probably they can't live until spring or if they can, they can't fly to wheat farms due to the lack of energy. If this heating up is exposed more, their lives will be threatened seriously. The work then is to find the proper frequency which now is more focused on RF ISM band.

3.2.3 Anti-freezing (Aliakbarian et al., 2007)

Sudden freeze of product in a cold day of spring is one of the most damaging agricultural events. In many desert areas, temperature reduction in a few days may cause huge economic injuries. These detriments will be more painful when occur for costly productions like pistachio. By the end of winter, at the beginning of spring, plants are about to flourish. Because of the fact that the weather is not stable, the temperature may fall all of a sudden. Therefore, the biological tissues of the budded pistachio or other products may be damaged. It has been found that if the temperature of the production is increased about two or three degrees, we can save them from being offended immensely.
The previous techniques of anti-freezing have been limited to physical, biophysical and genetic treatments. For instance, in some areas, farmers put a fan and a diesel heater under each tree. These methods are more expensive and hard to exploit than the solution which is suggested here. More over, they have some potential hazards for consumers. Additionally, they need much time than they can be exploited on demand when the weather gets colder. We must estimate the weather condition far before necessity while, with the use of electromagnetic waves, there is no need to an exact prediction of weather condition. Regarding these advantages, it seems that this method can find a suitable place among the other methods in anti-freezing application.



(a) (b)

Fig. 17. (a) Pistachio branch model (b) Volume loss density, the hatched lines show losses (Aliakbarian et al., 2007) © 2007 IEEE

The proposed idea is to warm up the pistachio remotely and selectively using electromagnetic exposure while the other materials of the environment are not warmed up. The most significant work is to find the optimum frequency in which the difference in the absorption rate of energy in pistachio and sensitive objects is the most. This frequency also depends on the electromagnetic characteristics of the objects and can be measured practically. We have done some primary simulations using approximate parameters. Fig.17 shows an HFSS model of a pistachio branch and the volume loss density caused by an incident electromagnetic wave respectively. The simulation in 2.4 GHz in Fig.17 shows that volume loss density in the pistachio is higher than leafs, branch lines, and stems due to difference in dielectric constant in the used frequency.

4. Conclusion

Electromagnetic waves have been suggested for use in a vast range of applications in agriculture and food processing society. Although there is sill a long way for them to be used commercially, the idea can help us to consider this method as an alternative solution for different problems. Heating effect of the waves, especially if used as differential heating, is an efficient way to keep the pests away from the valuable products. The treatment base on EM wave can be employed in indoor or outdoor environments. Nevertheless, it has already been used for indoor environments due to technical and environmental issues. Other topics such as anti-freezing and none-thermal treatment have also been discussed. In conclusion, the usage of the method in commercial scale is likely applicable in a near future .

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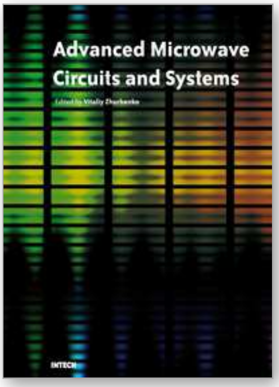

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This book is based on recent research work conducted by the authors dealing with the design and development of active and passive microwave components, integrated circuits and systems. It is divided into seven parts. In the first part comprising the first two chapters, alternative concepts and equations for multiport network analysis and characterization are provided. A thru-only de-embedding technique for accurate on-wafer characterization is introduced. The second part of the book corresponds to the analysis and design of ultra-wideband low- noise amplifiers (LNA).